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**Wear Performance Evaluation of Abradable Coatings:
A Tribological Investigation and Development of an
Abradable Test Rig**

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ABSTRACT

Wear Performance Evaluation of Abradable Coatings: A Tribological Investigation and Development of an Abradable Test Rig

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The increasing demand for fuel efficiency and reduced environmental impact in aircraft propulsion has accelerated the development of advanced clearance control systems for aircraft engines. Abradable seal coatings, applied to minimize the gap between rotating blade tips and stationary casings, reduce compressed air leakage, enhance operational safety, and lower fuel consumption, CO₂, and NO_x emissions. In low-pressure compressor (LPC) applications, thermally sprayed aluminum–silicon (AlSi) alloys, often combined with solid lubricants and engineered porosity, offer a balance between abrasability and durability under harsh operating conditions. However, due to the need for sophisticated custom-made abradable test rigs, developing and evaluating novel abradable materials under application-relevant conditions is challenging, typically very costly and time-consuming. Thus, this research addresses that gap by delivering a multi-scale evaluation of AlSi-based abradable coatings, linking fundamental wear mechanisms with application-relevant performance. A cost-effective abradable test rig was designed and validated to replicate LPC contact conditions, enabling rapid pre-screening of candidate materials. Three AlSi-based materials (AlSi-Poly, AlSi-hBN-Poly, and AlSi-MoCr-Poly) combined with different chemical compositions (hexagonal boron nitride, molybdenum and chromium) were thermally sprayed via Atmospheric Plasma Spraying (APS) and characterized through microstructural and tribological approaches. Wear performance was evaluated across multiple Technology Readiness Levels (TRLs), starting with ball-on-disk and ball-on-flat tests (TRL 3), and afterward compared with abrasability tests conducted under harsh conditions using the custom-built abradable test rig designed in this study (TRL 4). Both room-temperature and elevated-temperature (300 °C) assessments revealed distinct coating filler effects and negligible blade wear. hBN addition combined with polyester reduction promoted higher friction coefficient, rubbing forces and frictional heating, but also demonstrated improved thermal stability and reduced sensitivity to temperature-induced frictional changes. MoCr additions produced negligible changes in wear behavior compared to the baseline, suggesting viability as corrosion-resistant modifiers. Temperature elevation significantly reduced reaction forces for all coatings due to polymeric phase softening, without blade wear. Coating wear was dominated by abrasive cutting, with minimal aluminum adhesion to the titanium blades. Overall, this research provides new insights and practical tools for the development and evaluation of next-generation abradable materials, delivering benefits to both academia and industries engaged in advanced sealing technologies.

Keywords: Abradable Coatings; Abradability; Rig Development; Thermal Spray; Tribology.

Évaluation des performances d'usure des revêtements abrasables: étude tribologique et développement d'un banc d'essai d'abrasabilité

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La demande croissante d'efficacité énergétique et de réduction de l'impact environnemental dans la propulsion aéronautique a accéléré le développement de systèmes avancés de gestion des jeux dans les turboréacteurs. Les revêtements d'étanchéité abrasables, appliqués pour minimiser l'espace entre les extrémités des aubes en rotation et les carters fixes, réduisent les fuites d'air comprimé, améliorent la sécurité opérationnelle et diminuent la consommation de carburant ainsi que les émissions de CO₂ et de NO_x. Dans les compresseurs basse pression (CBP), les alliages aluminium-silicium (AlSi) projetés thermiquement sont appliqués, souvent combinés à des lubrifiants solides et à une porosité contrôlée, offrent un compromis entre abrasabilité et durabilité dans des conditions d'exploitation sévères. Cependant, le développement et l'évaluation de nouveaux matériaux abrasables sous conditions pertinentes d'application sont rendus difficiles, coûteux et longs en raison du besoin de bancs d'essai sophistiqués construits sur mesure. La présente recherche comble cette lacune par une évaluation multi-échelle des revêtements abrasables à base d'AlSi, reliant les mécanismes fondamentaux d'usure aux performances pertinentes pour l'application. Un banc d'essai abrasable peu coûteux a été conçu et validé pour reproduire les conditions de contact en CBP, permettant un pré-dépistage rapide des matériaux candidats. Trois formulations à base d'AlSi (AlSi-Poly, AlSi-hBN-Poly et AlSi-MoCr-Poly), incorporant respectivement du hBN, du Mo et du Cr ont été déposées par projection plasma atmosphérique (PPA) et caractérisées par des approches microstructurales et tribologiques. Les performances d'usure ont été évaluées à différents niveaux de maturité technologique (NMT), en commençant par des essais bille-sur-disque et bille-sur-plat (NMT 3), puis comparées à des essais d'abrasabilité en conditions extrêmes réalisés sur le banc développé (NMT 4). Les essais à température ambiante et à température élevée (300 °C) ont montré des effets distincts des charges de remplissage et une usure négligeable des aubes. L'ajout de hBN (avec réduction de la phase polyester) a entraîné une augmentation du coefficient de frottement, des forces de frottement et de l'échauffement par friction, tout en améliorant la stabilité thermique et en réduisant la sensibilité aux variations de température. Les additions de MoCr ont eu un impact négligeable sur le comportement d'usure comparé au témoin, suggérant leur viabilité comme modificateurs anti-corrosion. L'élévation de la température a réduit de manière marquée les forces de réaction pour tous les revêtements en raison du ramollissement des phases polymères, sans provoquer de dommages sur les aubes. L'usure des revêtements a été principalement dominée par des mécanismes de coupe abrasive, avec une adhésion d'aluminium minimale sur les aubes en titane. En somme, ce travail apporte de nouvelles connaissances et des outils pratiques pour le développement et l'évaluation de revêtements abrasables de nouvelle génération, au bénéfice du milieu académique et des industries engagées dans les technologies d'étanchéité avancées.

Mots-clés: Abrasabilité; Développement de banc d'essai; Projection thermique; Revêtements abrasables; Tribologie.

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CONTRIBUTION TO AUTHORS

This doctoral thesis follows a manuscript-based format, with each chapter prepared as an independent paper. Chapter 2 presents a comprehensive literature review, incorporating content adapted from a short review paper. Chapters 3 through 6 consist of reprints of manuscripts that have been published in high-impact, peer-reviewed scientific journals.

The research presented in these manuscripts was carried out under the supervision of Prof. Pantcho Stoyanov, who assisted with manuscript preparation, structural organization, experimental design, and critical evaluation of the results. Prof. Christian Moreau also played a key role by offering technical expertise and facilitating access to thermal spray processing facilities and related support.

Contributions from co-authors were as follows: Bruno E. Arendarchuck (Chapters 3, 5, and 6), Francisco R. E. Rivadeneira (Chapters 2–6), Leander Nolte (Chapter 6), and Maximilian Lehner (Chapter 6) participated in characterization activities, experimental planning, testing, and preliminary data analysis. Rakesh B. Nair (Chapters 2, 4, and 5) and Bruno C.N.M. de Castilho (Chapter 3) provided substantial assistance in manuscript revision and data interpretation. Barry Barnett, from Pratt & Whitney Canada, contributed throughout the project (Chapters 3–6) by offering industrially relevant insights, strategic guidance, and additional financial support.

The author of this thesis was primarily responsible for writing all manuscripts and carried out the thermal spray deposition, experimental procedures, material characterization, rig design and fabrication, as well as data analysis and processing.

The publications that form the basis of the chapters in this dissertation are listed below:

Chapter 2:

This chapter includes two review papers, reorganized and integrated to provide a coherent foundation for the discussions in this thesis.

[1] **K. Bertuol**, B.E. Arendarchuck, P. Stoyanov, An Overview of Metallic Abradable Coatings in Gas Turbine Engines, *Coatings* 15 (2025) 1216. <https://doi.org/10.3390/coatings15101216>.

[2] **K. Bertuol**, F.E. Rivadeneira, R.B. Nair, C. Moreau, P. Stoyanov, Advancing Abradable Evaluation: A Comprehensive Review and Development of an Innovative Cost-Effective Methodology, in: *Proceedings of the 27th International Congress of Mechanical Engineering, ABCM, 2023*. <https://doi.org/10.26678/ABCM.COBEM2023.COB2023-0143>.

Chapter 3:

[3] **K. Bertuol**, B.E. Arendarchuck, F.R.E. Rivadeneira, B.C.N.M. de Castilho, C. Moreau, P. Stoyanov, Design and Development of Cost-Effective Equipment for Tribological Evaluation of Thermally Sprayed Abradable Coatings, *J Therm Spray Tech* 34 (2024) 852–865. <https://doi.org/10.1007/s11666-024-01830-3>.

Chapter 4:

[4] **K. Bertuol**, F.R.E. Rivadeneira, R.B. Nair, B. Barnett, C. Moreau, P. Stoyanov, Influence of hBN on the abradable performance of AlSi-based coatings: Bridging the gap between tribological assessment and abradability testing, *Surf. Coat. Technol.* 489 (2024) 131060. <https://doi.org/10.1016/j.surfcoat.2024.131060>.

Chapter 5:

[5] **K. Bertuol**, F. Rivadeneira, B. Arendarchuck, R.B. Nair, B. Barnett, C. Moreau, P. Stoyanov, Effect of Mo and Cr on abradability and tribological performance of AlSi-based abradable coatings, *Wear* 571 (2025) 205837. <https://doi.org/10.1016/j.wear.2025.205837>.

Chapter 6:

[6] **K. Bertuol**, B. Arendarchuck, F. Rivadeneira, L. Nolte, M. Lehner, B. Barnett, C. Moreau, P. Stoyanov, Assessment of AlSi-Based Abradable Coatings with hBN and MoCr Additives for Aerospace Conditions: A Novel High-Temperature Rig Approach, *Aerospace Science and Technology* (2025) 110737. <https://doi.org/10.1016/j.ast.2025.110737>.

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LIST OF ABBREVIATIONS

AlSi – Aluminum-Silicon
APS – Atmospheric Plasma Spraying
APU – Auxiliary Power Units
BGRIMM – Beijing General Research Institute of Mining & Metallurgy
CBP – *Compresseur Basse Pression* (Low-Pressure Compressor)
CNC – Computer Numerical Control
CO₂ – Carbon Dioxide
CoF – Coefficient of Friction
Cr – Chromium
CS – Cold Spray
Dv50 – Maximum Particle Diameter Below 50% of Volume
EDS – Elemental Dispersive Spectroscope
Fn – Normal Reaction Force
Ft – Tangential Reaction Force
hBN – Hexagonal Boron Nitride
HPC – High-Pressure Compressor
HPT – High-Pressure Turbines
HR15Y – Rockwell Hardness Y with 15kgf Load
HT – High-Temperature
HV – Vickers Hardness
HVAF – High-Velocity Air-Fuel
HVOF – High-Velocity Oxy-Fuel
LD – Laser Diffraction
LPC – Low-Pressure Compressor
Mo – Molybdenum
NASA – National Aeronautics and Space Administration
NEMA – National Electrical Manufacturers Association
NMT – *Niveaux de Maturité Technologique* (Technology Readiness Level)
NO_x – Nitrogen Oxides
NRC – National Research Council - Canada
OEM – Original Equipment Manufacturers
P&WC – Pratt & Whitney Canada
PAI – Polyamide-Imide
PE and Poly – Polyester
PEEK – Polyetheretherketone
PPA – *Projection Plasma Atmosphérique* (Atmospheric Plasma Spraying)
PSZ – Partially Stabilized Zirconia
PTFE – Polytetrafluoroethylene

Ra – Average Roughness
Rq – Root Mean Square Roughness
RT – Room Temperature
Rz – Maximum Peak-to-valley Height Roughness
SAE – Society of Automotive Engineers
SD – Sliding Direction
SEM – Scanning Electron Microscopy
SFC – Specific Fuel Consumption
SoD – Stand-Off Distance
t/c – Thickness-to-chord Ratio
Ti6Al4V – Titanium Alloy
TRL – Technology Readiness Level
UHMW-PE – Ultra-High-Molecular-Weight Polyethylene
YSZ – Yttria-Stabilized Zirconia

1. CHAPTER 1

1.1. Introduction

The continuous drive for higher efficiency and reduced environmental impact in aircraft engines has led to advancements in materials development for clearance control systems. One of the innovations contributing to modern aero-engine optimization is the application of abradable seal systems, which aid in minimizing clearance between stationary and rotating components within gas turbine engines [4,7,8]. This reduced clearance helps decrease compressed air leakage, enhancing engine efficiency and operational safety and ultimately lowering pollutant emissions and energy consumption [9,10]. Improved sealing efficiency directly translates into reduced fuel consumption, CO₂ output, and NO_x emissions. Abradable systems can deliver efficiency gains of up to 3%, with studies showing that a mere 25 µm reduction in tip clearance can yield a 0.1% decrease in Specific Fuel Consumption (SFC), equivalent to an annual savings of approximately 0.02 billion gallons of fuel for U.S. airlines [11,12].

Abradable materials are designed to wear away under contact with harder blades, allowing for minimal wear of the blade tips, while the abradable material is sacrificed [13,14]. This ability to act as a sacrificial layer is particularly valuable in reducing factors such as casing deformation, rotor misalignment, and shroud issues, further contributing to the reliability of engine operations [15,16]. The ideal abradable material must possess a balance of properties, including good abrasability to prevent blade damage during contact and adequate resistance to corrosion and erosion [13,17]. This duality presents a significant design challenge, requiring that the material be both abradable and durable enough to withstand the harsh operating conditions inside aero-engines [7,13]. In order to address these requisites, these materials traditionally consist of a matrix that provides structural integrity, a solid lubricant or dislocator phase that facilitates crack propagation, and controlled porosity to dissipate energy during blade-coating interactions [14,18]. Typical materials used in low-temperature applications, such as in the low-pressure compressor (LPC) section of aircraft engines, include aluminum-silicon (AlSi) alloys, which provide good performance at temperatures up to 450°C [19,20].

The fabrication of abradable coatings is predominantly achieved using thermal spray processes, such as atmospheric plasma spraying (APS), favoured for its versatility, cost-effectiveness, and ability to precisely control coating properties [21,22]. Particularly, APS is well-known for its capacity to deposit coatings with the attributes required for abradable applications, such as a consistent microstructure [17,23], low residual stresses [24] and low hardness [25]. These coating attributes enable smooth interaction with blade tips without seriously wearing down or harming the counter element [17].

While substantial research has focused on optimizing the formulation and manufacturing of abradable coatings, there remains a limited understanding of the wear mechanisms involved

during blade-coating interactions under application-relevant conditions. The wear behaviour of abrasion-resistant coatings is influenced by complex phenomena, including abrasion, cutting, adhesion, smearing, and erosion, which can vary depending on test conditions, composition and microstructure of the coating [7,13,26,27]. Advanced abrasion-resistant test rigs that simulate real-world operating conditions have been developed to study these interactions more precisely, providing critical insights into the performance of abrasion-resistant materials [2,28]. Some examples include custom-made high-speed abrasion-resistant test rigs from NASA [29], Oerlikon Metco [30], National Research Council Canada (NRC) [17,31], Beijing General Research Institute of Mining & Metallurgy (BGRIMM) [25], and the University of Sheffield (UK) [32].

Although high-velocity abrasion-resistant test rigs are effective, the abrasion-resistant assessment remains costly and time-consuming due to their custom design for specific industrial needs, which are often confidential in aerospace and military sectors. The complexity of these systems, requiring precise stability, advanced data acquisition, and strict safety measures, further drives up costs [33–36]. As a result, individual tests can cost tens of thousands of dollars, limiting data collection and hindering a comprehensive understanding of material performance [14].

This economic and confidential barrier highlights the need for cost-effective, flexible testing alternatives that operate at a fraction of the cost of full-scale equipment, yet still capture the essential physics of blade–abrasion-resistant interactions. Such approaches reduce per-test costs, from thousands to hundreds of dollars, and accelerate assessment times, which is critical for progressing through multi-TRL development. By enabling accessible and scalable methodologies, these systems not only speed up material screening and qualification but also foster early-stage innovation, allowing academia and industry to iterate designs efficiently and bridge the gap between laboratory research and industrial application.

Thus, this research focuses on gaining fundamental insights into the wear performance of abrasion-resistant coatings and identifying similarities in wear mechanisms and behaviours across different technology readiness levels (TRL) in a scale-up assessment. Starting from the technology concept, experimental proof-of-concept, and moving forward with the sub-scale experiment. As summarized in the schematic flow presented in Figure 1.1. Overall, this study begins with the design and development of a cost-effective abrasion-resistant test rig for evaluating abrasion-resistant materials under closely simulated LPC conditions within an aircraft turbine. This is followed by evaluating the wear performance of different thermally sprayed AlSi-based abrasion-resistant coatings, specifically focusing on the influence of solid lubricants as hexagonal boron-nitride (hBN), and elements such as molybdenum (Mo) and chromium (Cr), under different operating temperatures.

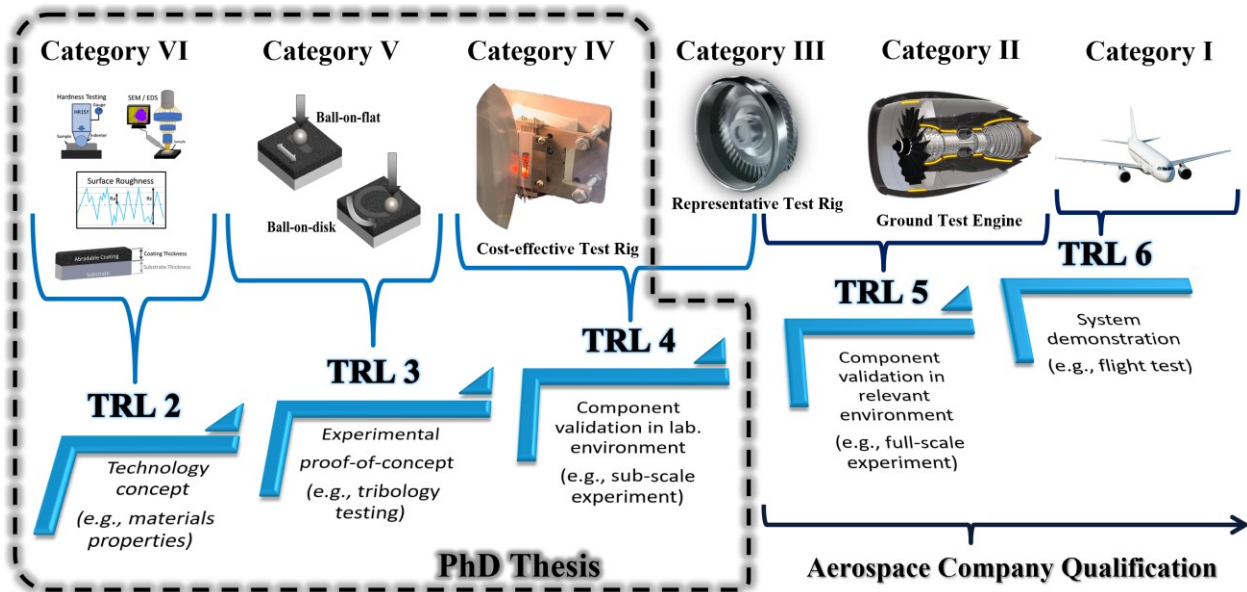


Figure 1.1. Schematic representation of the TRL process for material qualification in aerospace applications. Adapted from NASA [37] and DIN50322.

1.2. Objectives

This study aims to advance the understanding and performance of abradable coating systems of gas turbine compressors, with a focus on the rubbing wear mechanisms and the development of more effective evaluation methodologies. In addition, the work seeks to design and validate next-generation abradable coatings with improved durability, erosion and corrosion resistance, and optimized abradability. The overarching goal is to enhance compressor efficiency by enabling tighter clearances between rotating and stationary components, while maintaining structural and thermal reliability.

To this end, the study investigates novel abradable material formulations, explores their deposition via thermal spray processes, and develops reliable test methods for characterizing their performance under representative operating conditions. Emphasis is placed on evaluating coatings across multiple TRLs, from laboratory-scale material development to application-relevant testing. The research is structured around the following core objectives:

- Develop and produce distinct candidate abradable materials via thermal spray deposition, employing established industrial parameters to ensure process relevance and material reproducibility;
- Investigate the microstructural and mechanical properties of the deposited coatings through systematic characterization of thickness, hardness, filler distribution, porosity, surface roughness, and chemical composition;
- Enhance abradability assessment capabilities by designing and constructing a novel, cost-effective test rig capable of replicating rubbing interactions representative of operational conditions in aircraft engines;
- Advance the understanding of the tribological behavior and abradability performance of the coatings under controlled conditions, supporting material down-selection and performance benchmarking across different TRL stages;
- Extend the abradability evaluation framework by developing and integrating a high-temperature testing module, allowing thermomechanical performance evaluation under relevant low-pressure compressor conditions.

By addressing these objectives, the research seeks to contribute to the systematic design and evaluation of next-generation abradable coatings, supporting more efficient, durable, and high-performance turbomachinery components.

1.3. Organization of Dissertation

This dissertation is structured around three core components. It begins with the synthesis and detailed characterization of the abradable coatings, continues with the design and fabrication of a custom-built test apparatus tailored for abradability assessment, and culminates in a comprehensive evaluation of the coatings' wear behavior under more representative aircraft operating conditions. A schematic representation of the overall research methodology and its sequential stages is presented in Figure 1.2.

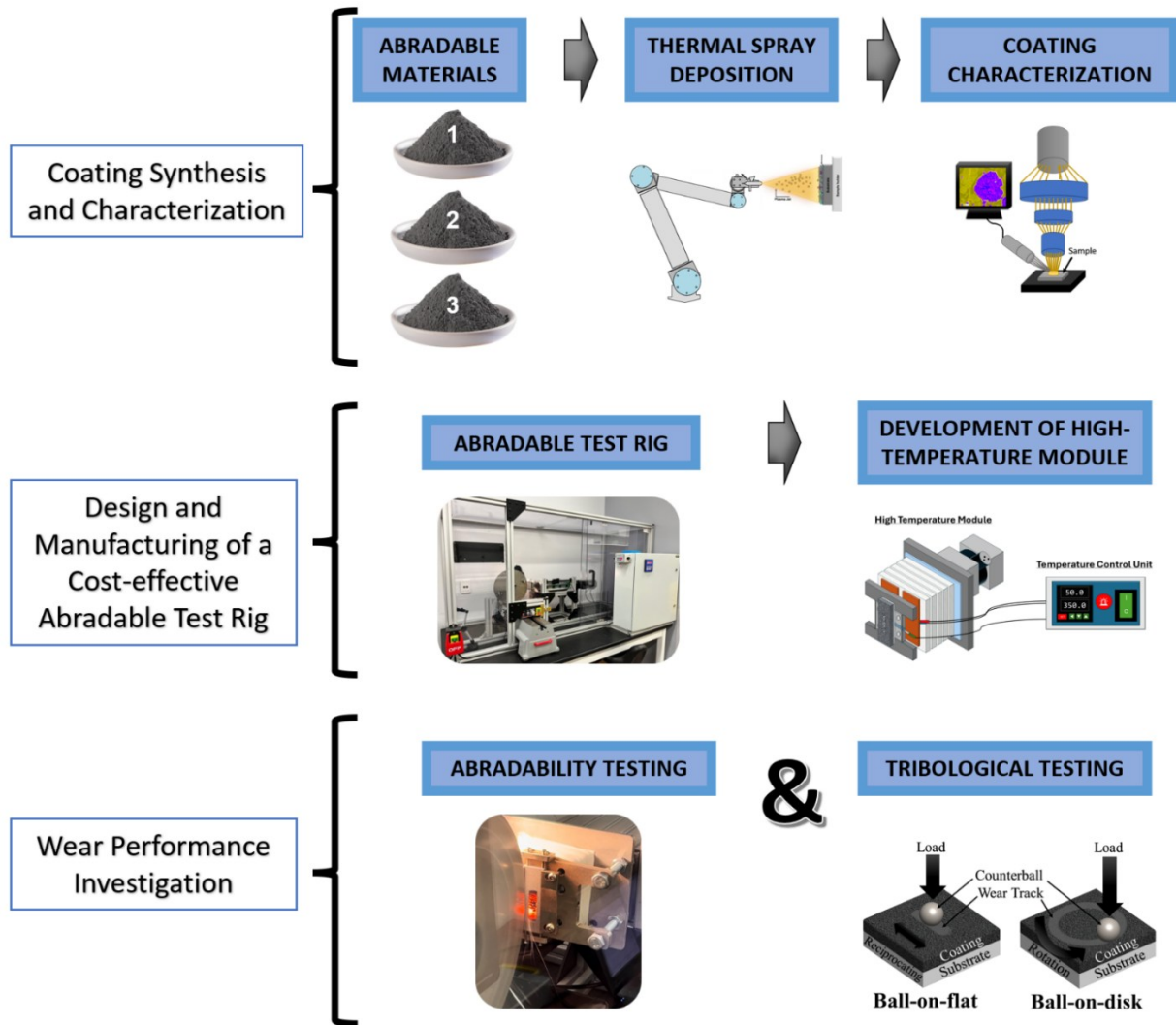


Figure 1.2. Schematic overview of the research methodology.

Furthermore, the overall structure of the dissertation, along with the rationale behind the progression of chapters, is illustrated Figure 1.2. The thesis is divided into seven chapters, each outlined in detail immediately following the figure to provide clarity on the scope and flow of the research work.

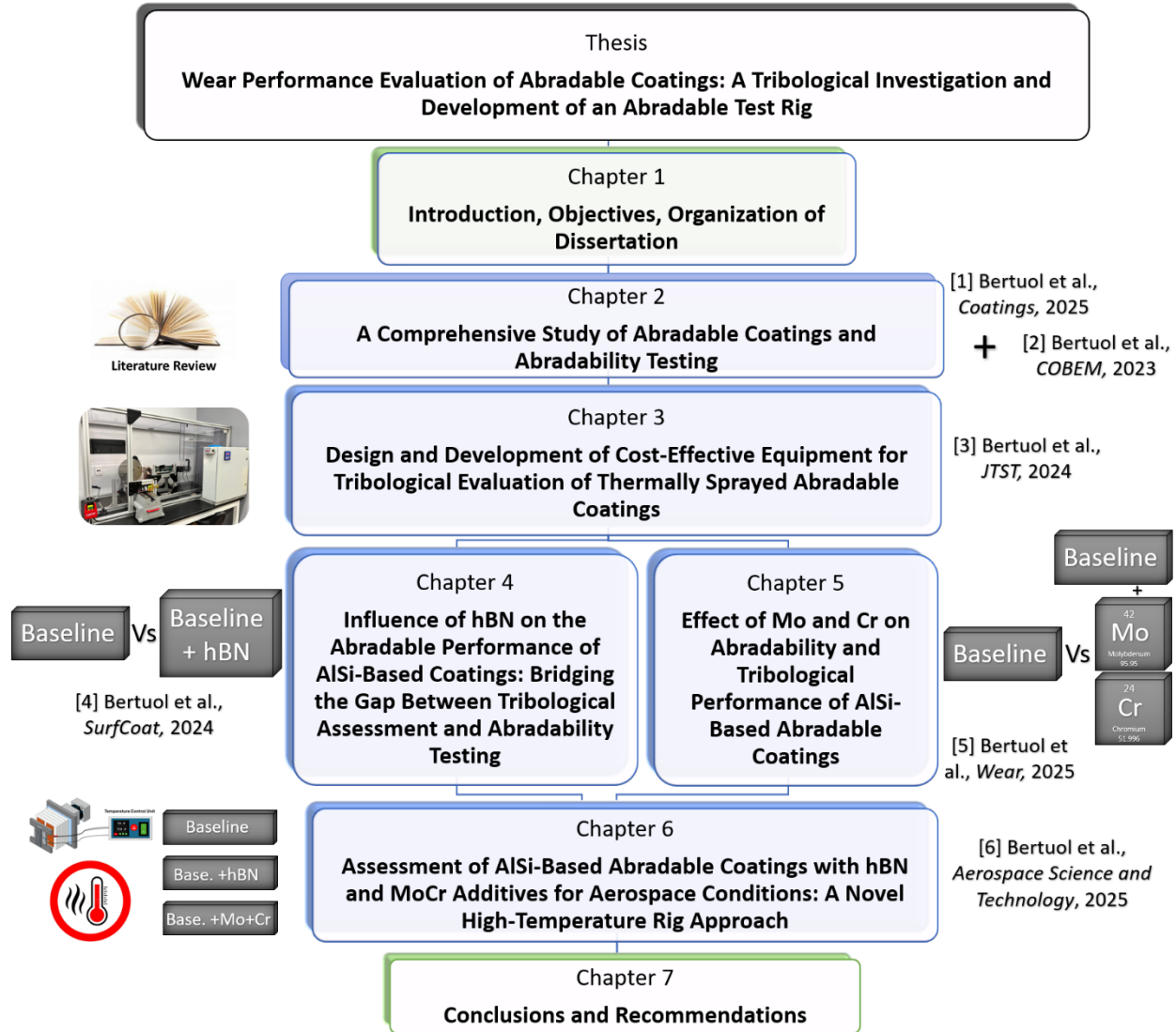


Figure 1.3. Thesis structure.

Chapter 1 establishes the foundational context for this thesis. In the introduction topic, it begins by presenting the motivation behind the research and situating it within the broader scientific and industrial landscape. The chapter then outlines the primary research objectives and provides an overview of the methodology employed, along with a roadmap of the thesis structure.

Chapter 2 provides a comprehensive review of abradable coatings and the experimental approaches used to assess their abradability performance in aerospace turbine engines. It integrates two review papers: one still under revision in *Coatings* [1] and the other in the *International Congress of Mechanical Engineering (COBEM)* [2]. The chapter begins with the fundamental principles of abradable materials, an overview of thermal spray deposition techniques, and the demanding performance requirements imposed on metallic abradables coatings by extreme thermomechanical environments. It then explores the abradability assessment methods,

highlighting established high-speed abradable test rigs, blade–coating interactions, apparatus design, and key instrumentation tools for future abradability testing methodologies.

Chapter 3 is a published study in the *Journal of Thermal Spray Technology* (JTST) [3], which focuses on the design, manufacture, and validation of a novel abradable test rig. This custom-made rig was specifically engineered to replicate aircraft engine conditions, serving as a valuable tool for the pre-screening of abradable materials. Its cost-effective design enables the evaluation of various materials under different operational conditions, offering critical insights into the development of abradable systems. This innovation ultimately improves material assessment efficiency, contributing to advancements in the field.

Chapter 4 is based on a paper published in *Surface and Coatings Technology* (SurfCoat) [4]. This study focuses on gaining fundamental insights into the influence of hBN on the wear mechanisms of Al-based coatings during interaction with titanium. It compared AlSi-Poly and AlSi-hBN-Poly coatings in terms of tribological and abradability performance, aiming to identify similarities in wear mechanisms and behaviour across different TRLs and providing a foundation for scale-up assessments. These insights are crucial for understanding the role of hBN on the wear resistance of abradable coatings for aerospace applications.

Chapter 5 is a published paper in *WEAR* [5]. It focuses on the effects of MoCr in minor fractions on the wear behaviour of Al-based abradable coatings. This study investigates how these corrosion-resistant elements influence the abradability performance when interacting with Ti6Al4V blades in the simulated low-pressure compressor conditions. Additionally, the study explores connections between different TRLs by examining wear mechanisms through tribological and abradability tests. The findings reveal a minimal impact on wear performance with the inclusion of Mo and Cr, supporting their potential use in advanced coating applications. Furthermore, the study emphasizes the comparable results based on coatings and blade investigations, including the reaction forces during the blade-abradable interaction.

Chapter 6 consist of a published study in *Aerospace Science and Technology* [6]. This chapter details the design and upgrade of a high-temperature testing module engineered to evaluate abradable coatings under elevated thermal conditions, simulating the regime of LPC temperature operation. The high-temperature module allows for more comprehensive testing and comparison of the three different AlSi-based coatings under critical operating conditions. Overall, an increase in test temperature to 300 °C led to polyester softening, which significantly reduced normal forces, increased wear-track Ra roughness and the F_t/F_n ratio, indicating temperature sensitivity of polyester-rich systems.

Chapter 7 consolidates the key findings, conclusions, and contributions of this research study, offering a comprehensive summary of the advancements made. This chapter will also provide recommendations for future research, identifying potential directions for further exploration in abradable coatings and their performance in aero-engine applications.

A Comprehensive Study of Abradable Coatings and Abradability Testing ¹

Abstract

This chapter presents a comprehensive study of abradable coatings and the advanced testing methodologies used to evaluate their performance in gas turbine engines. Abradables are engineered to act as sacrificial materials that permit minimal blade tip wear while maintaining tight clearances between rotating blades and stationary components, particularly under high-speed aerospace conditions and across a broad range of operating temperatures. The chapter begins by analyzing the critical factors influencing the design and selection of metallic-based abradable coatings for aerospace applications. These include material composition, thermal resistance, and microstructural modifications through the inclusion of phase modifiers, porosity formers, and solid lubricants. The performance of various metallic matrix materials is also discussed concerning their operational temperature ranges and wear characteristics. It then delves into abradability evaluation techniques, emphasizing the importance of replicating engine-like conditions to study blade-coating interactions, frictional responses, and wear mechanisms. High-speed abradability test rigs are highlighted as applicable tools for providing repeatable and accurate performance assessments. Finally, the chapter reviews the state-of-the-art abradable test rigs developed by leading research institutions and industry players. These rigs offer precise control over key variables like blade speed, incursion movements, and test temperatures, which are currently used worldwide as references for qualifying new coating systems. Overall, this chapter integrates a comprehensive review of material science, tribology, and experimental methods to support the development and validation of high-performance abradable coatings for next-generation turbine engines.

Keywords: Abradable Test Rig, Abradability Testing, Aerospace Application, Metallic Abradable Coatings.

¹ The initial part of this chapter has been published in *Coatings*, and the second part has been published in the proceedings of the 27th *International Congress of Mechanical Engineering (COBEM)*.

K. Bertuol, B.E. Arendarchuck, P. Stoyanov, *An Overview of Metallic Abradable Coatings in Gas Turbine Engines*, *Coatings* 15 (2025) 1216. <https://doi.org/10.3390/coatings15101216>.

K. Bertuol, F.E. Rivadeneira, R.B. Nair, C. Moreau, P. Stoyanov, *Advancing Abradable Evaluation: A Comprehensive Review and Development of an Innovative Cost-Effective Methodology*, in: *Proc. 27th Int. Congr. Mech. Eng.*, ABCM, 2023. <https://doi.org/10.26678/ABCM.COBEM2023.COB2023-0143>.

2.1. Introduction

Optimizing clearances between rotating blades and stationary casings is a critical determinant of gas turbine engines' efficiency and operational integrity. Excessive gaps incur aerodynamic leakage and efficiency losses, whereas overly tight tolerances risk damaging blade-casing contacts [10,38]. Abradable coatings provide an engineered solution to this challenge, acting as a sacrificial layer on casing surfaces. Designed to wear back upon blade incursion, thereby preserving optimal clearances while minimizing blade damage, significantly enhancing engine efficiency and operational safety across diverse flight regimes and temperatures [7,39,40].

Since the early years, the use of sacrificial coatings has challenged the engineering process. Different coating systems have been developed over the past years or are being evaluated at present [41]. The deployment of abradable coatings, particularly within aero-engine applications, necessitates a complex balance of often antagonistic material properties under demanding thermomechanical conditions [42,43]. It works together with the blade, as mentioned by DeMasi-Marci & Gupta [44], the blade tips, spinning at high speeds, must function as an efficient cutting tool. This is essential to prevent damage to the seal or the blades themselves, as ineffective cutting can lead to blade fracture. Achieving this balance necessitates sophisticated composite microstructures, typically comprising a matrix material for strength and environmental resistance, combined with solid lubricants or fugitive phases to promote controlled fracture and crack propagation, and often deliberate porosity to further enhance abrasability [13,31,45]. However, this microstructural complexity, coupled with the influence of thermal spray deposition processes, makes predicting in-service performance from fundamental material properties difficult.

Consequently, abrasability evaluation under representative engine conditions is indispensable. Conventional tribological tests lack the high-speed, transient thermomechanical fidelity required to reproduce blade-coating rub events, which involve rapid frictional heating, evolving stress fields, and potential adhesive transfer. To bridge this gap, specialized high-speed abradable test rigs have been developed by leading research institutions and industry partners, such as Oerlikon Metco [30], NRC Canada [31], the University of Sheffield [32], and BGRIMM [25]. These rigs have emerged as a solution to simplify and economize evaluation processes [10,16]. It fundamentally works by rotating a simulated turbine blade at relevant tip speeds against a stationary abradable specimen while precisely controlling key inputs: blade speed, incursion rate, incursion depth, and operating temperature. Sophisticated instrumentation captures critical outputs such as tangential and normal reaction forces, rubbing temperatures, blade wear, and adhesive transfer, alongside indirect observations such as debris morphology and surface topology.

The precise control and measurement offered by these rigs are essential for generating reliable, application-relevant data on wear mechanisms, frictional response, and overall coating

performance, enabling the validation and optimization of next-generation metallic abradable systems for increasingly demanding aerospace applications [7,28].

Based on this current situation, this review addresses the lack of a systematic synthesis connecting material design, thermal spray processing, and high-speed abradability testing. The paper is structured in sections, starting with an overall concept of abradable materials. The second discusses the deposition process, focused on the thermal spray process, followed by a discussion of material design strategies for metallic abradable coatings. In the final section, the study then explores abradability testing methodologies and addresses the scientific basis of abradability evaluation, highlighting the limitations of conventional tribological approaches, the role of advanced high-speed test rigs in producing engine-representative experimental data and the state-of-the-art test rigs that have become industry benchmarks.

2.2. Abradable Materials

Abradable materials are engineered sacrificial layers primarily used in gas turbine engines to manage clearances between rotating and stationary components. Their core function is to reduce air leakage by enabling tight blade tip clearances, which improves engine efficiency, reduces fuel consumption, and prevents structural damage during transient blade-shroud contacts [7,8,15]. The materials are designed to be selectively worn away during blade incursion while preserving the structural integrity of the rotating component, making them an essential part of modern turbomachinery sealing strategies [7,13,46].

Figure 2.1 illustrates a representative interaction between rotating blades and the abradable material applied to the engine casing. The rightmost image shows a cross-sectional view of the resulting wear track, highlighting the controlled sacrificial wear of the abradable. This behavior is critically dependent on the material's engineered properties, which must ensure predictable wear without compromising blade integrity [47].



Figure 2.1. Schematic representation of blade–abradable interaction in a gas turbine engine. Adapted from [47].

From a design point of view, the successful performance of an abradable system relies on a complex balance of thermomechanical properties, tribological behavior, and microstructural design. According to industry standards and recent research [13,17,48], abradable materials should meet the following performance criteria:

- Be readily abradable but mechanically stable;
- Exhibit corrosion and oxidation resistance;
- Have a low coefficient of friction;
- Resist erosion from gas flows and solid particles;
- Present a consistent microstructure;
- Minimize wear of blade tips or knife edges;
- Avoid material transfer between the blade and the abradable;
- Disintegrate into fine particles, as large debris can potentially damage the engine;
- The rubbing process should break the bonds between particles rather than melting them;
- Maintain a smooth post-wear surface to reduce aerodynamic losses.

2.2.1. Abradable Classification

To fulfill these diverse and often conflicting requirements, abradable materials are typically categorized into polymeric, metallic, and ceramic systems based on their operational temperature range. Usually, combinations of these materials are used to create composite abrasives that leverage the advantages of each class. The selection of a specific material category is primarily determined by the intended engine zone and its associated operating conditions [13,49]. Table 2.1 provides a classification and representative examples of the metallic, polymeric, and ceramic abradable seals.

Table 2.1. Classification of abradable coating materials based on their primary chemical composition [13,50–53].

Polymeric [13,49,51,54]	Ceramic [50,52,53]	Metallic [13,52,55]
<i>Widely investigated materials</i>		
Epoxy-based [51,56,57]	ZrO ₂ - 7Y ₂ O ₃ [50,53,58]	AlSi+40Polyester [4,59,60]
<i>Alternative materials</i>		
Polytetrafluoroethylene (PTFE)	DySZ-based	Co-based alloys
Polyetheretherketone (PEEK)	YAG-based	Ni-based alloys
Polyamideimide (PAI)	Yb-based	Cu-based alloys

2.2.1.1. Polymeric materials

Polymeric abrasives are primarily employed in low-temperature regions of aircraft engines, typically below 250 °C, such as in auxiliary power units (APUs), fan modules, and, in some cases, in the low-pressure compressor (LPC) stages [13,51]. These materials are based on thermoplastic or thermosetting polymers, often reinforced or blended with solid lubricants and fillers to optimize tribological and thermal properties [13,49,54]. Common examples include epoxy resin-based and silicon-based materials [13,49,54]. Although their thermal stability is limited compared to metallic or ceramic counterparts, polymeric abrasives are valued for their low hardness, excellent conformability, ease of repair, and capacity to minimize damage to blade tips during contact events [49,51].

2.2.1.2. Ceramic-based materials

On the other hand, ceramic abrasives are employed in the hottest regions of gas turbine engines (above 760 °C), including turbine shrouds and high-pressure stages [58,61]. They are typically based on partially stabilized zirconia (PSZ), such as yttria-stabilized zirconia (YSZ), which offers low thermal conductivity, excellent high-temperature mechanical strength, and robust resistance to oxidation and erosion [62,63]. However, the inherent brittleness and elevated hardness of these ceramics can exacerbate blade wear upon contact [27]. To mitigate this, ceramic abrasives are often formulated with a release agent that lowers the friction coefficient of the coating and a fugitive polymer phase that burns out and generates controlled porosity to improve abrasivity [7,58].

2.2.1.3. *Metallic-based materials*

Metallic abrasives are used in moderate-temperature environments (typically 250 – 750 °C), such as in the LPC and high-pressure compressors (HPC) stages of aircraft engines [19,64]. These materials generally use soft metals in the main matrix, combined often with a polymeric phase and solid lubricants (e.g., polyester, graphite, or hBN) to enhance their abrasivity properties [7,64]. When compared to polymeric and ceramic abrasives, metallic abrasives offer a favourable balance between structural strength and ease of wear during blade interaction [7,49].

2.2.2. Manufacturing Process of Abradable Materials

Due to the multifaceted and often conflicting property requirements, the manufacturing method used to produce each class of abradable materials plays a critical role in determining their overall performance and reliability in service. The selection of fabrication technique not only affects the microstructure and mechanical behavior but also governs the material's consistency, manufacturing repeatability, and scalability for industrial use. Table 2.2 presents a summary of some of the processes and some main characteristics achieved by the material using this methodology.

Table 2.2. Characteristics of common manufacturing methods used for abradable seal coatings.

Manufacturing method	Characteristics	Typical materials
Compression molding	Higher processing pressures during polymer melt forming may enhance mechanical properties and increase crystallinity, leading to denser, harder-to-cut, and stronger materials [51,65].	Polymers and composites
Sintering	Aids to grain growth at elevated temperatures, improving bonding strength while redistributing internal defects, yet retaining controlled porosity [53,66].	Ceramics and composites
Thermal spray	Exhibit strong anisotropy, as splats solidify in layered sequences where particle shape and inter-splat bonding largely govern the resulting properties [55,67].	Metals and composites

For polymeric abrasives, common manufacturing techniques include conventional polymer processing methods, such as compression molding [51], casting [19,68], and more

recently, additive manufacturing (3D printing) [69]. These methods offer good flexibility in terms of geometrical design and can incorporate lubricants or fillers to enhance abrasability properties.

In contrast, ceramic abrasables are typically fabricated using powder-based methods (e.g. additive manufacturing [70], sintering [71]), these processes are effective at achieving dense microstructures and high-temperature phase stability but often lack the level of microstructural tunability required for abrasability, such as controlled pore networks or embedded dislocator phases. To address this, plasma spraying of ceramic blends with engineered porosity has gained attention in recent years, especially for applications demanding thermal barrier-like behavior combined with controlled erosion resistance [58,72].

For metallic-based abrasables, the choice of fabrication technique significantly influences performance. While some fabrication methods overlap with those used in polymeric and ceramic systems, the most widely adopted method for metallic abrasables is thermal spraying. Given the critical role that thermal spray processes play in manufacturing and optimizing metallic abrasable systems, the following dedicated section aims to explore in detail the fundamentals of thermal spray technology, its parameters, and its influence on coating properties.

2.3. Thermal Spray Deposition Process

Thermal spraying is a surface engineering technique in which a feedstock material, typically in the form of powder, wire, or suspension, is heated and accelerated toward a substrate, forming a protective or functional coating. This process relies on the plastic deformation and solidification of high-velocity, high-temperature particles upon impact, creating a dense, layered coating structure [22]. Nearly any material that can be melted without decomposition can be thermally sprayed [13,73]. The heat source may be derived from combustion or an electric arc [74]. The coating is then formed by a series of overlapping layers in a lamellar shape, arising from the scattering of the molten and semi-molten particles [74]. Figure 2.2 presents a simplified schematic of the thermal spraying process.

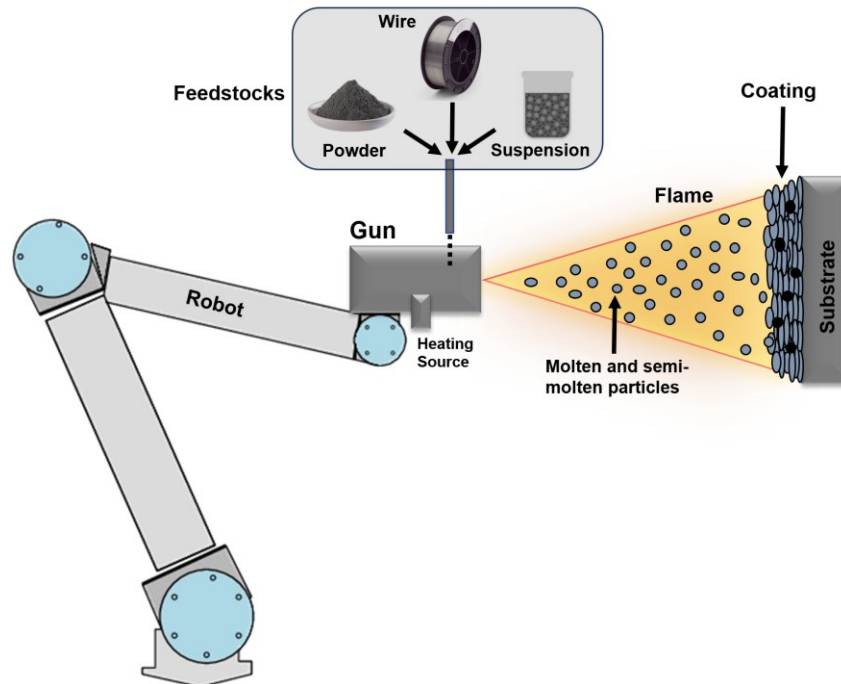


Figure 2.2. Schematic representation of a generic thermal spray process.

The primary objective of thermal spray coatings is to enhance the surface properties of components while protecting the underlying substrate. Depending on the application, coatings can be tailored to improve wear resistance, corrosion protection, thermal insulation, or extend fatigue life. In the case of abradable coatings, the aim is to enable controlled sacrificial wear to optimize sealing performance in turbomachinery. Achieving the desired coating characteristics depends strongly on the selection of process parameters, particularly flame temperature and particle velocity, which influence particle melting, adhesion, and microstructural development [75–78].

Coatings produced by thermal spray processes are usually highly anisotropic, having a layered and lamellar structure. The shape of these individual deposits and their interaction with each other determines much of the coating properties, including inter-lamellar pores caused by

rapid solidification, very fine voids formed by incomplete inter-splat contact, and cracks generated by thermal stresses [13]. Therefore, porosity, cohesion, and oxide presence are good examples of coating properties that can be controlled by the selection of spraying parameters [75,79].

There are several advantages of using the thermal spray approach. The main ones are versatility in terms of materials (both coating and substrate) and relatively low operating costs [76,80]. Among the various methods available, key techniques include Atmospheric Plasma Spray (APS), Cold Spray (CS), Arc Spraying (Electric Arc AS), Flame Spraying (Flame), High-Velocity Oxy-Fuel (HVOF) and High-Velocity Air-Fuel (HVOF), as highlighted by Pawlowski [22].

The fundamental differences between these processes lie in the interaction of the gas flow with the feedstock particles, specifically the temperature and velocity conditions, which govern the particle state during deposition [81]. These dynamics play a critical role in defining the coating microstructure and performance. Figure 2.3(a) presents a schematic classification of the main thermal spray processes, categorizing them by their energy source. In the processes, Figure 2.3(b) outlines the typical operational ranges of each spraying technique in terms of particle temperature, velocity, and feedstock size, illustrating their suitability for different material systems and coating requirements.

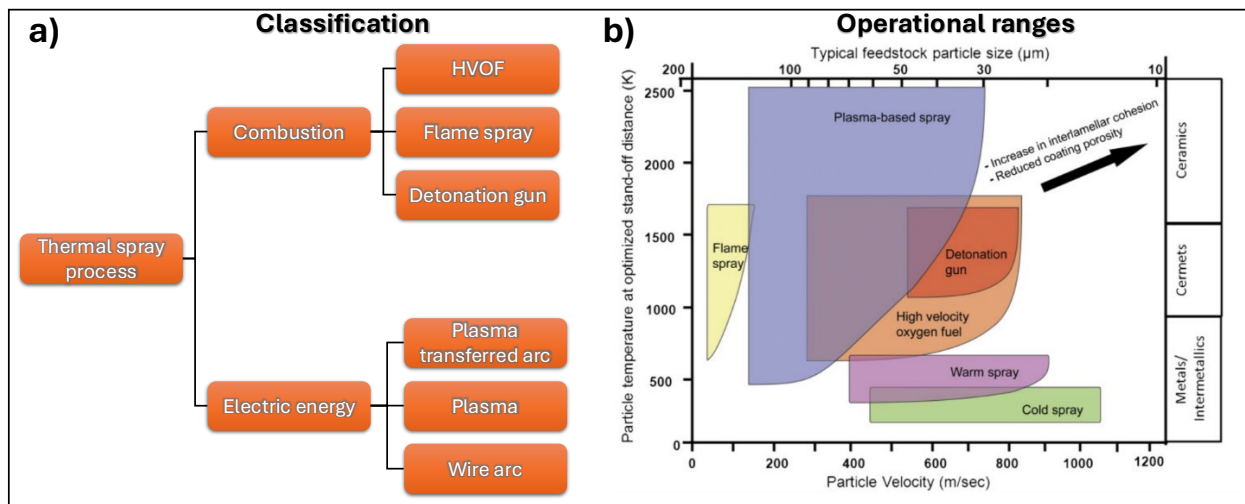


Figure 2.3. Thermal spray map illustrating the (a) classification of the process by energy source [55,82,83]; and (b) typical operational ranges of the major techniques based on particle velocity, temperature, and size. Adapted from [84].

The APS technique is distinguished by its high versatility, enabling the deposition of a broad range of materials across varied temperatures, particle velocities, and powder size distributions. In APS, particles typically can reach velocities of up to 300 m/s and temperatures exceeding 30,000 K [21,76,85,86]. This flexibility makes APS particularly suitable for processing complex material systems, including metallic-polymer composites. Several studies [25,87,88] have employed APS to fabricate such composites, leveraging its capability to accommodate wide particle size ranges (e.g. abrasable feedstocks between 11 and 176 μm [89]) while maintaining effective deposition and microstructural control.

In this technique, an electric arc is formed between a tungsten electrode and a copper anode, which heats and ionizes the gases, usually argon, helium, nitrogen, hydrogen, or a mixture, to create a plasma flame. As the gases pass through the arc, they are heated and expand axially and radially, thus being accelerated through the outlet nozzle. The powder is then injected into the plasma flame, where the particles are fused and sprayed onto the substrate [21,76]. The basic concept of how the plasma spray process works can be seen in Figure 2.4.

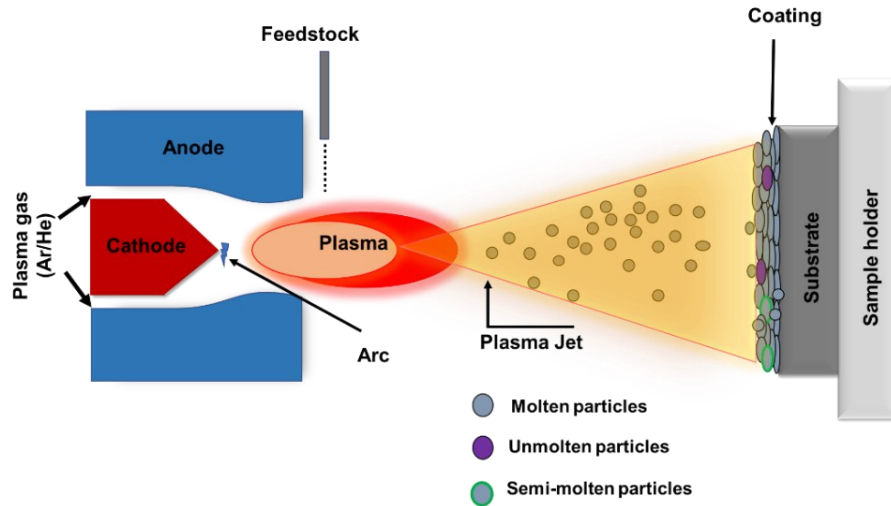


Figure 2.4. Schematic model of the atmospheric plasma spray process.

Plasma spray technology enables the fabrication of coatings with a broad range of thicknesses, offering adaptability to meet diverse industrial requirements. For instance, studies by Liu et al [25] and Jech et al [90] demonstrated the successful deposition of AlSi–Polyester composite coatings with thicknesses ranging from several micrometres to a few millimetres. This level of control is particularly advantageous in applications requiring tailored layer dimensions for mechanical or thermal performance. A prominent example is found in gas turbine abradable coatings, where thick deposits, often exceeding 3 mm [21], are necessary to ensure sufficient material for blade incursion without compromising structural integrity or sealing efficiency.

The ability to apply such complex coatings while maintaining microstructural consistency underscores the value of thermal spray processes in critical aerospace components. Furthermore, from a materials design perspective, precise control over thermal spray parameters, and resulting coating properties is essential for achieving the desired balance of performance characteristics. In the context of this study on abradables, the following section turns to how these engineered coatings are composed and crucial for gas turbine applications.

2.4. Metallic-based Abradable Coatings

Metallic abradable coatings play a pivotal role in gas turbine compressor applications, where precise clearance control between rotating blades and stationary casings is essential for maximizing efficiency and preventing damage during transient incursions. However, formulating a coating that simultaneously provides high abradability along with robust erosion and corrosion resistance remains a significant materials engineering challenge [7,91–93].

2.4.1. Coating Requirements

Abradable coatings require several demanding properties, such as being soft enough to be removed without damaging the blades or other engine components, while also maintaining strong bonding strength and resistance to solid particle erosion and corrosion. Integrating these competing, and often opposing, properties within a single material system is particularly challenging and is typically addressed through the development of composite materials. Metallic-polymer composite materials stand out as promising abradable materials [13,42,93–95].

The design of abrasives faces a fundamental paradox: while high porosity is essential for achieving excellent abradability and protecting blade tips, it simultaneously compromises the coating's performance in other critical areas. This high void content significantly reduces the material's resistance to high-velocity particle erosion and thermal flow. Furthermore, it creates easy diffusion pathways for corrosive agents, leading to material degradation and premature failure. Although high porosity offers superior thermal insulation, it can also heighten the risk of cracking from thermal shock. Consequently, the central challenge in developing these coatings is to achieve a precise balance between abradability and crucial properties such as erosion resistance, corrosion resistance, and thermal stability, all while maintaining the necessary structural integrity for demanding high-temperature service [53].

Figure 2.5 presents a schematic of the key factors to consider in the selection and development of an abradable coating, where properties such as hardness and interparticle bonding strength often stand in contrast when optimizing for erosion resistance versus abradability.

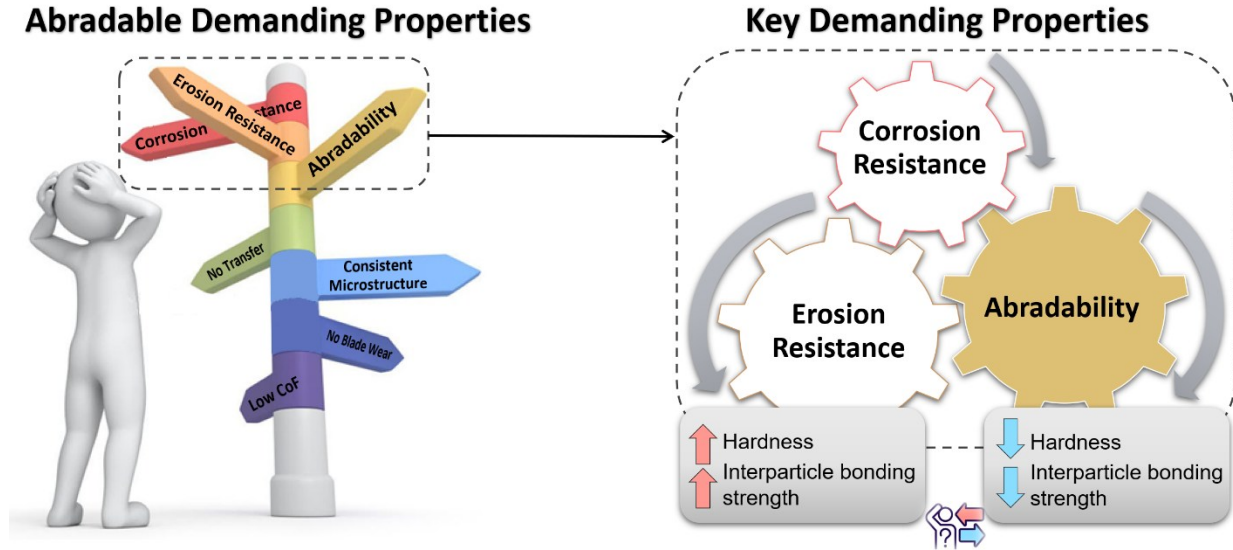


Figure 2.5. Schematic highlighting the main demanding properties of abradable materials and the contrast between erosion resistance and abrasibility.

To satisfy this challenging set of criteria, metallic-based abradable coatings are typically formulated using a combination of a metallic matrix, a solid lubricant or dislocator phase, and a controlled level of porosity [13,31,45]. Each component serves a critical function. The metallic matrix, commonly composed of aluminum–silicon, nickel, cobalt, or copper alloys, provides structural integrity and contributes to the overall strength and wear resistance of the coating [96]. Embedded within this matrix, the solid lubricant or dislocator phase facilitates crack initiation and propagation, introducing inherent weakness that ensures fine and controlled wear debris [13,15,45]. Typical examples of such phases include hexagonal boron nitride (hBN), molybdenum disulphide (MoS_2), and graphite [97–100]. These phases generally do not chemically bond with the metallic matrix [13], helping ensure that the resulting debris remains sufficiently small to avoid downstream damage.

In addition to compositional design, porosity is often deliberately introduced through feedstock engineering or by adjusting thermal spray parameters. While increased porosity, generally governed by the volume fraction and size of pores, tends to improve abrasibility, it often reduces erosion resistance, thereby requiring careful optimization [13,31]. For instance, Liu et al [25] demonstrated that the volume of filler material plays a significant role in determining the abrasibility of aluminum-based coatings. Beyond porosity control, polymeric additives are also employed to reduce stress propagation during blade-coating interactions [18]. Stringer and Marshall [87] further emphasized that such additives help limit damage to the structural matrix phase, supporting coating integrity under service conditions. Figure 2.6 presents a typical coating configuration of a metallic-based abradable coating incorporating polymer filler material, illustrated through macro photography, micro-CT imaging, and SEM analysis. The figure highlights the distribution of filler material, the porosity network, and the underlying bond coat layer applied to enhance adhesion to the substrate.

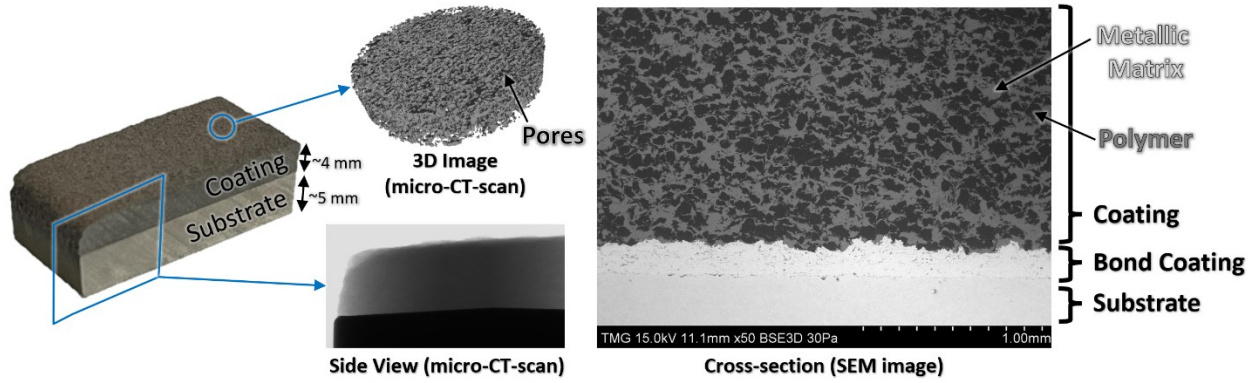


Figure 2.6. Metallic-based abrasion-resistant coating with polymer filler via macro photography, micro-CT, and SEM imaging.

A well-established metallic-based abrasion-resistant coating system is AlSi incorporated with 40 wt.% polyester [93,101,102], in which the polyester serves as a fugitive filler phase. The polyester lowers the overall coating hardness and promotes controlled porosity, without significantly compromising adhesion strength [16]. Figure 2.7 presents cross-sectional micrographs of AlSi coatings containing different polyester contents, illustrating the inverse correlation between filler concentration and HR15Y hardness. In the images, the lighter regions correspond to the aluminum–silicon metallic matrix, while the darker regions indicate the presence of the polymer filler.

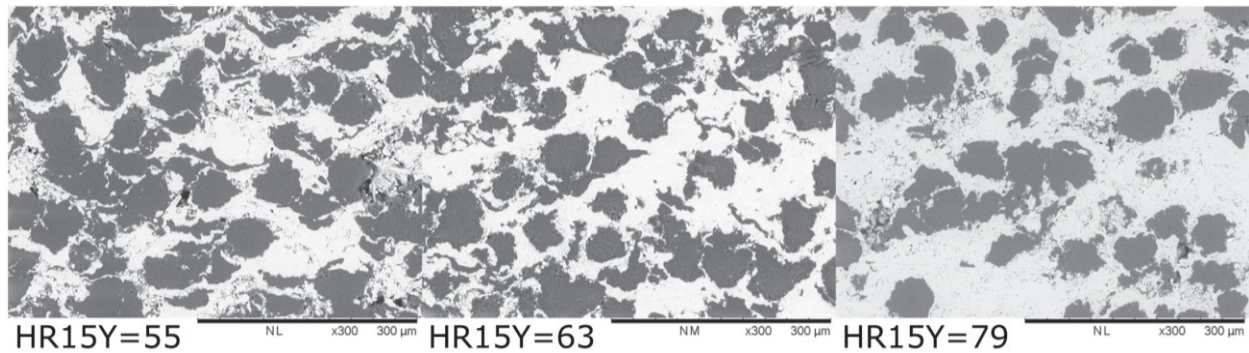


Figure 2.7. Cross-section images of Al-based coatings with varying filler material content and HR15Y hardness values. Adapted from [103].

However, the thermomechanical stability of these coatings remains a critical concern. Polyester additives improve abrasion resistance by absorbing mechanical energy, they are prone to softening at elevated temperatures, which can reduce performance [104,105]. Conversely, hBN, a solid lubricant, improves thermal stability and lubrication but may introduce microstructural heterogeneities that influence wear behavior [4,100]. Previous studies [106–108] have highlighted temperature-driven changes in coating behavior, including increased polymer softening, shifts from ductile-dominant to mixed or brittle wear modes, and enhanced adhesive transfer to the blade at higher temperatures.

This complex interplay between material composition, microstructure, and thermomechanical behavior highlights the need for a systematic understanding of how different metallic abradable coatings perform across varying temperature regimes inside the gas turbine engines [109].

2.4.2. Temperature-Based Categorization of Metallic Abradable Coatings

Given the highly heterogeneous composite structure of abradable coatings [18] and the inherent complexity of thermal spray processes [110], the investigation, comparison, and development of new coatings remain challenging, particularly when tailored to distinct application environments. In aero-engines, abradable coatings are employed at various locations, each subjected to specific and often demanding temperature conditions. From this perspective, a practical and widely adopted classification approach is to categorize these coatings based on their temperature capability. Figure 2.8 illustrates the typical temperature regimes encountered in jet engines, along with the corresponding abradable materials commonly used at each stage [13,48].

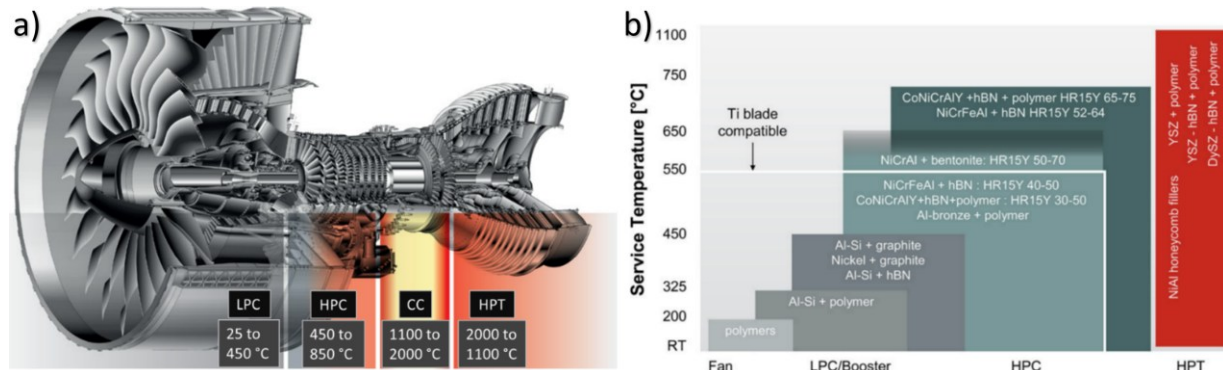


Figure 2.8. a) Schematic of jet engine areas and its range of operational temperatures; b) Temperature regime map illustrating the suitability of different abradable coatings by engine area. Adapted from [10].

Below 450 °C (LPC zones), usually AlSi-based alloys offer an optimal balance between abradability and erosion resistance [10,15,61]. In the intermediate temperature range of 450 °C to 750 °C, corresponding to high-pressure compressor (HPC) regions, cobalt-based, copper-based, nickel-based, and M-CrAlY alloys are commonly employed due to their favorable combination of corrosion resistance, lubricity, and erosion resistance. For high-temperature environments such as high-pressure turbines (HPT), yttria-stabilized zirconia (YSZ) is the conventional abradable material of choice [10,15]. A summary of traditional metallic abradable coatings is presented in Table 2.3, highlighting their main chemical compositions, operating temperature ranges, key performance attributes, and relevant references.

Table 2.3. Conventional metallic abradable coatings. Adapted from [20].

Abradable Materials (Metallic-based)		Operating Temperature [20]	Description [20]	References
Aluminum-based Alloy	AlSi + BN	< 450 °C	Good erosion resistance	[25,39,88,96,111–113]
	AlSi + Graphite	< 480 °C	Balance of abradability and erosion resistance	[102,114–116]
	AlSi + Polymer	< 325 °C	Balance of abradability and erosion resistance	[25,32,90,117–119]
	AlSi + Polyester + BN	< 325 °C	Balance of abradability and erosion resistance	[120]
Cobalt-based Alloy	CoNiCrAlY + BN + Polyester	< 750 °C	Great corrosion resistance	[18,31,66,95,121–123]
Copper-based Alloy	CuAl (Al+ Bronze) + Polyester	< 650 °C	Good corrosion resistance	[100,118,124]
Nickel-based Alloy	Ni + Graphite	< 480 °C	Balance of lubricity and erosion resistance	[102,115,116,122,123]
	NiCrAl + Bentonite	< 650 °C	Good erosion resistance	[18,96,112,123]
	NiCrFeAl + BN	< 815 °C	Balance of lubricity and erosion resistance	[123,125,126]

As detailed in Table 2.3, metallic-based abradable coatings cover a wide range of compositions and operating temperature regimes. These coatings are intrinsically complex due to their heterogeneous composite structures, often comprising multiple phases and engineered porosity, introducing microstructural inhomogeneities that significantly influence wear behavior [18]. This structural complexity poses substantial challenges for understanding wear mechanisms and correlating microstructural features with performance metrics.

The selection of abradable coating material is fundamentally governed by the thermophysical requirements of each specific engine region. The matrix generally provides the coating strength and resistance to the environment while ensuring that the material can be preferentially worn to prevent excessive blade wear. Al and Cu alloys are typically utilized as the matrix material, and due to their relatively lower melting temperatures, they are generally employed in the low-temperature zones of the LPC [13]. These alloys are specifically designed to balance erosion resistance with excellent abradability.

As we move towards the hotter sections of the engine, such as the high-pressure compressor (HPC) and turbine (HPT), more advanced materials are required. Here, Co and Ni-based alloys and ceramic abrasives are applied to support the hotter temperatures, with the choice of matrix being a function of the specific region's thermal load. Under high-temperature service conditions (≥ 1300 °C), however, conventional metal-based materials increasingly exhibit service performance limitations due to their insufficient thermal stability [53].

Regardless of the matrix material, a critical component is the addition of solid lubricants or dislocator phases, such as graphite and boron nitride, which are among the most commonly used dislocator materials. These function as an initiation and propagation route for cracks, providing the coating with an inherent weakness while ensuring that the abradable debris is sufficiently small so it cannot block cooling channels or instigate downstream erosion [13,55].

Moreover, the thermal spray deposition processes used to manufacture these coatings introduce additional variables, including residual stresses [24], splat morphology, and inter-splat bonding characteristics [127] which further complicates performance assessment. Standardized evaluation methods are difficult to apply universally, as the tribological behavior of these materials is highly dependent on their specific mechanical configurations. Given these intricacies, the following section is therefore dedicated to reviewing and analyzing the primary techniques employed for evaluating the performance of abradable coatings, with a focus on abradability evaluation.

2.5. Abradability Evaluation

The physical interaction between rotating blade tips and abradable coatings during rubbing events presents a highly complex, transient thermomechanical phenomenon. This complexity arises primarily from the contact between dissimilar materials, including composites, operating under the harsh conditions characteristic of aerospace applications, such as high rotational speeds and elevated temperatures [8,128].

2.5.1. Conventional Tribological Tests and Limitations

Although existing friction models [129,130] offer first-order approximations of contact forces and frictional heating during rubbing events, they are insufficient for capturing the full spectrum of thermomechanical interactions, particularly the rapid temporal and spatial variations in temperature, stress, and material response. As a result, experimental validation through physical testing remains indispensable for accurate characterization.

During blade–abradable interactions, the high tip velocities generate significant transient heat, leading to complex distributions of frictional forces, such as tangential and normal reactive forces at the interface. These forces are strongly influenced by localized, rapidly evolving thermal fields that alter the mechanical behavior of both the blade material and the abradable coating. The resulting variations in hardness, strength, and ductility further complicate the force dynamics. Additionally, incursion-induced mechanical instabilities in the blade are poorly understood and represent an area of ongoing research [17,105,131].

Conventional methods, such as the Scratch, Impact test, Scratch hardness, and Sliding wear tests, are characterized by their ease of implementation and cost-effectiveness. These techniques are valuable for initial material screening and for providing fundamental tribological data, often by measuring mass loss or wear rate under controlled conditions. However, a significant shortcoming is their limited capacity to replicate actual operational environments. These methods fail to incorporate the high-speed rubbing, elevated temperatures, and specific contact kinematics of a gas turbine engine, leading to a substantial deviation from real-world performance [53].

To overcome these limitations, a multifaceted assessment strategy has emerged as a standard practice. Abradability evaluation is employed using specialized test rigs capable of simulating engine-representative conditions. These tests provide critical insights into coating wear mechanisms, blade degradation, frictional responses, and potential material transfer phenomena at the blade tip [18,30,33]. A schematic representation of the rubbing process in conventional abradability testing is shown in Figure 2.9.

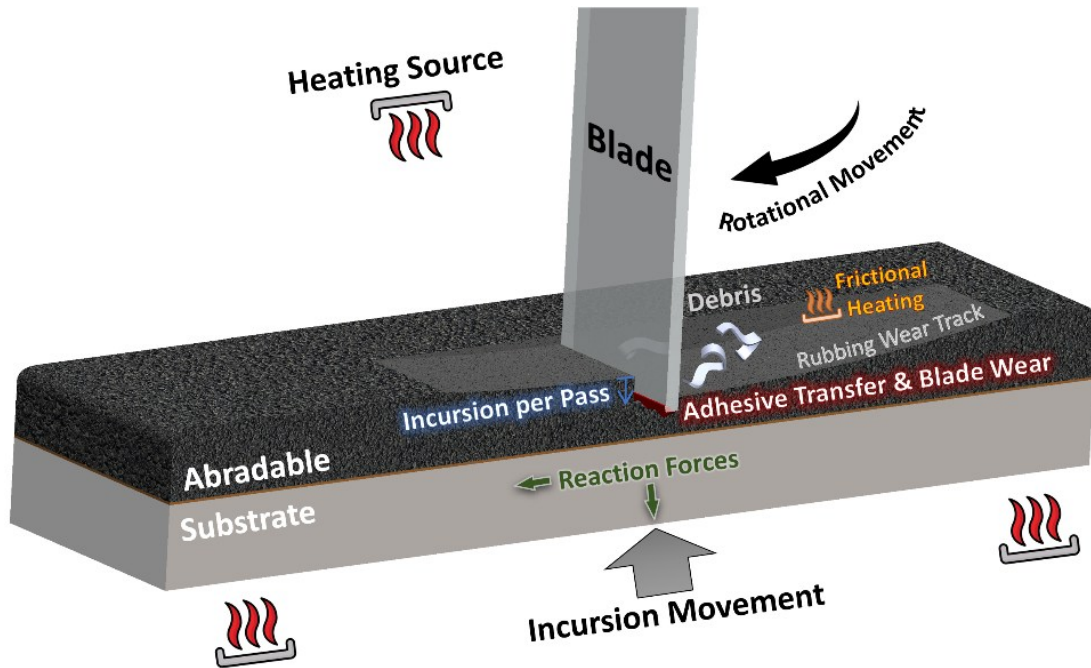


Figure 2.9. Simplified schematic of abrasability testing.

According to Xue et al [88], and Stringer and Marshall [87], identifying wear mechanisms and blade wear in different operating conditions, as well as determining frictional heating and rubbing reaction forces, are crucial in validating all abradable systems. Similar studies also support these findings [31,132]. Post-rubbing surface analysis of the coating is commonly performed to assess abradability and associated blade wear. To support such evaluations, various studies have designed dedicated rigs for assessing abradable materials [17,28,30,33,87,117,133]. A widely adopted approach is the use of high-speed abradable test rigs, which enable precise control over the main parameters such as blade speed (up to 500 m/s), incursion rate (1–2000 $\mu\text{m/s}$), incursion depth (typically up to 2 mm), and operating temperature (up to 1200 °C).

Several studies have reported quantitative performance outcomes for metallic abradables. For instance, AlSi-based coatings have been widely investigated, where different filler additions (e.g., polyester, hBN, or metallic reinforcements) were shown to influence wear track morphology, groove depth, and surface roughness after rubbing.

2.5.2. High-Speed Abradable Test Rigs

Compared to full-scale engine tests, high-speed abradable rigs significantly reduce testing time and cost, while still providing an accurate assessment of coating abradability. The main idea of the equipment is to simulate the rubbing process that happens in an aero-engine system on a smaller scale. It simulates the condition of a rotating blade inside a stator component [16,117].

The typical setup includes a dummy blade mounted on a rotating disk and an abradable specimen under investigation. An incursion motion is induced using a stepper motor, providing the interaction between the abradable and the dummy blade. Some rigs are equipped with a heating apparatus to replicate the real-engine operating temperatures. Various sensors can be employed to gather pertinent data, including reaction forces, rubbing temperatures, incursion depth, and disk speed [18,30]. Figure 2.10a shows a schematic of a high-speed abradable test apparatus developed by Sulzer Metco [30], while Figure 2.10b displays typical post-rubbing surface features observed after testing.

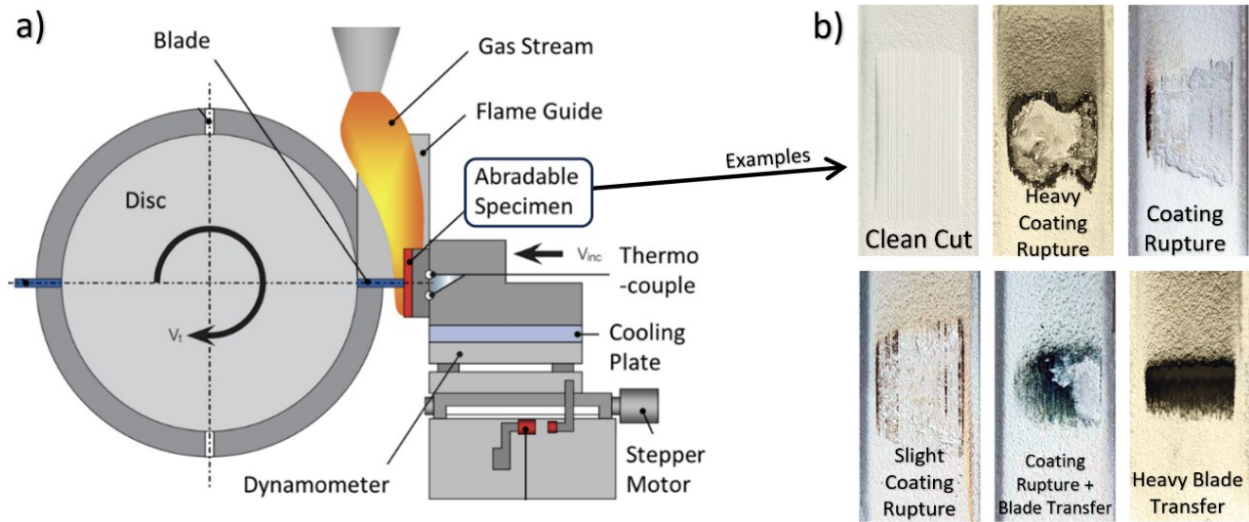


Figure 2.10. a) Schematic of the abradable test rig developed by Sulzer Metco; b) Abradable specimens illustrating different types of abrasibility. Adapted from [30].

Abradable test rigs are designed to offer a broad range of configurable input parameters. Key input parameters include: blade rotational speed, incursion rate, incursion depth, abradable materials, and operating temperature. These variables allow for flexible test scenarios tailored to specific material evaluations or application targets.

Table 2.4 summarizes the main inputs and outputs typically evaluated on abrasability assessments by abradable test rigs, categorized by qualitative and quantitative analysis. The outputs provide valuable data to assess the mechanical and thermal interactions between the blade and abradable material. Moreover, post-test analysis is enabled through the removal of specimens from the rig, allowing for a thorough inspection of the abradable degradation, blade wear and material transfer. Additional laboratory evaluations, such as surface roughness measurements, wear mechanism identification, and debris characterization, can offer deeper insights into understanding and optimizing the performance of turbine blade systems.

Table 2.4. Typical main inputs and outputs of abrasability tests and their corresponding units.

Category	Type	Key Parameters	Units	Main Measurement Methods
Quantitative	Input	Blade speed	[rpm or m/s]	Tachometer / encoder / high-speed camera
		Incursion rate	[$\mu\text{m/s}$ or $\mu\text{m/pass}$]	Linear displacement / laser sensor / high-speed camera
		Incursion depth	[μm]	Laser sensor / profilometry / gauges
		Operating temperature	[$^{\circ}\text{C}$]	Thermocouples / IR pyrometer
	Output	Blade Wear	[μm , % loss]	Optical surface analysis / profilometry / scale / stroboscopic image
		Coating Wear	[μm , mm^3/Nm]	Optical surface analysis / profilometry / scale
		Rub Grooves profile	[μm]	Profilometry / roughness tester
		Reaction Forces	[kN]	Load cell / strain gauges / force transducer
		Rubbing Temperature	[$^{\circ}\text{C}$]	Thermocouples / IR pyrometer / IR camera
	Qualitative	Abradable material	-	EDS / X-ray / RAMAN
		Blade material	-	EDS / X-ray / RAMAN
		Adhesive Transfer	-	SEM / optical surface analysis
		Wear Mechanism	-	SEM / optical surface analysis
		Densification	-	SEM / optical surface analysis
		Debris Characteristics	-	Laser-diffractometer / SEM / EDS
		Rub Grooves Characteristics	-	SEM / optical surface analysis

Based on abrasability test data, coatings are generally preferred when they exhibit low reaction forces and minimal frictional heating during incursion. High reaction forces are generally undesirable, as they are correlated with increased blade wear, surface damage, and potential structural instabilities. They are often associated with a rougher scar appearance on the abrasable surface [17], increased adhesive material transfer to the blade tip [88], and more pronounced wear features such as grooves or micro-cracks [36].

In summary, as discussed by Wang et al. [53], the adoption of customized test rig methodologies has become increasingly prevalent for evaluating the abrasability of aerospace seal coatings primarily because they provide a high degree of fidelity to actual operating conditions. However, the application of these comprehensive tests is sometimes limited by their high cost and the lack of standardized criteria for wear evaluation, which could be addressed by the research area by the use of abrasable test rigs with a low velocity [134].

Reliable performance assessment requires recognizing the limitations of both conventional tribological tests and abrasability rigs. While conventional methods remain useful for initial pre-screening, abrasability rigs provide engine-representative data and capture key outputs. A robust evaluation of ASC performance necessitates a hybrid approach. By combining both evaluation stages, researchers can comprehensively characterize a coating's performance and address the multifaceted demands of modern aerospace applications, supporting the design and validation of next-generation metallic abrasable coatings.

2.6. State of the Art: Abradable Test Rigs²

The following sections provide an overview of some of the most widely recognized and publicly documented abradable test rigs. These setups have been essential in advancing the evaluation of abradable coatings, offering valuable insights into their mechanical behavior under simulated engine conditions.

2.6.1. Abradable Test Rig Developed by Oerlikon Metco

The company named Oerlikon Metco developed a dedicated incursion test facility capable of replicating engine rub conditions, offering blade tip velocities up to 500 m/s (1640 ft/s) and rotor incursion rates up to 2000 $\mu\text{m/s}$ (0.079 in/s), all at elevated temperatures reaching 1200°C (2192°F) [30]. Figure 2.11 shows a schematic of Metco's rig.

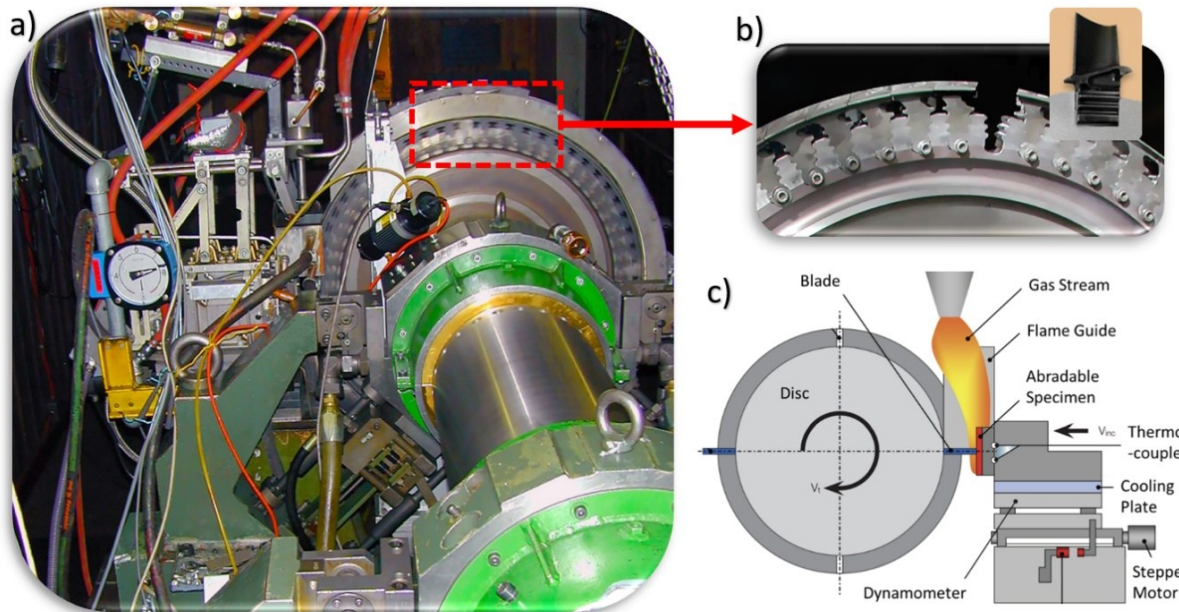


Figure 2.11. Abradable test rig developed by Oerlikon Metco; a) Photography of the rig; b) 750 mm rotor and OEM blade; c) Schematic diagram of the rig. Adapted from [30].

This advanced testing platform plays a critical role in elucidating shroud and blade wear mechanisms under various operating conditions. It enables precise quantification of key parameters such as frictional heating, rubbing forces, and material response, essential for validating the performance of abradable systems. While initially developed for internal testing and

² Part of this section has been published in the proceedings of the 27th International Congress of Mechanical Engineering (COBEM).

K. Bertuol, F.E. Rivadeneira, R.B. Nair, C. Moreau, P. Stoyanov, Advancing Abradable Evaluation: A Comprehensive Review and Development of an Innovative Cost-Effective Methodology, in: Proc. 27th Int. Congr. Mech. Eng., ABCM, 2023. <https://doi.org/10.26678/ABCM.COBEM2023.COB2023-0143>.

validation of Oerlikon Metco's own abradable coatings, the rig has since become a widely recognized industry benchmark. Several Original Equipment Manufacturers (OEMs) in the aerospace and power generation sectors now employ this facility as a risk mitigation tool for evaluating and qualifying new clearance control systems in gas and steam turbines [30].

The rig's ability to conduct accelerated, high-fidelity tests under controlled conditions enables the generation of reproducible and application-relevant data. In many cases, it serves as an effective alternative to even more expensive evaluations, such as engine test cells, on-wing trials, or full-engine assessments [16,30]. It is frequently used to benchmark candidate materials and coating systems, as well as to characterize as-sprayed coatings. Data obtained from these tests are instrumental in refining spray parameters and optimizing coating performance for specific engine environments [30].

2.6.2. Abradable Test Rig Developed by NRC Canada

The high-speed abradable test rig from the National Research Council of Canada (NRC) effectively replicates operational wear by employing a simulated turbine blade or knife edge. It comprises a rotor powered by an air turbine and supported by hybrid rolling-element bearings. Capable of reaching speeds of up to 40,000 rpm, equivalent to a blade speed of 425 m/s, the rig's table, supporting the test coupon holder, is controlled axially and radially through two servo motors. This stage provides incursion rates from 2.5 $\mu\text{m/s}$ to 760 $\mu\text{m/s}$, and the fixture is adaptable to accommodate both flat and curved profiles of abradable coupons [17,31]. Furthermore, the rotating disk is capable of holding up to eight blades simultaneously. Figure 2.12 presents an image of the aforementioned abradable test rig.

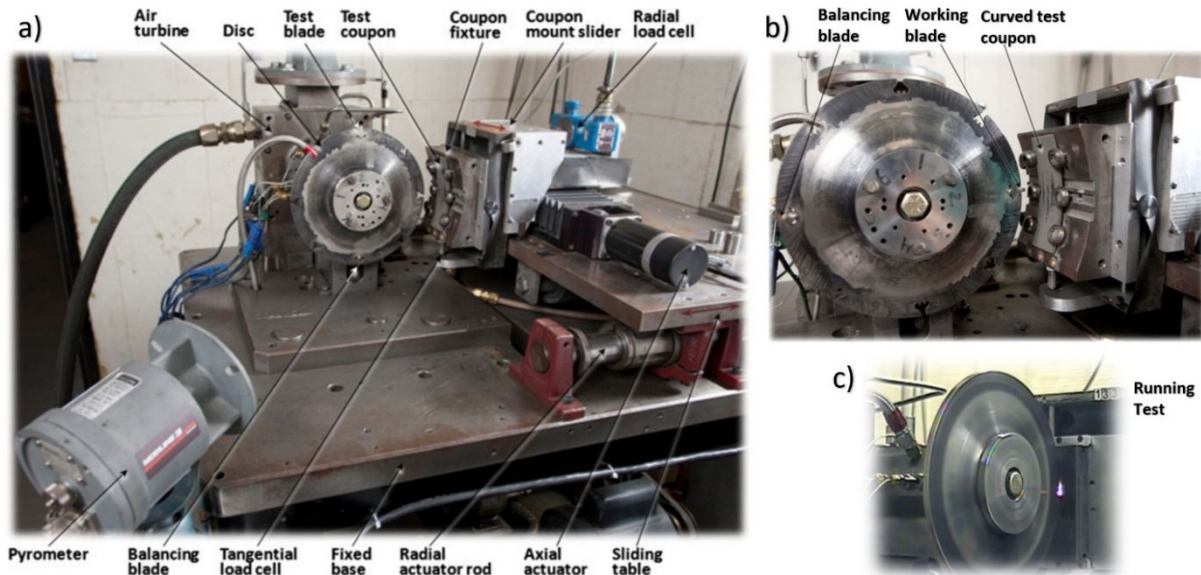


Figure 2.12. Abradable test rig developed by NRC; a) Overview of the rig; b) Close view of the rotor and coupon holder; c) Rig running. Adapted from [31].

The NRC rig can assess heated abradable materials up to 600°C using a ceramic-encased, wire-wound resistor situated at the test coupon's rear [17,31]. According to Irissou et al [31], the pivotal parameters for evaluating abradable seal performance encompass blade tip speed, incursion rate, and working temperature, such specifications are typically outlined by end users or manufacturers, aiming to faithfully replicate the typical operational conditions endured by abradable seals.

Additionally, the rig is equipped with diverse sensors, the rig captures rub temperature, radial and tangential rubbing forces, speed, and seal incursion rate. Subsequent to each test, the wear on both the blade and abradable seal is quantified. Parameters like vibration and bearing temperature are also closely monitored throughout testing. Data collection is facilitated by a computerized data acquisition system [17,31].

2.6.3. Abradable Test Rig Developed at the University of Sheffield

The University of Sheffield has developed a high-speed abradable test rig designed to replicate compressor-like conditions during blade–abradable interactions. The rig consists of several key components, including a high-speed spindle, a precision incursion stage, bearing supports, a rotating disk, and a robust containment structure composed of steel plates and concrete-filled blocks [32]. Images of the test setup are shown in Figure 2.13.

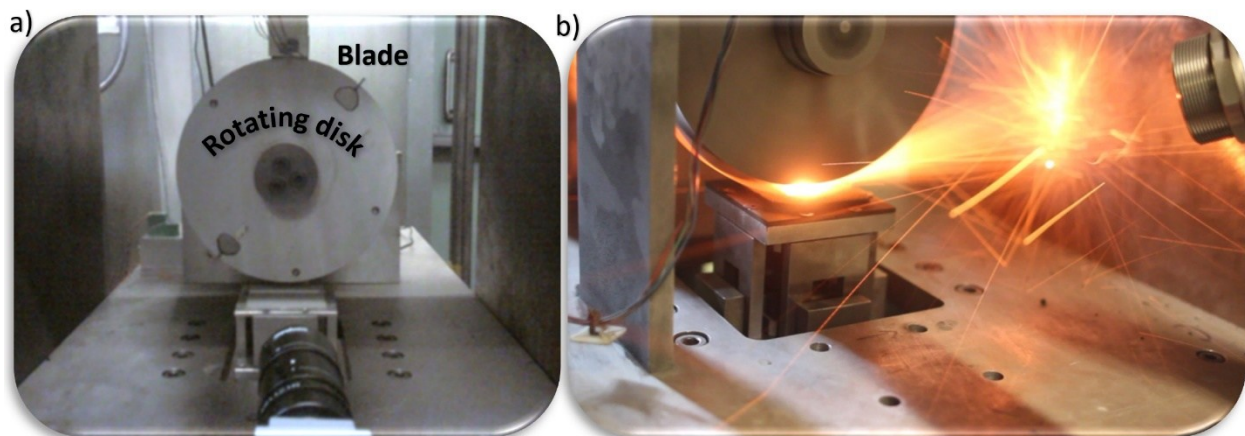


Figure 2.13. Abradable test rig developed at the University of Sheffield; a) Overview of the rig; b) Rig in operation. Adapted from [87,103].

At the heart of the system is a bench-mounted machine tool spindle capable of reaching speeds up to 21,000 rpm, delivering 13 kW of power and blade tip velocities up to 200 m/s. The metallic disk allows for rapid blade insertion and removal between tests. Two opposing slots (180° apart) accommodate both a cutting blade and a dummy blade to ensure dynamic balance during operation [32,87,103].

The incursion stage advances the abradable sample toward the rotating blade at a constant and programmable velocity. It features a front plate mounted on a force dynamometer and a sample holder. The stage is driven by a ball screw mechanism with gearboxes and is precisely controlled by a Z-axis microscope stage connected to a programmable controller. This setup enables incursion rates from 0.1 to 2000 $\mu\text{m/s}$ in 0.1 $\mu\text{m/s}$ increments, along with the ability to program complex movement sequences on the abradable material [32,87,103].

Key instrumentation includes a Kistler Type 9347C 3-component force dynamometer and a front-on imaging system. The front-on imaging system is based on a stroboscopic imaging technique used to capture real-time photography of the rotating blade during contact events [32,87].

2.6.4. Abradable Test Rig Developed by BGRIMM

The Beijing General Research Institute of Mining & Metallurgy (BGRIMM), China, has developed the BGRIMM BKY-HVT300-800 test rig to support the advancement of abradable materials for turbomachinery applications. This rig aims to replicate the realistic aero-turbine operating conditions and consists of four primary subsystems: a high-speed rotor, an incursion mechanism, a heating system, and an integrated control unit [25,28]. A schematic and photograph of the rig are provided in Figure 2.14.

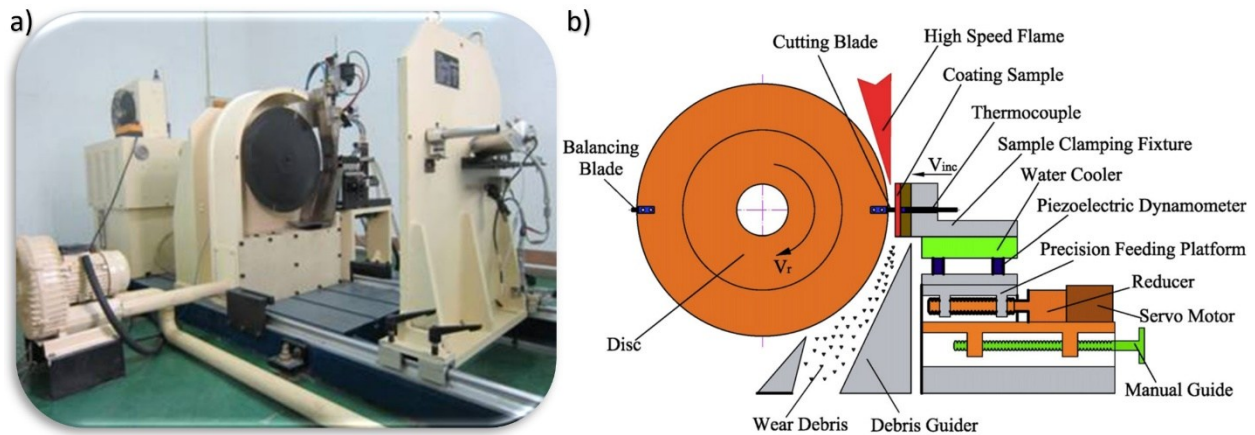


Figure 2.14. Abradable test rig developed by BGRIMM; a) Overview of the rig; b) Schematic of the rig and its parts identification. Adapted from [25].

The rig's rotor accommodates a 475 mm diameter disk, with a theoretical maximum rotational speed of 15,000 rpm, enabling blade tip velocities up to 350 m/s. Lateral positioning of the sample relative to the rotor is controlled by programming the feed rate and displacement. The feed rate is adjustable from 5 to 500 $\mu\text{m/s}$, with a precision of better than 5%. Zero-calibration ensures accurate displacement control and repeatability [25,28].

To simulate the high-temperature environment of turbomachinery, the system employs an oxygen-acetylene flame spray gun capable of heating the coating surface up to 800 °C. A pyrometer is directed at the center of the sample surface to monitor and adjust the temperature in real time [25].

Additional instrumentation includes a 3-axis force sensor mounted on the specimen stage to capture both vertical and tangential forces during blade–coating interactions, enabling detailed evaluation of cutting behavior and material response under thermal and mechanical loads [25,28].

2.7. Alternative Approaches for Abradability Testing

While high-velocity abradable test rigs remain the standard for evaluating abradability, a few researchers have also been developing alternative methodologies to complement or simplify it. These include low-speed abradable test rigs [122,135], ballistic benches [105,136], scratch test [102], pin-on-disk [137], and even a modified high-speed milling machine [138]. Notably, Xue et al. [88] applied a single-pass pendulum scratch test as a supplementary method, enabling a more controlled comparison of rub behavior alongside data from high-speed abradable rig tests. These combined methodologies provide a broader perspective on the wear mechanisms and allow for more nuanced material selection and performance validation.

2.8. Conclusions

This chapter presented a comprehensive analysis of abradable materials, thermal spray deposition process, metallic abradable coatings and the experimental methodologies essential for evaluating their performance in aerospace turbine engines. The selection and optimization of these coatings demand meticulous attention to material composition, thermal stability, and engineered microstructural characteristics to achieve effective abradability under extreme operating conditions. Key metallic matrix systems were examined, highlighting their distinct operational temperature regimes and traditional compositional formulations.

To ensure these coatings perform reliably in service, replicating engine-like contact conditions through high-speed abradability testing is currently applied. This chapter reviewed worldwide established apparatus, placing significant emphasis on the design, capabilities, and contributions of advanced test rigs developed by industrial and research institutions. These platforms provide the critical data needed to understand blade–coating interactions, blade and coating architectures, and typical instrumentation used to validate abradable performance.

By synthesizing principles from materials science, tribology, and mechanical developments, this chapter establishes a robust foundation for the continued development, qualification, and optimization of metallic abradable coatings. Furthermore, it provides a critical reference framework for advancing the design and development of future abradability testing methodologies.

Design and Development of Cost-Effective Equipment for Tribological Evaluation of Thermally Sprayed Abradable Coatings³

Abstract

Thermally sprayed abradable coatings are essential for enhancing gas turbine engines' performance, as they are commonly used for clearance control purposes. Abradables act as protective barriers between the stationary casing and rotating blades. However, evaluating the abradability performance of novel coatings is challenging, because it is typically very costly and time-consuming. Thus, the goal of this project is to create a cost-effective test rig that can evaluate and pre-screen different thermally sprayed abradable coatings and understand how they interact with titanium blade tips under application-relevant conditions. The rig is capable of providing various inputs and outputs, including blade tip velocity, incursion rates, incursion depths, reaction forces, and interfacial temperatures. Aiming to validate the rig, a detailed dynamic evaluation was conducted, as well as abradability tests on aluminum, thermally sprayed polyester, and AlSi-40Polyester abradable coating. The reaction forces for aluminum and polyester were overall higher when compared to AlSi-40Polyester. However, thermally sprayed polyester showed the highest interfacial temperatures of all materials tested. The difference in the reaction forces and interfacial temperature correlates well with the different wear mechanisms and thermal conductivities. Overall, the equipment showed to be a promising pre-screening methodology to evaluate and develop novel thermally sprayed abradable coatings.

Keywords: Abradable Coating, Abradability Assessment, Cost-effective Equipment, Pre-screening Methodology, Thermal Spray.

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3.1. Introduction

Abradable materials are frequently used as clearance control elements within gas turbine engines, to reduce the gap between rotating and stationary components. Smaller gaps can lead to higher engine efficiency, reduced power loss, lower pollutant gas emissions and environmental costs [10,38,139]. However, achieving these benefits requires abradable materials to be removed smoothly by rubbing against a more abrasive moving material (e.g. blade), ensuring that the material wears while the abrasive part faces minimal wear [40].

The development of abradable coatings commonly involves thermal spray processes such as plasma spray, flame (combustion) spray, and high-velocity oxy-fuel (HVOF) [10,21,22,140]. Such coatings are desired to possess a relatively low hardness and elastic modulus, facilitating smooth rubbing without causing significant damage to the blade tips. Simultaneously, these coatings are also intended to have a strong bonding strength as well as be resistant to corrosion and solid particle erosion. Balancing all these properties in a single material system is a considerable challenge, and thus, a typical abradable coating usually comprises three different phases: a matrix, a solid lubricant, and a binder [13,31,42,43,45]. For instance, commercially available metallic abrasives include Aluminum Silicon-Polyester, Aluminum Silicon-Graphite, Nickel Graphite, and Nickel Chromium Aluminum-Bentonite [20]. Furthermore, innovative approaches take advantage of polymer properties, such as softness and corrosion resistance, which have led to robust abradable sealing coatings like AlSi + 40 wt.% Polyester, Aluminum Bronze-Polyester, and MCrAlY-BN-Polyester [16].

Despite substantial research on novel plasma-sprayed abradable coatings, their assessment is very challenging, especially regarding their wear resistance [13,31,45]. Thus, only a few research groups focus on the wear mechanisms within abradable coatings-blade tip interactions and the interfacial process under application-relevant contact conditions [10,16]. Furthermore, by precisely assessing coating abrasibility under relevant conditions, high-speed abradable test rigs can lower evaluation costs by reproducing the rubbing processes in aero-engines on a smaller scale. This simulation replicates the conditions of a rotating blade inside a stator component to assess the wear and friction processes between abradable coatings and blade tips [16,117].

Due to the importance of abrasibility evaluation on aero-engine applications, some research centers and companies have developed custom-made rig capabilities. A review of different testing rig facilities is discussed in the literature [28,141]. For instance, the Beijing General Research Institute of Mining & Metallurgy (BGRIMM) has developed a rig that contains a rotating disk with a single rectangular plate “bladelet” embedded radially in the circumference of the disk. The abradable is then moved at a specific speed into the rotating disk. The rig can be operated at a range of incursion rates and has the capability to introduce a hot gas to change the operating temperature of the rub. The rig is capable of measuring the rub forces through several

force transducers. Similarly, NASA and Oerlikon Metco have developed abradable testing rigs, which have the capability to measure a wide range of rub forces and temperatures [28]. In addition, the National Research Council Canada (NRC) has also developed a rig with the capability to have several bladelets installed in the rotating wheel instead of just one in the rig [17]. More recently, a sophisticated rig has been developed at Ohio State University (OSU), which can reach representative engine diameters and speeds [33].

Although high-velocity abradable test rigs are effective, performing tribological assessments on abradable coatings is still expensive and time-consuming. They are custom-made due to specific industrial requirements and testing conditions that are often kept confidential by aerospace and military entities. The complexity of these systems, which requires precise stability, advanced data acquisition, and stringent safety measures contributes to their high cost [33–36]. Consequently, abradability tests can exceed tens of thousands of dollars per condition, leading to limited data sets and restricting research to a comprehensive understanding of materials' performance and conditions [14].

Thus, the primary objective of this research is to design and develop a cost-effective test rig method that can evaluate various thermally sprayed abradable coatings and their interactions with blade tips in an environment relevant to the aero-engine application. This cost-effective approach can significantly aid the tribological pre-screening of thermally sprayed coatings.

3.2. Design and Construction of a Cost-Effective Abradable Test Rig

3.2.1. Rig Overview

The cost-effective abradable test rig provides an efficient and inexpensive method to evaluate abradable coatings in a wide range of conditions. It is a low-risk, versatile, and cost-effective solution for abradable systems compared to other testing apparatus like high-speed abradable test rigs, test cells, on-wing, or in-situ testing on operating turbine engines.

This rig aims to bridge the gap between low Technology Readiness Levels (TRL) using tribological tests (i.e., ball-on-flat and ball-on-disk) and high TRL with a dedicated high-speed abradable test rig. It allows a wide range of thermally sprayed materials to be tested under various conditions, primarily for pre-screening promising abradable materials before advancing to higher TRLs. This approach facilitates a thorough initial evaluation, helping to identify the most promising materials for further, more detailed, and expensive testing.

The newly designed abradable test rig offers numerous functional advantages, highlighted in Table 3.1. This rig excels in its ability to simulate diverse operational conditions with precision, ensuring reliable data acquisition crucial for optimizing abradable coating and blade performance. Its pre-screening approach facilitates early identification of optimal coating candidates, thereby enhancing efficiency in material assessment and scalability in industrial applications.

Table 3.1. Key advantages of the cost-effective abradable test rig.

Advantage	Description
Cost-Efficiency	Significantly reduces expenses for tribological evaluations, making testing more accessible (e.g., Conducting multiple abradable coating tests within limited resources)
Versatility	Able to accommodate different blades and abradable materials at different conditions (i.e., Blades with different geometries and thickness-to-chord ratios)
Laboratory Simulation	Capable of simulating gas turbine engine conditions with precise control over key parameters
High-Resolution Data Acquisition	Provides detailed measurements of critical parameters like reaction forces and temperature (e.g., Monitoring force fluctuations at each 5 microseconds)
Reliability and Repeatability	Ensure reliable experiments with reproducible and precise control (e.g., Consistent wear behaviour in repeated tests)

Early Issue Detection	Allows early identification of potential coating issues, facilitating prompt adjustments (e.g. Detecting premature coating failure under specific conditions)
Comparative Analysis	Enables side-by-side comparisons of different coatings under identical conditions (e.g., Evaluating performance between different material compositions or blade materials)
Validation of Coating Performance	Offers a platform for validating performance and optimizing spray parameters and material selection (e.g. Pre-screening optimal spray parameters in terms of abrasability performance)
Wide Range of Operational Conditions	Accommodates various operational conditions to mimic different real-world scenarios (e.g., Testing the effects of varying incursion rates on coating wear)
Adaptable for Scaling Up to Higher TRL	Facilitates transition to higher TRL for broader industrial and research applications, enabling larger-scale industrial testing to meet enhanced operational and performance criteria.

Critical aspects in validating different abrasable systems include determining the rubbing reaction forces, and frictional heating as well as identifying wear mechanisms and blade wear under various operating conditions [31,132]. Therefore, the custom-built abrasable test rig offers a wide scope of inputs and outputs.

Table 3.2 outlines the abrasable test rig's main inputs and outputs, along with their corresponding descriptions and operational ranges. These inputs and the rig's adaptiveness allow testing over a wide range of conditions, which can play a crucial role in simulating real-application scenarios to evaluate the performance of turbine blade systems. In addition, the outputs obtained from the abrasable test apparatus play a significant role in understanding and optimizing the performance of abrasable materials and turbine blade systems.

Table 3.2. Inputs and outputs of the abrasable test rig, their descriptions and range of operation.

Input Parameter	Description	Range
Blade Tip Velocity	The linear speed of the blade tip at its outermost edge	0 – 60 m/s
Incursion Rates	The rate at which the blade penetrates the abrasable material	5 – 500 $\mu\text{m/s}$
Incursion Depths	The maximum depth of blade incursion into the abrasable material	0 - 5 mm
Operating Temperature	The operating temperature of the abrasable material and the blade	Room Temperature

Output Parameter	Description	Range
Reaction Forces	The resultant rubbing forces created by the blade-abradable interaction	Up to 30 kN
Interfacial Temperature	The localized temperatures generated during blade-abradable contact	Up to 1200°C
Blade Wear	The measurement of material loss or degradation of the blade	-
Transfer	The material transfer from the abrasible coating to the blade	-
Wear Mechanism	The study of the mechanisms by which wear occurs at the blade-abradable interface	-
Debris Characteristics	Analysis of debris generated during blade-abradable interactions	-

It should be noted that the main limitation of the cost-effective abrasible rig is its restricted blade speed, which is capped at 60 m/s. This is notably lower compared to the typical high-speed abrasible rig, which can reach speeds of 300 m/s or even 500 m/s in certain instances [17,30,31,87,88]. Nevertheless, this testing setup is essential for pre-screening candidate material compositions and evaluating actual sprayed abrasible coatings, facilitating the optimization of spray parameters. A few authors also investigated the blade-abradable interaction using simplified setups, such as ballistic bench [105,136], scratch test [102], pin-on-disk [137,142], single-pass pendulum scratch test [88], and adapted high-speed milling machine [138]. Each of these simplified setups has its limitations, varying in terms of speed, geometry, and aero-engine representativeness.

Figure 3.1 presents a schematic representation of the blade-abradable interaction. It shows the movement of the abrasible coating towards the rotating blade, resulting in material removal, adhesive transfer to the blade tip, and debris formation. Additionally, it highlights some of the key input parameters for the system, such as the incursion movement and depth. The incursion movement refers to the horizontal motion of the abrasible material, allowing the blade tip to penetrate into the material and start rubbing.

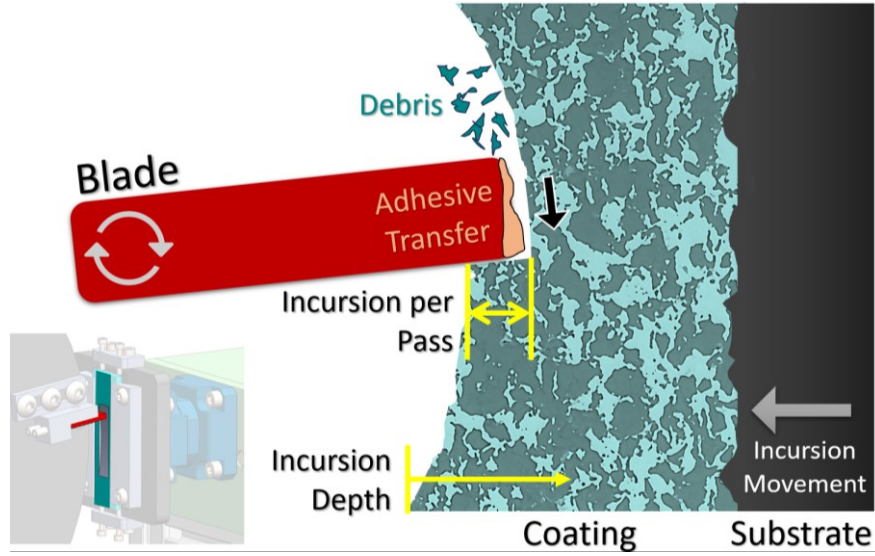


Figure 3.1. Schematic of the abradable test.

3.2.2. Mechanical Layout

Using SolidWorks 3D software, a model of the full equipment was designed, and it is presented in Figure 3.2. The testing apparatus can be divided into rotational and linear stages. Regarding the rotational stage, a rotating disk is connected to a motor providing high tangential speed during testing. In addition, a dummy blade tip can be mounted on the disk to simulate a rotating blade in a real application environment in an aircraft turbine (see Figure 3.2b and Figure 3.2c). The three-dimensional modelling was generated to visualize the ultimate product and fine-tune the components before the commencement of physical production.

In terms of the blade tip geometry, an equivalent simplified geometry was proposed to mimic the rotor blade–casing interaction. The cost-effective abradable test rig was designed to accommodate several configurations depending on the target thickness-to-chord ratio (t/c) of relevant application scenarios, as seen in Figure 3.2c. In the custom-built abradable test rig, the chord can range between 5 and 15 mm, and the thickness can range between 0.5 and 4 mm. These values were selected based on conventional blading techniques proposed by Saravanamuttoo [143], which suggests a t/c ratio of 0.1 up to 0.2. Similarly, Kacker and Okapuu [144] and Moustapha and Zelesky [145] suggest a typical t/c ratio for a blade cross-section ranging between 0.13 and 0.32.

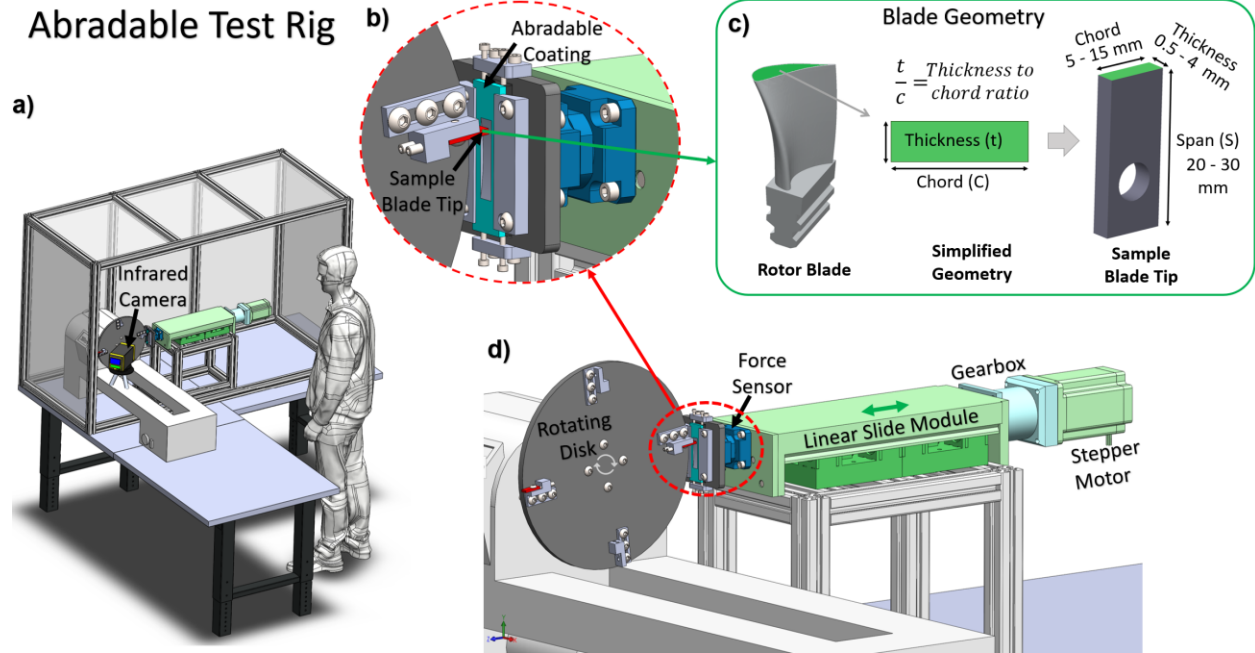


Figure 3.2. 3D modelling of the cost-effective abrable test rig; a) Overview of the equipment; b) Close view of the abrable coating and blade mounted; c) Simplified sample blade tip geometry; d) Detailed view of the movable specimen stage and rotating disk.

In terms of the specimen size dimensions of the abrable coating, the mechanical design of the sample holders was engineered to accommodate flat samples with a width ranging from 20 mm to 30 mm and a thickness from 2 mm to 10 mm. Since the samples are flat, the length of the sample is directly related to the expected length of the rubbing wear track, which is associated with and limited by the maximum incursion depth [146,147]. Typically, abrability tests are conducted with incursion depths ranging from 0.4 mm to 2 mm [17,88,147]. Considering the blade's rotational radius (300 mm), the suggested length of the flat samples varies from 40 to 95 mm, ensuring additional dimensions for safety.

In order to establish a cost-effective and reliable approach for evaluating thermally sprayed abrable coatings, the apparatus was constructed through the integration of mechanical and electronic components, such as a rotor, linear guide, stepper motor and planetary gearbox. For the rotor, the King KWL-1218VS lathe was selected for its capacity to vary rotational speed up to 3,800 rpm (equivalent to 63.3 Hz) and a swing-over bed of 305 mm. Figure 3.3a illustrates a photograph of the lathe. In addition, a 300 mm diameter stainless-steel disk was machined and attached to the headstock, resulting in a linear blade speed of 60 m/s due to the combination of lathe speed and disk diameter.

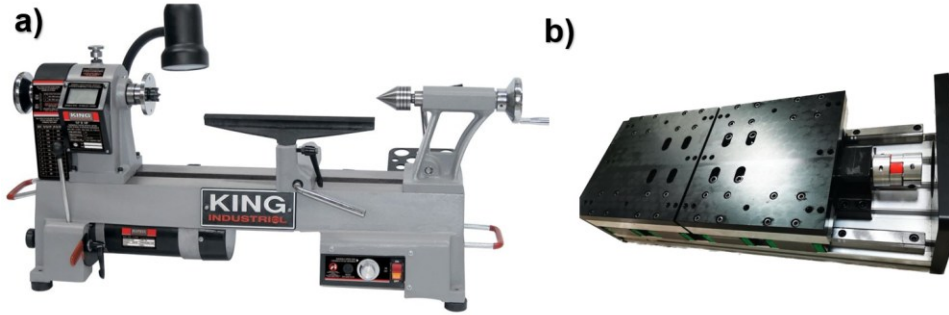


Figure 3.3. a) Wood lathe model King KWL-1218VS, b) Linear guide module model GX120-2505-200.

A linear slide module integrated with a gearbox, stepper motor, and sample holder was engineered to provide the linear movement of the abradable material. This setup facilitates the blade insertion process into the sample, emulating real-world rubbing scenarios. To achieve a range of incursion rate from $5 \mu\text{m/s}$ to $500 \mu\text{m/s}$, a custom-built GX120-2505-200 linear guide module equipped with 2 trolleys was designed (Figure 3.3b). Also, a commercially available NEMA 34 stepper motor (generating 12 Nm) and a 100:1 planetary gearbox were selected and attached to the movable specimen stage. This choice was based on considerations of precision and the extensive range achievable through the collaboration of a linear guide module and a stepper motor.

3.2.3. Instrumentation and Data Acquisition

The device in Figure 3.4a, identified as a triaxial load cell Kistler 9347C, is a piezoelectric force transducer designed to accurately measure all forces acting on the three orthogonal components in any direction. The load cell is installed between two plates with a preload and can measure both normal and tangential forces acting on the abradable coating during the test. Utilizing the piezoelectric principle, a force generates an electric charge that enables simple, direct, and highly accurate measurements. For the measurement signal processing, a Kistler LabAmp Laboratory Charge Amplifier quasi-static, model 5167A (Figure 3.4b) is essential for converting the measurement signal into an electrical voltage and facilitating comprehensive reaction force measurement.

The combined instrumentation system of the load cell and amplifier possesses a sampling capability of 200 kSps (kilo samples per second) per channel [148], far exceeding the necessary data measurement requirements. Considering the inverse relationship between frequency and period, this system can extract data every 5 microseconds. This sampling rate is approximately 3000 times higher than the period between each impact, which is 17 milliseconds considering the rig's rotational speed (i.e., up to 3000 data points can be acquired between each full blade

revolution). Detailed frequency analysis and validation of this system are elaborated on and discussed in the section "Data Acquisition and Rig Validation".

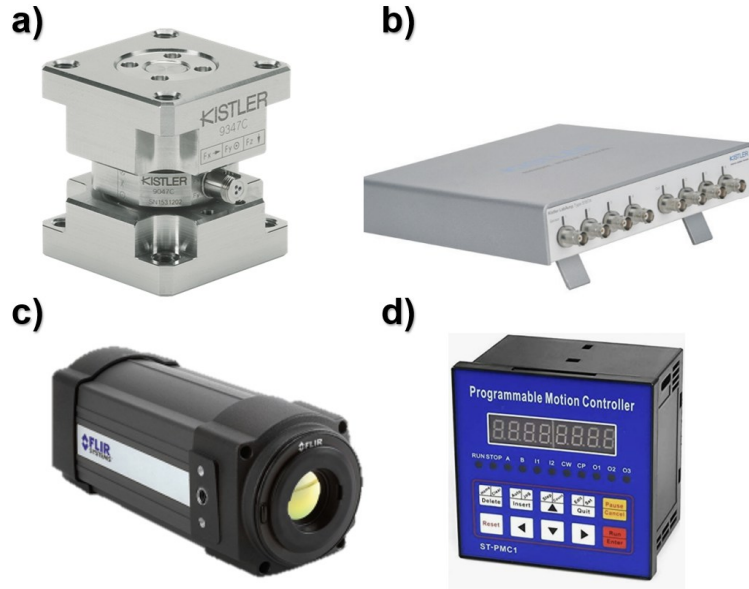


Figure 3.4. a) Triaxial load cell model Kistler 9347C [149]; b) Laboratory amplifier model Kistler LabAmp 5167A [148]; c) FLIR A320 ThermoVision infrared camera [150]; d) Programmable Controller model ST-PMC1 [151].

In order to accurately measure the surface temperature of the abradable coating during the abrasability tests, an A320 ThermoVision infrared camera (FLIR Systems, MA) was integrated into the test rig. This infrared camera (Figure 3.4c) is calibrated to detect temperature variations within the range of 0 to +350°C, maintaining an accuracy of $\pm 2^\circ\text{C}$. The camera system is equipped with a dynamically updated reference temperature to ensure precise monitoring. Although the setup is designed to monitor the overall interfacial temperature (e.g., caused by friction heating) of the coating over time, the camera's detector has a response time of 12 milliseconds, enabling real-time temperature monitoring and data extraction between each impact period. These measurements, combined with the incursion rate, can be accurately converted and associated with the rubbing depth during the abrasability tests, providing a comprehensive understanding of the overall rubbing temperature evolution. Before testing, parameters such as material emissivity, measurement distance, and required data accuracy must be known and adjusted.

In addition, several electronic devices were carefully chosen to allow flexible adjustment of the incursion rate, such as controlling and monitoring the movable specimen. These devices include a CNC Servo Driver model 2HSS86 that connects to the stepper motor and the Stepper Motor Programmable Controller model SainSmart ST-PMC1 (Figure 3.4d). Two adjustable power supplies with a capacity of 480W and a voltage range of 0-48V were also selected to provide power to the system. Additionally, a digital readout kit was integrated into the moveable stage to facilitate precise monitoring of the incursion depth by the operator during the test.

3.2.4. Manufacturing and Assembly

In pursuit of the rig's optimal functionality, machining techniques were applied to fabricate minor components crucial for interconnecting various rig devices. Key concerns included stability, balancing, and the management of static and dynamic loads under operational conditions. The list of components includes the rotating disk, sample holders, joints, and supports. The rotating disk was laser-cut and machined to ensure precise weight and geometric distribution, as well as the blade sample holders that were uniformly distributed to balance the mass. This careful engineering ensures smoother operation by minimizing vibrations and enhancing the reliability of experimental results.

In addition, aluminum extrusion profiles were also employed to facilitate joining and support for the mechanical assembly. To enhance operational safety, a protective case was fabricated, featuring a covering composed of a 6 mm-thick bullet-resistant polycarbonate sheet (Lexan, GE). This material was selected since it exhibits high impact strength and heat resistance, making it suitable for severe dynamic impact and thermal loads [152]. A few ballistic tests have already proven the efficiency of the polycarbonate under both normal and inclined dynamic impacts [153–155]. Among those, Radin and Goldsmith [155] performed bullet tests at 82.1 m/s and 93.9 m/s against polycarbonate plates with similar thicknesses.

The fully assembled cost-effective abrasable test rig is illustrated in Figure 3.5a. A more detailed perspective of the sample holder, showcasing the mounted abrasable coating before initiating the test, is presented in Figure 3.5b. Additionally, Figure 3.5c exhibits the assembled movable specimen stage.

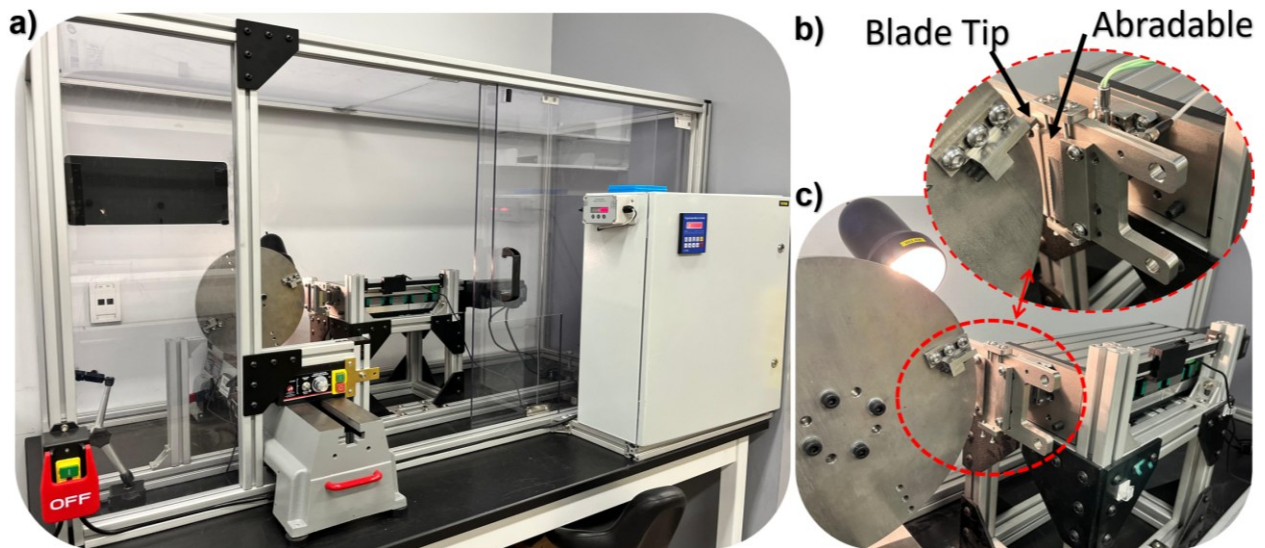


Figure 3.5. a) Overview of the cost-effective abrasable test rig; b) Abrasable coating mounted on the sample holder; c) Close view of the disk and moveable specimen stage.

3.2.5. Data Acquisition and Rig Validation

3.2.5.1. Dynamics Evaluation

A detailed investigation, especially in terms of dynamics, was conducted to provide insights into the performance and reliability of the abrable test rig under operational conditions. To validate the accuracy of rotational speed, linear incursion position, and incursion rate, a high-speed camera (Model HSI FASTCAM SA1.1) [156] was used to monitor the position over time at 20000 fps. Thereby, qualifying the dynamic mechanism system, such as the lathe and the ST-PMC1 Programmable Controller inputs (e.g., rpm, and incursion rate). Figure 3.6 is a visual representation of the methodology and results mentioned.

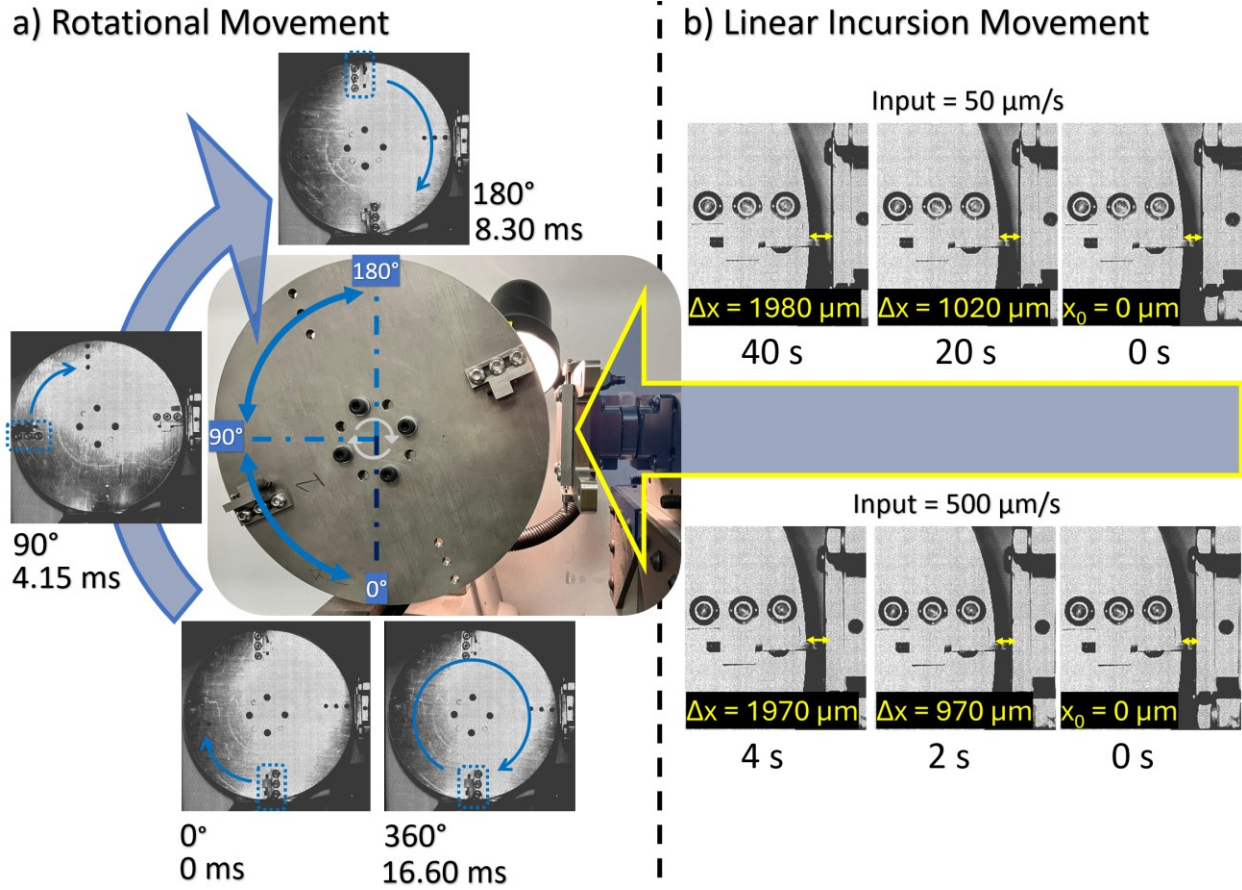


Figure 3.6. Investigation of the system dynamics at 3600 rpm and at two different incursion rates; a) Evaluation of the rotating speed using high-speed camera imaging; b) Analysis of the linear incursion movement at 50 $\mu\text{m/s}$ and 500 $\mu\text{m/s}$ using high-speed camera imaging.

For the linear incursion movement analysis, images were captured at specified time intervals (as depicted in Figure 3.6b), and the position of each was measured to confirm the

incursion rate input and system stability. A comparable approach was utilized for the rotational movement analysis (Figure 3.6a). In this case, four distinct positions were selected, and the time interval required to move between them was observed to verify the rotational speed. The data indicated that both the linear and rotational movements were within the expected operational range, confirming the accuracy of the input parameters and the stability of the system. This comprehensive validation underscores the reliability and precision of the test rig's dynamic performance under operational conditions.

Given the rig's rotational speed input of 3600 rpm, resulting in an impact frequency of 60 Hz and, consequently, an impact interval of about 17 milliseconds between each full blade rotation, a comprehensive investigation was conducted. This investigation aimed to establish a practical and theoretical correlation to qualify the natural frequency and direct impact forces. Kistler Triaxial Accelerometer model 8763B500 [157] alongside the data acquisition force system were used to qualify the dynamics impact during tests and compare with the theoretical impact frequency. Figure 3.7 illustrates the main results, demonstrating that the data aligns with the anticipated acquisition range, showing a peak every 17 milliseconds (first touch point). These findings confirm the rig's accuracy, ensure the natural frequency of the rig outside the operational range, and validate the reliability of the force acquisition system.

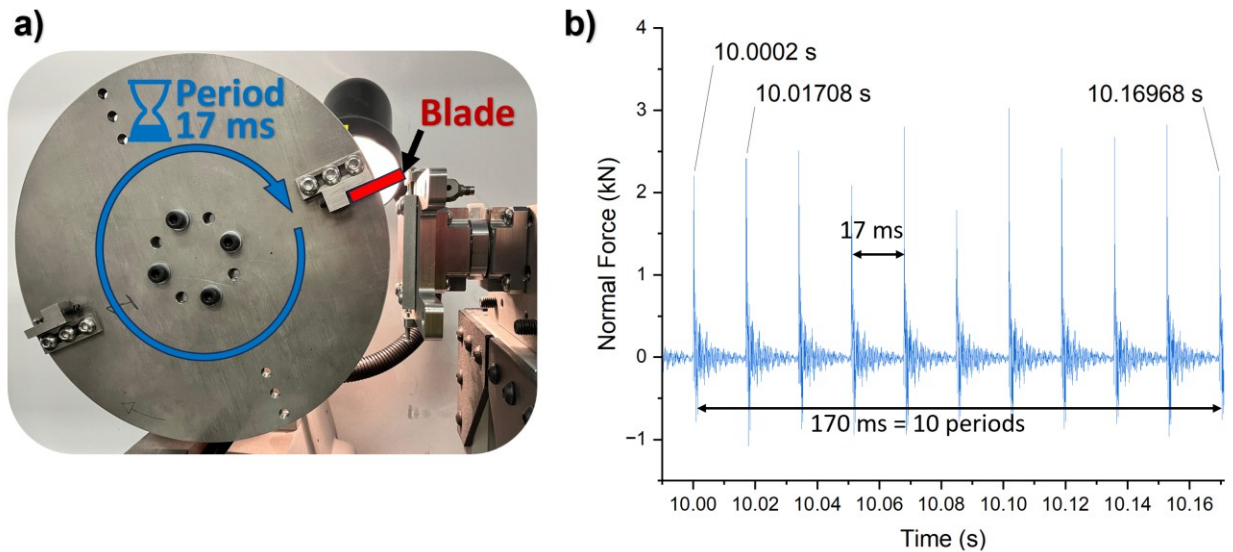


Figure 3.7. Evaluation of the blade impact period during testing; a) Side view of the abrasable test rig, illustrating the theoretical blade impact period; b) Plot of normal reaction forces over time, showing the observed blade impact periods during the test.

3.2.5.2. Materials Testing

Aiming to validate the abrasable test rig in terms of materials pre-screening, three different materials were tested. The first material was a conventional thermally sprayed abrasable

material AlSi-40Polyester, and due to its significance as an abradable coating, three tests were performed on this material. More details on the spraying equipment and parameters can be found elsewhere [158–160]. In addition to the validation process, a thermally sprayed polyester and a conventional aluminum sheet metal were also selected since they are the primary elements found in traditional aluminum-silicon-polyester abradable coatings. This selection was made to facilitate comparative analyses and ensure a comprehensive evaluation of the performance and characteristics of the abradability testing. The tested parameters used on all samples can be found in Table 3.3.

Table 3.3. *Abradable test parameters.*

Abradable Test Parameters			
	Description	Value	Unit
Blade and Abradable Characteristics	Blade Material	Ti6Al4V (Grade 5)	-
	Sample Dimensions	25 x 76	[mm]
	Rubbing Surface (Blade Contact Area)	10 x 3.18 mm = 31.8	[mm ²]
Input Parameters	Blade Speed	50	[m/s]
	Incursion Rate	50 (0.83 μ m/pass)	[μ m/s]
	Incursion Depth	1500 & 2000*	[μ m]
Extras	Disk Rotation	3600	[rpm]
	Operational Temperature	Room Temperature	[°C]
	Humidity	20%	-

*AlSi-40Polyester (2000 μ m); Polyester coating & Aluminum sheet metal (1500 μ m).

3.2.5.3. Reaction Forces and Temperatures

The normal and tangential forces during rub are commonly used to analyze the abradability properties of thermally sprayed abradable materials [132,146], and minimal rubbing reaction forces are desired in order to protect the blade [36,158]. Figure 3.8b and Figure 3.8c present the reaction forces acting on the specimens during their respective rubbing tests. It should be noted that for comparison reasons, Figure 3.8 only presents results up to 1500 μ m, despite the incursion depth of the AlSi-40Polyester sample being performed up to 2000 μ m. Other specimens, such as polyester coating and Al sheet metal, were tested up to 1500 μ m incursion depth due to safety concerns related to the available thickness of the samples. The normal and tangential forces for AlSi-40Polyester were evidently lower compared to the aluminum and polyester. Indeed, the AlSi-40Polyester was specifically designed to be an effective abradable.

Both thermally sprayed coatings, AlSi-40Polyester and polyester demonstrated consistent and effective cutting, as evidenced by the uniform distribution of forces throughout the rubbing depth (Figure 3.8b and Figure 3.8c). Similarly, Zhang et al. [117] measured the reaction forces of AlSi-Polyester against Ti6Al4V blades using a comparable incursion rate ($50\mu\text{m/s}$), noting a cycle force pattern with peaks similar to the force behaviour presented in this study (see Figure 3.8b and Figure 3.8c).

In a quantitative evaluation, AlSi-40Polyester exhibited the lowest reaction force (156 N), which was almost 2.5 times lower than that of the polyester material. These results are close to the ones available in the literature using other custom-made abradable rigs, even using distinct cutting characteristics. Recently, Zhang and Marshall [146] observed equivalent reaction forces in a range of about 100 N and rubbing temperatures of about 200°C on tests using a different high-speed abradable test rig, by means of a knife-edge methodology on coatings with similar chemical compositions.

On the other hand, the aluminum sheet metal tested as a denser and harder material exhibited numerous ruptures and non-uniform cutting, leading to larger chips, higher maximum reaction forces (2305 N), and discontinuous loads.

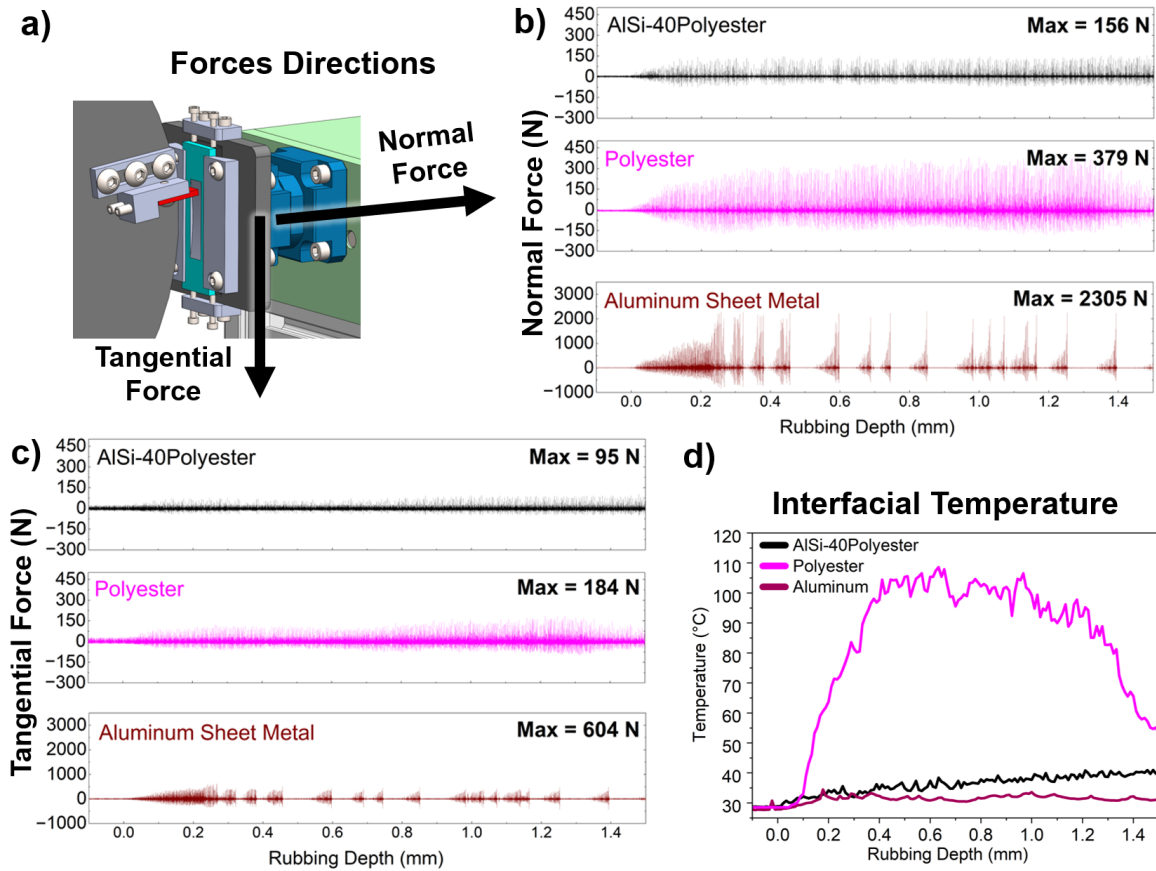


Figure 3.8. Reaction forces and interfacial temperatures along the rubbing depth; a) Schematic illustrating the direction of the reaction forces; b) Normal force of AlSi-40Polyester [158], polyester, and aluminum sheet metal; c) Tangential force; d) Interfacial temperature of the three materials during the abrasibility test

Figure 3.8d shows the interfacial temperature for the three materials tested as a function of the rubbing depth. AlSi-40Polyester exhibited a steady increase in temperature, reaching a maximum of 44°C at the maximum incursion depth. Similar investigations have explored the interfacial temperature in abradable coatings and its association with friction forces [31,87,161]. Additionally, the results observed by Watson and Marshall [103] performed on a different abradable rig indicated that the peak temperature was achieved using 0.2 $\mu\text{m/pass}$ (below 200°C), which was close to the 0.83 $\mu\text{m/pass}$ used in the current study.

On the other hand, the interfacial temperature for the thermally sprayed polyester was significantly higher, reaching up to 109°C. However, for the aluminum, the maximum temperature was 35°C, which is lower than the temperatures on AlSi-40Polyester tests. This can be attributed to its higher thermal conductivity and non-continuous cutting, which helped to lower the heat generated during the rubbing.

Similarly to the findings in this validation process, many studies observed equivalent outcomes that can be associated with reaction forces, including rougher scar appearance [17], adhesive transfer [88], and blade wear [36].

3.2.5.4. Coating and Blade Analyses

The AlSi-40Polyester abradable coating presented a clean and smooth cut in all tests (Figure 3.9a, Figure 3.7b, and Figure 3.7c), indicating a consistently good abradability of the coating and high stability of the apparatus. This can be observed by the shallow grooves on the rubbing wear track (see Figure 3.9), which is associated with the expected dominant abrasive wear mechanism. This is consistent with previous studies on thermally sprayed abradable coatings, which showed similar wear tracks [25,132,146].

The tests performed on aluminum sheet metal showed a significantly higher adhesive transfer to the titanium blade due to aluminum's high chemical affinity [162], and its higher metallic content compared to the abradable coating AlSi-40Polyester. As observed in the literature [25,101], a higher concentration of aluminum typically leads to a higher adhesive transfer, as shown in Figure 3.9e. This feature also explains the increased reaction forces observed in Figure 3.8, which were driven by a higher contribution of aluminum's adhesive transfer to the blade and the fact that aluminum sheet metal was a denser and bulk material.

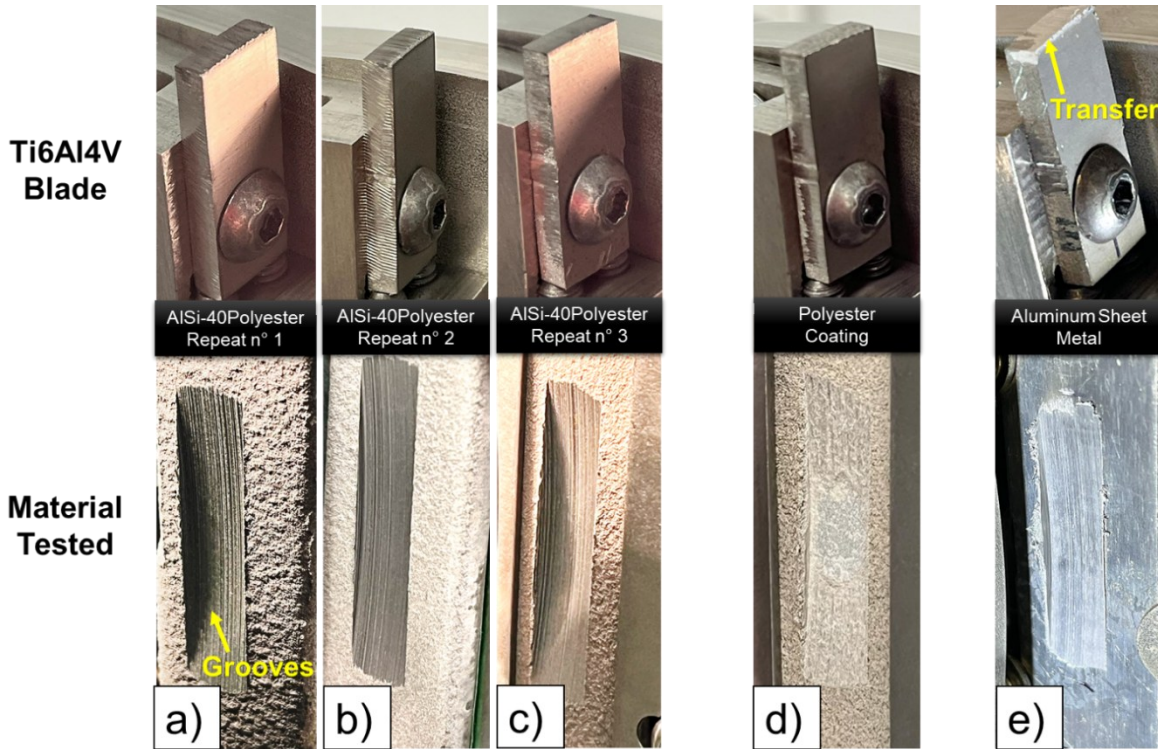


Figure 3.9. Different materials tested in the cost-effective abrasible test rig; a) AISi-40Polyester, repeat number 1 [158]; b) AISi-40Polyester, repeat number 2; c) AISi-40Polyester, repeat number 3; d) Thermally sprayed polyester; e) Aluminum sheet metal.

Moreover, several research groups have observed similar wear behaviours on different abrasible test rigs. Mutasim et al. [118] conducted an abrasibility evaluation of Al-based coatings, comparing them with other abrasibles and pure aluminum against a 4043 steel blade. Their results indicated no coating debonding, chipping, or smearing, with clean and uniform groove cuts observed. At the same time, aluminum samples did not perform well in the abrasibility tests, similar to the findings of the rig used in this study.

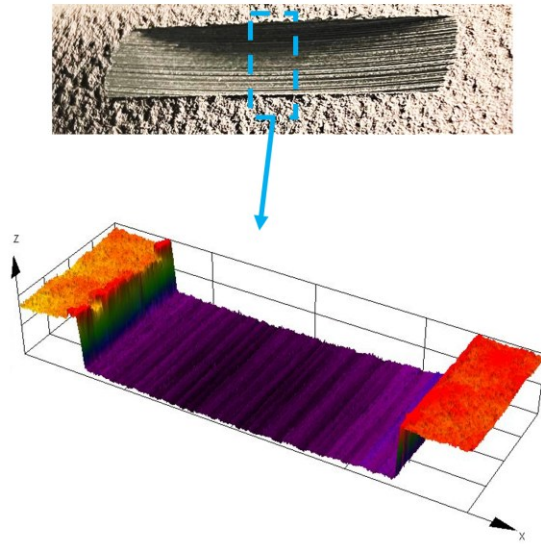
In order to elucidate the effective cutting of the AISi-40Polyester abrasible coating in the cost-effective abrasible rig, the samples were investigated in more detail in terms of wear and adhesive transfer. Figure 3.10a shows a 3D microscopical image of the wear track of the rubbed abrasible material. The worn surface exhibits grooves produced by the abrasive wear mechanism parallel to the direction of motion.

Similarly, Zhang et al. [117], when carrying out tests at 350°C using a high-speed abrasible test rig, showed that the blades also formed parallel grooves on the coating with similar cutting behaviour. Using a different abrasible test rig, Liu et al. [25] also observed groove formation in the coatings without debonding, with regular-shaped wear tracks and relatively smooth surfaces, consistent with the findings from the rig developed in this current study.

Meanwhile, in Figure 3.10b, the Ti6Al4V blade tip used against the AISi-40Polyester reveals no wear on the blade. However, as found by some authors [13,32,42,163], the blade showed

the evident formation of a transfer film, which can be seen on the front and top view (see Figure 3.10b). This adhesive transfer film was predominantly formed by the aluminum from the abradable coating to the blade.

a) AlSi-40Polyester (after test)



b) Ti6Al4V Blade (after test)

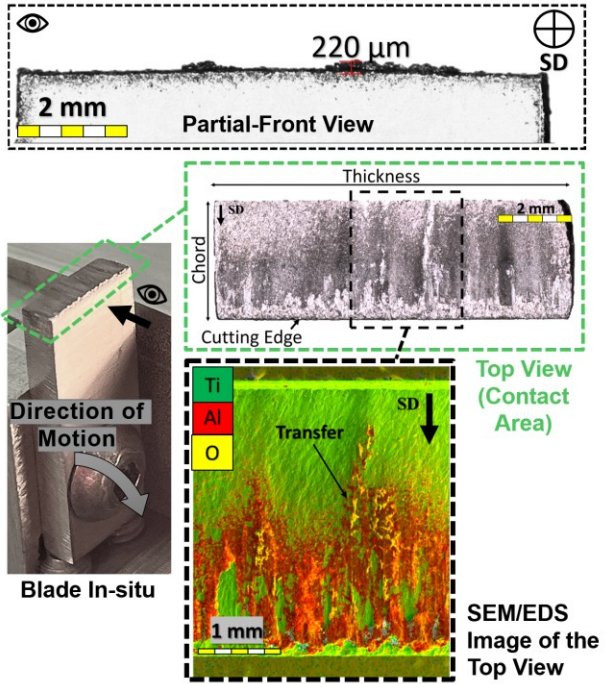


Figure 3.10. a) Photograph and 3D microscopical image of AlSi-40Polyester wear track after rubbing test; b) Ti6Al4V blade images and elemental mapping after rubbing test [158].

An equivalent adhesion mechanism was also observed by Rahimov et al. [32]. They tested the AlSi-Polyester coating against Ti6Al4V blades and found parallel groove formation in the coating when analyzed at a close blade speed (85 m/s), corroborating the previous discussion's results. These results reinforce the reliability of the conclusions and data acquired from the cost-effective abradable test rig compared to other abradable test rigs.

3.3. Conclusions

In this study, a cost-effective abrasible test rig was designed to pre-screen thermally sprayed abrasible systems. This setup provides valuable insights into the interaction between abrasible coatings and blade tips, and their wear behaviour. Its ability to simulate operational conditions, adapt to different materials, and take a prompt, cost-effective approach is crucial for enhancing the efficiency of material assessment.

In order to validate the rig, a detailed dynamic evaluation was conducted to provide insights into the performance and reliability of the abrasible test rig under operational conditions. In addition, two thermally sprayed materials (AlSi-40Polyester and polyester) and a commercial aluminum sheet metal were investigated. The AlSi-40Polyester presented the lowest reaction forces with no significant blade wear. In addition, the polyester coating showed significantly higher interfacial temperature, which can be attributed to its low thermal conductivity. The tests performed on the aluminum sheet metal, on the other hand, presented significantly higher adhesive transfer on the blade and the highest reaction forces.

Moreover, a comprehensive understanding of the rig's design and setup can significantly benefit other research groups by serving as a reference for developing similar test rigs. This can foster consistency and comparability across different studies, facilitating advancements in the field. Detailed documentation of our rig's validation process can help other researchers replicate our setup, adapt it to their specific needs, and ultimately contribute to a broader and more reliable body of knowledge within the community. Such collaborative progress is essential for pushing the boundaries of fields such as tribology and thermal spray, which can be a powerful ally when pre-screening new thermally sprayed candidate coatings for abrasible systems.

Influence of hBN on the Abradable Performance of AlSi-Based Coatings: Bridging the Gap Between Tribological Assessment and Abradability Testing ⁴

Abstract

Abradable coatings have been proven to significantly improve the performance of turbomachinery by serving as a protective barrier between rotating blades and stationary casing. However, there is still a pressing need to develop more efficient abradable materials that can withstand the growing energy requirements and prolong the service life of gas turbines, which continues to pose a significant challenge to the aerospace industry. In the present study, two thermally sprayed aluminum-silicon-based (AlSi) coatings were investigated, the first containing 40 wt.% polyester (referred to as AlSi-Poly), and the second containing 6 wt.% hexagonal boron nitride (hBN) and 20 wt.% polyester (referred to as AlSi-hBN-Poly) as filler material. The microstructure, HR15Y hardness, and surface roughness were systematically examined in the fabricated coatings. Tribological studies were conducted using ball-on-flat and ball-on-disk testing conditions against titanium counterballs. In addition, a cost-effective abradable test rig has been developed to assess the abradability performance of both coatings under closer simulated aircraft turbine conditions. The microstructural examination of the coatings revealed that the filler materials were uniformly distributed throughout the coating, with the hBN particles embedded within the matrix. The average hardness of the AlSi-hBN-Poly coating was higher than that of the AlSi-Poly coating, which is consistent with the area fraction of filler materials present in each coating. The tribological assessment of the coatings revealed similar frictional coefficients, no apparent wear on the counterballs, and higher wear depth and width for AlSi-hBN-Poly coating. This was attributed to significant third-body abrasion and higher transfer during testing in the case of the AlSi-hBN-Poly coating. Similarly, the abradability evaluation showed no blade wear against both coatings and slightly different transfer film formation. However, the AlSi-Poly coating presented a smoother rubbing wear track than the AlSi-hBN-Poly, which showed deeper rubbing grooves. These findings provide valuable insights into the tribological behaviour of these coatings and can aid in the development of more effective wear-resistant coatings.

Keywords: Abradable Coating; Abradable Test Rig; Thermal Spray Coating; Tribology; Wear.

⁴ This chapter has been published in *Surface and Coatings Technology (SurfCoat)*.

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4.1. Introduction

The continuous improvement in reducing power consumption as well as increasing engine efficiency of aircraft turbines is an ongoing evolution. One of the design approaches to improve aircraft engine efficiency is to maintain a tight clearance between the stator and rotor blades in the low-and-high pressure compressor regions [8,42]. The tight clearance minimizes the escape of compressed air between the rotor blades and the casing. Adequate sealing is vital, in order to provide such tight clearance, which not only seals the gap but also safeguards the rotor blades from rubbing against the stator [15,164].

These sealing materials are commonly known as abrasables or clearance control materials and consist of a combination of a matrix, a solid lubricant or dislocator phase, as well as controlled porosity [13,45]. The matrix aims to provide strength and resistance to the abrasable coating. The solid lubricant or dislocator phase promotes crack initiation and propagation, providing an inherent weakness and assuring a small size of debris [13,15]. Once dislocators essentially have no potential to form chemical bonds with matrix materials, hexagonal boron nitride (hBN), graphite, and silicon are the most often used dislocators [13]. The hBN stands out due to its excellent lubricating properties, good thermal stability, and environmental friendliness [165,166]. It presents a layered structure with a highly lubricious characteristic, low strength, and a graphite-like crystal lattice. Adding hBN to abrasable materials reduces the continuity of the matrix and makes it easy to shear [96,165].

Alternatively, the bonding weakness can be controlled by the level of porosity in the coating by adding a specific amount of polyester to the abrasable coating [14,167]. Pores and voids allow the blade energy to be transmitted to the matrix and fracture the inter-particle bond, leading to clean cuts with little material transfer to the blade [45,112]. Consequently, the abrasability and erosion resistance of the coatings are sensitive to the volume percentage and size of the pores [93,112]. Generally, coating abrasability improves with increasing porosity, while erosion resistance reduces with the increase of porosity level [13,31]. In addition, besides the induced porosity, a polymer is added to reduce stress propagation during an interaction between the blade and the coating [18].

Abrasable materials are desired to be soft enough to yield to blade tips without causing scratches, yet hard enough to withstand the erosive impact of passing air, potentially laden with fine abrasive particles [42,43]. Additionally, abrasable seals must also fulfill requirements such as oxidation and corrosion resistance [112], resistance to thermal shock [13,101], debris compatibility and spontaneous combustion [112]. Currently, abrasable coatings are strategically applied at distinct locations within an aeroengine, each facing unique operating temperatures [13,48]. Specifically, metallic abrasable coatings tailored for low-temperature environments, like those in the low-pressure compressor area, are primarily composed of aluminum-silicon (AlSi), demonstrating optimal performance below 450°C [10,61].

Although there are numerous manufacturing methods to fabricate abradable materials (e.g. sintering [168], casting [19], 3D printing [69], diffusion bonding and brazing [19], and thermal spray [169]), the operation of the refurbishment of the abradable seals must be simple, efficient, and reliable [112]. Typically, abradable materials are fabricated by thermal spraying processes, which are superior compared to other manufacturing techniques. This is due to the ability to facilitate repairs and attain desirable properties by manipulating process parameters, consequently influencing the microstructure of the coatings [21,22]. Commercially available metallic abradable powders, used as feedstock for spraying, are usually alloys based on aluminum, cobalt, copper, and nickel and are typically mixed with boron nitride, polyester, and graphite [20].

The formulation and evaluation of abradable coatings are primarily conducted within industries, with limited representation in scientific publications. Several industries and research institutions have developed dedicated high-speed abradable test rigs to understand the physics of abradable rub interaction [28,30]. While there is existing research on the overall performance of abradable coatings, there is a distinct lack of comprehensive studies combining closely reassembled practical conditions and intricacies of wear mechanisms during the interaction between abradable coatings and blade tips. Indeed, defining the wear mechanisms on blade-abradable interaction is a highly complex task and typically includes cutting, rubbing, erosion, crushing, tribo-oxidation [13,87], melting, and adhesive material transfer [25,88].

In this study, a custom-built cost-effective abradable test rig was used to evaluate the performance of abradable coatings. The primary objective is to gain fundamental insights into the influence of hBN on the wear mechanisms of AlSi-poly coatings as they interact with Ti6Al4V blades, closely simulating low-pressure compressor conditions within an aircraft turbine. Two abradable materials, AlSi-Poly and AlSi-hBN-Poly were developed for this study and evaluated in terms of their tribological and abradability performance. These evaluations aimed to identify similarities in wear mechanisms and behaviours across different technology readiness levels (TRL) in a scale-up assessment. More specifically, the performance of these coatings has been assessed using ball-on-flat and ball-on-disk methods (TRL-3) for comparison with the abradability test (TRL-4). This comprehensive approach aims to elucidate the mechanisms involved, including abrasive wear, adhesive transfer film, counterface wear and associated forces.

4.2. Materials and Methods

4.2.1. Coating Preparation

AlSi-40 polyester and AlSi-6hBN-20 polyester feedstocks were used in this study. The initial one, denoted as AlSi-Poly, constitutes a conventional abrasible coating containing 40 wt.% polyester as an additional filler material. The second aluminum-based powder, referred to as AlSi-hBN-Poly consists of 20 wt.% polyester and 6 wt.% hexagonal boron nitride (hBN). The hexagonal form of boron nitride was carefully selected as a solid lubricant for the AlSi matrix due to its excellent stability and lubricating properties. Additionally, the specific percentage (6%) was determined based on commercially available literature of AlSi mixed with polyester [20].

Through scanning electron microscopy (SEM) images, elemental dispersive spectroscopy (EDS) analysis, and laser diffraction (LD) analysis, the feedstocks were characterized and presented in Figure 4.1. Both powders exhibited irregular and rounded particle morphologies. The first coating showed a median particle size (Dv50) for volume distribution of about 60 μm , while the second coating showed a Dv50 of about 70 μm . In both cases, the predominant method employed for powder manufacturing was blending, except for the AlSi-hBN-Poly powder, which underwent an additional process of mechanical cladding.

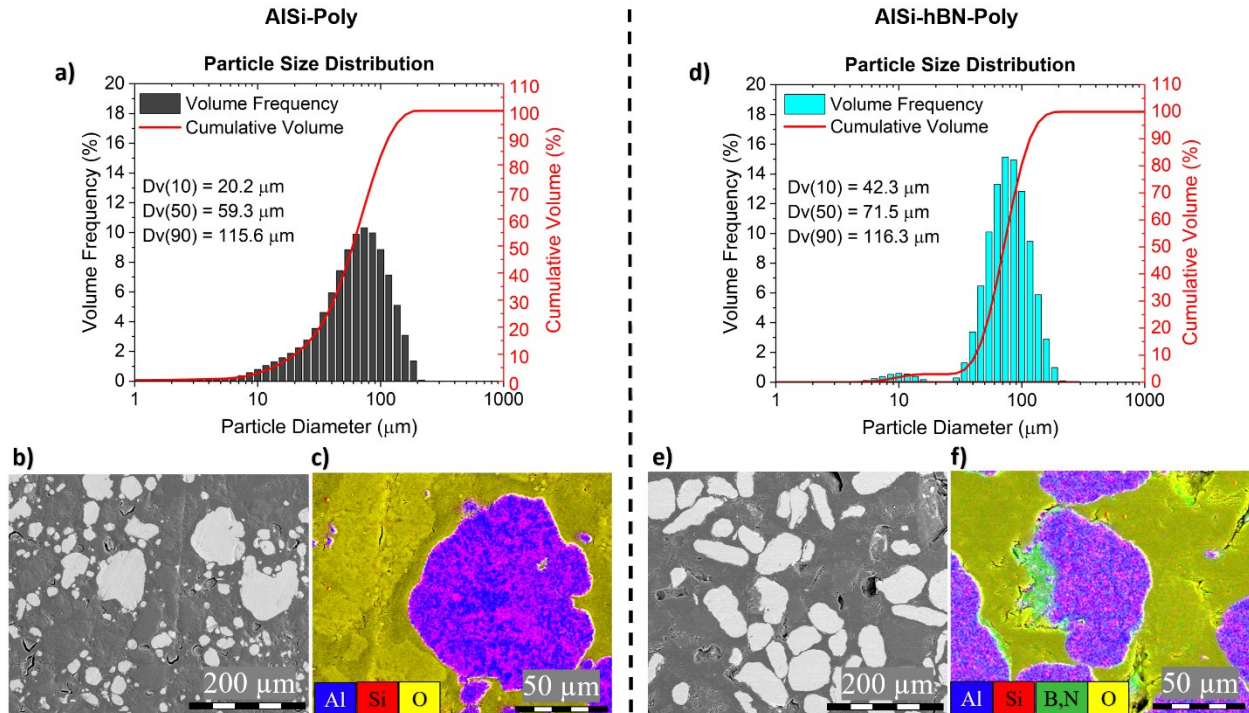


Figure 4.1. Powder particle characterization through LD, SEM and EDS analysis of the aluminum-silicon abrasible powders; a) Particle size distribution of AlSi-Poly; b) Cross-section image of AlSi-Poly powder; c) Mapping composition of AlSi-Poly powder; d) Particle size distribution of AlSi-hBN-Poly; e) Cross-section image of AlSi-hBN-Poly powder; f) Mapping composition of AlSi-hBN-Poly powder.

SAE 304 stainless steel plates with dimensions 25 x 150 x 5 mm were used as substrate material since this material is common in the static structures of aircraft engines. The deposition was carried out using a radial injection 3MB plasma gun (Oerlikon Metco, USA). Before deposition, the substrates were grit blasted with 80 grit alumina particles and reached a surface roughness average (Ra) of $6.15 \pm 1.16 \mu\text{m}$, followed by cleaning with compressed air to remove sand residue. The grit blasting ensures better interlocking of coating deposition.

The plasma spray parameters used were recommended by the powder supplier for AlSi-poly. In this regard, the same parameters were utilized for AlSi-hBN-Poly in order to replicate similar conditions and characteristics on both coatings. The APS parameters can be seen in Table 4.1. The plasma spray gun is attached to a fixed robot assembly (HP-20, Motoman, Yaskawa Electric Corp., Waukegan, IL, USA) in order to deposit the coatings with constant stand-off distance and speed. A total of 50 passes were performed to develop a coating thicker than 3 mm.

Table 4.1. Atmospheric plasma spray parameters used to thermally spray the abradable coatings.

Plasma spray parameters recommended by the powder supplier									
Gun	Nozzle	Linear Velocity (m/s)	Powder Feed Rate (g/min)	Carrier Gas Pressure (scfh)	SoD (mm)	Argon Flow Rate (nlpm)	Hydrogen Flow Rate (nlpm)	Current (A)	Voltage (V)
3MB	GP	1	30	20	90	93	2.6	500	66

4.2.2. Coating Characterization

The as-sprayed samples were cross-sectioned into pieces measuring about 25.4 x 10 mm using a high-speed abrasive cutting machine (Struers, Canada). These cut pieces were then mounted on cold epoxy resin (ANAMET, Canada) and kept at room temperature for at least 24 hours in order to harden them. After mounting, the samples were ground down using abrasive papers from 240-1200 grits, followed by polishing using 9 μm , 3 μm , and 1 μm water-based diamond suspensions, respectively. The final polishing step was done by using a 0.04 μm colloidal silica suspension. An automatic grinding-polishing machine (Struers, Canada) was used. Finally, the samples were carefully cleaned with water and dried. For metallographic observations of the polished surfaces, scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS) was used.

The hardness of as-sprayed coatings was measured using the Rockwell HR15Y hardness scale. For this test, 3 as-sprayed samples with 25.4 x 25.4 mm dimensions were prepared. In order to certify uniformity during the thermal spraying deposition, samples from different positions on the thermally sprayed plates were selected, and a total of 20 measurements using the 12.7 mm steel ball were applied over random positions at the top surface. In addition, surface images and

roughness analysis were conducted using a confocal laser microscope (LEXT OLS 4100, Olympus Corporation). The examination was based on topographic maps extracted from 10 different optical sections over the 25.4 x 25.4 mm samples, with a particular emphasis on assessing the roughness average (Ra), the maximum peak-to-valley height roughness (Rz), and the root mean square roughness (Rq).

4.2.3. Tribological Testing

A ball-on-flat (reciprocating) and ball-on-disk (rotational) tribometer (Anton Paar tribometer TRB³, TriTec SA, Switzerland) were used for wear testing under dry conditions. The equipment is located in the Tribology Laboratory at Concordia University, Canada, under controlled environmental conditions, and the tests were performed at room temperature with the relative humidity maintained around 20%. Schematic images illustrate the testing methodologies (Figure 4.12). Annealed Ti6Al4V balls with a mirror-finished surface, 6.35 mm in diameter, and hardness $HV_{200} = 329.8 \pm 5.3$ were used as counterball materials against the abradable coatings.

The use of Ti6Al4V as a counter body was justified in order to replicate the engine-relevant conditions. Testing was carried out on as-sprayed samples at a constant load of 10 N and a speed of 7 Hz frequency (equal to 0.22 m/s). The maximum Hertzian contact pressure (96 MPa) was calculated considering Poisson's ratio (0.23) [170] and elastic modulus (2.08 GPa) [115] for the thermally sprayed aluminum-silicon abradable coating. Furthermore, due to the approximate composition between both abradable coatings, no significant difference in contact pressure is expected. The sliding speed was determined by the maximum equipment speed for ball-on-flat reciprocal testing, with sliding direction (SD) bidirectional. The stroke length, stroke wear diameter and sliding cycles were fixed for 10 mm and 5000 cycles for the tests. These contact conditions were determined based on the capability of the testing equipment. At least two repetitions were made in order to check the reproducibility.

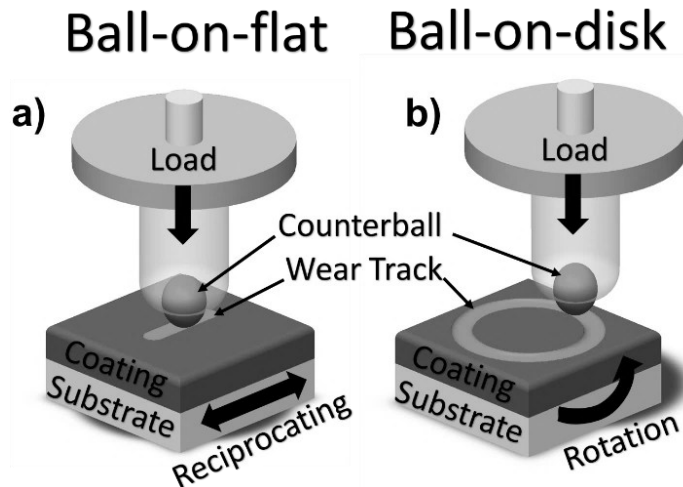


Figure 4.2. Schematic images of the different tribological test conditions; a) Ball-on-flat; b) Ball-on-disk.

Table 4.2 describes the primary information and parameters used in tribological studies. It shows relevant information such as equipment, counter ball details, load, cycles, speeds, etc.

Table 4.2. Detailed information about ball-on-flat and ball-on-disk test conditions.

	Ball-on-flat	Ball-on-disk
Equipment	Anton Paar TRB ³	
Counterballs Material	Ti6Al4V	
Counterballs Dimension	Ø6.35mm	
Normal Load [N]	10	
Hertzian Contact Pressure [MPa]	96	
Sliding Cycles	5000	
Sliding Amplitude [mm]	10	-
Wear Track Diameter (mm)	-	10
Total Sliding Distance (m)	100	157
Sliding Speed [m/s]	0.22 (7Hz)	
Test conditions	Room Temperature and 20% humidity	
Sample Size [mm]	25.4 x 25.4	

Ex-situ analysis was performed on the worn samples and the counter balls using SEM, EDS, and confocal microscope. The coefficient of friction (CoF) was extracted directly from the equipment. The wear profile was acquired utilizing the confocal microscope, involving 30 cross-sectional profiles obtained and averaged across various positions along the wear track.

4.2.4. Abradability

4.2.4.1. Abradable Test Rig

The abradable test rig was designed and developed for this study in order to simulate the rubbing process in an aero-engine system on a smaller scale, as shown in Figure 4.3 [171]. The rig test is composed of a blade mounted on a rotating disk and an abradable specimen that is being investigated. Throughout a test, an incursion motion is induced using a stepper motor, providing

the interaction between the abradable and the dummy blade. The test rig provides the flexibility to perform experiments at a range of numerous parameters, including rotational speed, incursion rates, incursion depth, and humidity. In addition, several sensors are employed to gather pertinent data throughout the testing, including reaction forces measured by a dynamic load cell and rubbing temperatures obtained by an infrared camera. Figure 4.3d illustrates a schematic of the abradable test, presenting the abradable coating moving toward the direction of the rotating blade, resulting in coating material removal, debris formation and material transfer to the blade tip, while Figure 4.3b and Figure 4.3c present, respectively, an overall and a detailed photography of the abradable test rig.

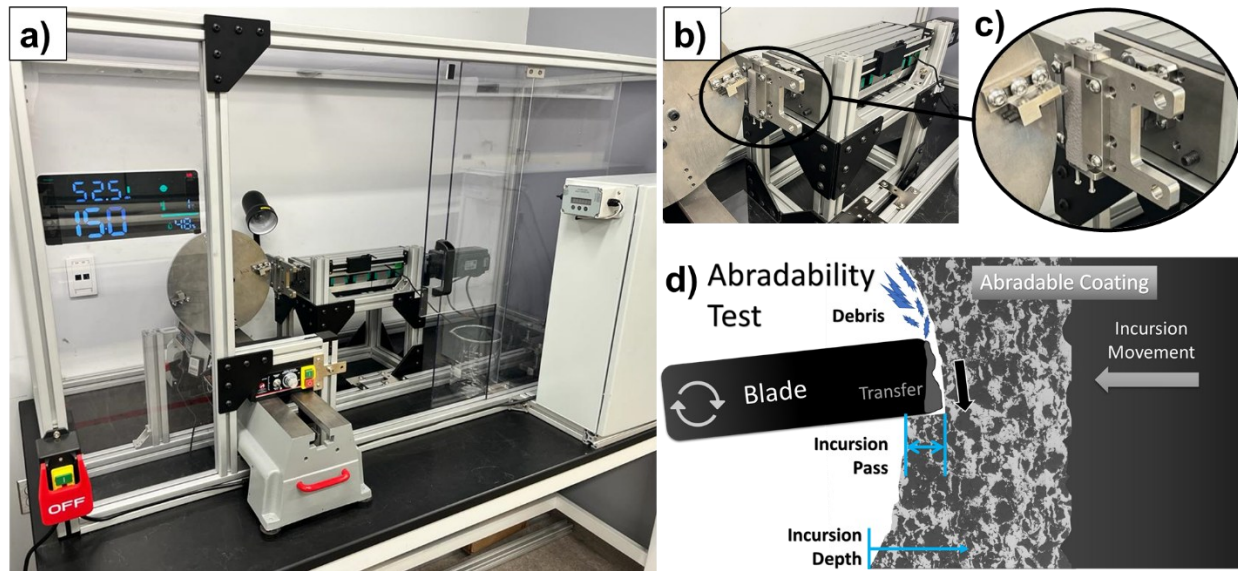


Figure 4.3. Cost-effective abradable test rig developed at Concordia University; a) Overview of the abradable test rig; b) Movable specimen stage; c) Close view of the abradable sample holder; d) Schematic of the abradability testing.

4.2.4.2. Abradability Testing

The abradable performance of the fabricated coatings was evaluated using the test parameters listed in Table 4.3. The test conditions were selected based on the maximum capabilities of the rig. Ground-finished Ti6Al4V (titanium alloy) blades were specifically manufactured by water jet cutting for this study with dimensions of 10 x 25 x 3.18 mm and Rockwell C30. The testing was carried out at a constant incursion rate of 50 $\mu\text{m/s}$ until it reached 2 mm as the maximum incursion depth. The incursion parameters were determined based on similar abradability test conditions observed in the literature [88,117]. The blade rotatory disc was rotated at 3600 rpm to achieve a maximum linear speed of 50 m/s at the blade tip. The combination of the settled blade speed and incursion rate resulted in an incursion per revolution of 0.83 $\mu\text{m/pass}$, a term that is conventionally named in machining processes as feed rate per revolution. Furthermore, aiming to set similar conditions during all tests, the humidity was maintained at 20%, and the test was conducted at room temperature.

Moreover, the apparatus could generate direct and indirect outputs. Direct outputs were provided by the rig during the test, as an example of the resultant rubbing forces applied on the abradable material by the blade-abradable interaction, named reaction forces (normal and tangential). A second example of direct output is the localized temperatures generated during blade-abradable contact caused by frictional heating, called rubbing temperature. In terms of indirect outputs, ex-situ analysis was performed on the rubbed surfaces and the counter blades using SEM, EDS, and confocal microscope. The focus was to observe the wear mechanism of the rubbed samples, blade wear, and material transfer from the abradable coating to the blade.

Table 4.3. Abradability testing parameters for the abradable coatings.

Abradability Testing	
Blade Material	Ti6Al4V
Blade Speed [m/s]	50
Cutting Surface (Blade Area)	10 x 3.18 mm = 31.8 mm ²
Incursion Rate [μm/s]	50
Incursion per Pass [μm/pass]	0.83
Incursion Depth [μm]	2000
Disk Rotation [rpm]	3600
Sample Size [mm]	25 x 76
Operating Temperature	Room Temperature
Humidity	20%

4.3. Results and Discussion

4.3.1. Coating Microstructure Analyses

Figure 4.4 shows the cross-sectional images of both coatings from low to high-magnification images. Both thermally sprayed abrasible coatings (AlSi-Poly and AlSi-hBN-Poly) have a thickness greater than 3 mm with a uniform polyester distribution between the aluminum-silicon matrix, as well as along the full thickness of the coating. Higher-magnification images reveal the presence of hBN particles embedded within the AlSi matrix on AlSi-hBN-Poly coating, resulting in an intrinsic porosity in AlSi particles (see Figure 4.4e and Figure 4.4g). According to Morrel et al [172], using hBN as the dislocator phase in abrasible coatings deposited by plasma spraying may be challenging, especially due to an imbalance in the mass of AlSi and hBN particles. On the other hand, in this work, due to the mechanical cladding of hBN and AlSi matrix performed on the powder manufacturing (Figure 4.1f), a uniform distribution of hBN within the thermally sprayed coating was successfully obtained (Figure 4.4e). The presence of hBN is in close agreement with the chemical composition matrix obtained by EDS point analysis. According to the literature [13,100], the hBN has no potential to form chemical bonds with the matrix material, which may lead to a reduction in the bonding force of AlSi particles, and therefore, causing the intrinsic porosity within the AlSi matrix that can lead to an inherent weakness of the coating.

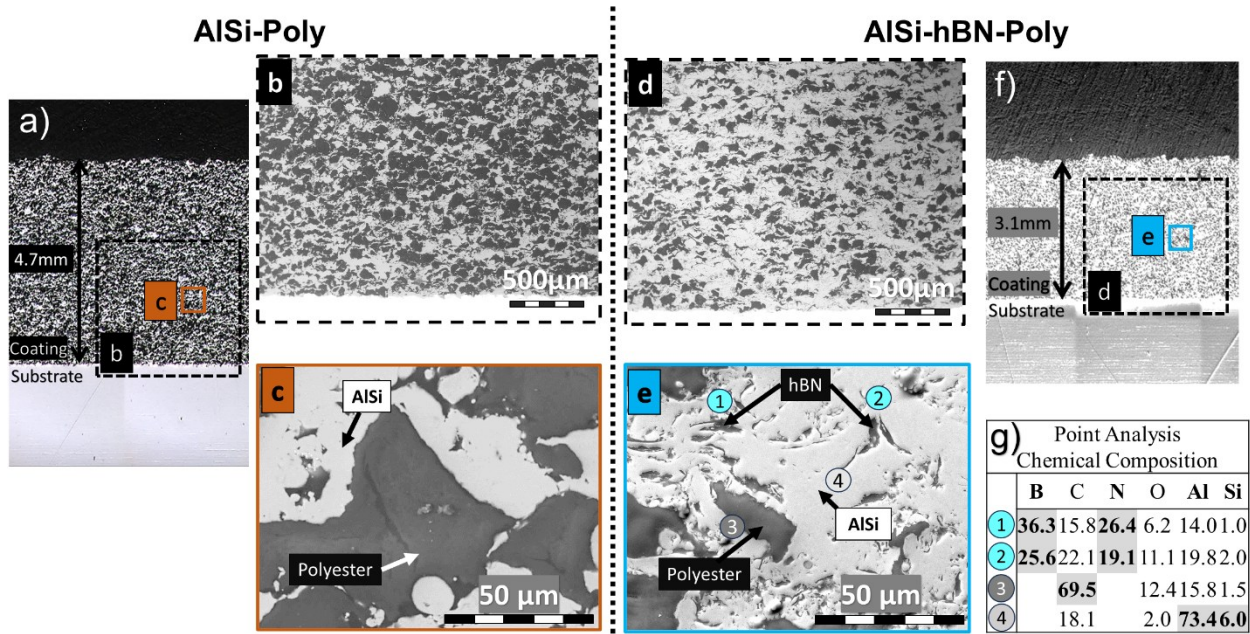


Figure 4.4. Microstructural characterization of the cross-section of both abrasible coatings under different positions and magnifications; a) Optical image of the entire coating thickness of AlSi-Poly coating; b) Low-magnified cross-section image of AlSi-Poly coating; c) High-magnified cross-section image of AlSi-Poly coating; d) Low-magnified cross-section image of AlSi-hBN-Poly coating; e) High-magnified cross-section image of AlSi-hBN-

Poly coating; f) Optical image of the entire coating thickness of AlSi-hBN-Poly coating; g) Chemical composition of the AlSi-hBN-Poly coating.

Despite both powders initially containing considerable percentages of polyester, AlSi-Poly exhibits a higher content at about 40%, compared to 20% in AlSi-hBN-Poly. However, it is essential to highlight that the composition may undergo alterations during the spraying process. Figure 4.5 provides a comprehensive analysis of the area fraction of filler material in each coating, along with the hardness measurements. The observations indicate that as the area fraction of filler materials (such as polymer) increases, it introduces a porosity level and a softer phase into the overall structure. This increase in porosity correlates well with the lower macrohardness values [31,120], as evidenced by AlSi-Poly, which presented 60.9 % of filler material and 74.7 HR15Y of hardness (see Figure 4.5). Conversely, a decrease in the area fraction of filler materials (34.6 %) results in higher metallic content, leading to elevated macrohardness values (83.8 HR15Y) observed in the case of AlSi-hBN-Poly.

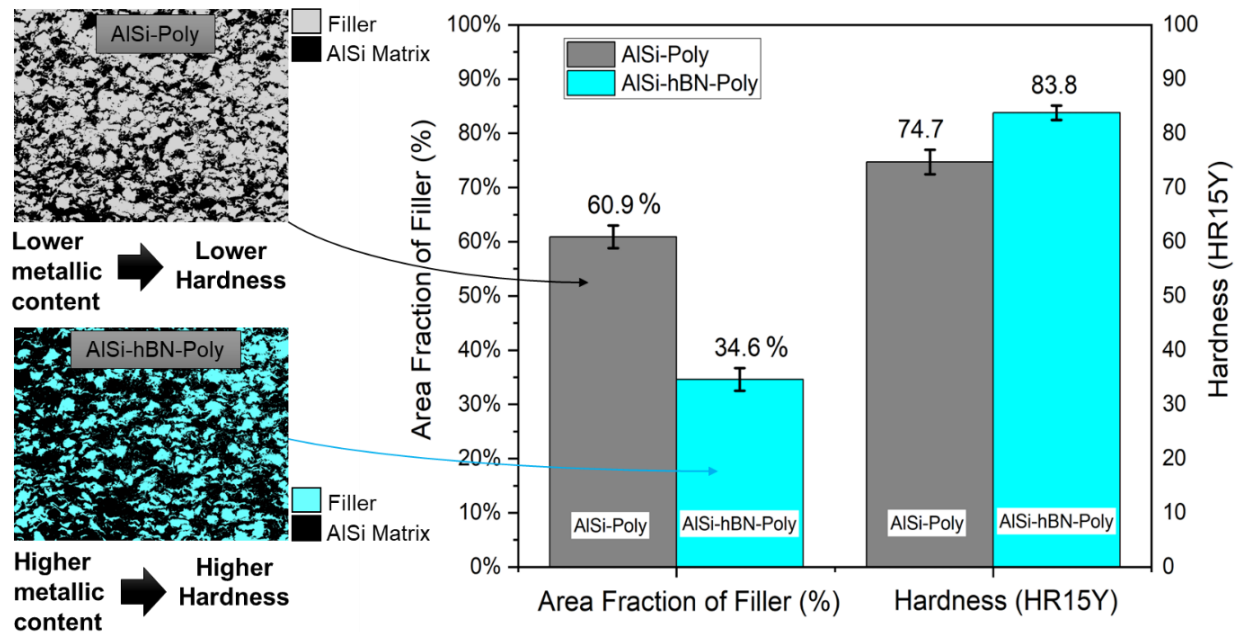


Figure 4.5. Area fraction of filler materials and HR15Y hardness of both aluminum-silicon abrasable coatings.

Surface roughness measurements of each coating were performed and are presented in Table 4.4. The as-sprayed surface of the abrasable coatings exhibited equivalent Ra and Rz values, given that both powders were subjected to the same plasma-spray conditions. The results show that the presence of hBN, and lower polyester content in the AlSi-hBN-Poly coating, did not significantly impact the surface roughness characteristics when compared to AlSi-Poly coating, which does not contain hBN and exhibits a higher area fraction of filler.

Table 4.4. Surface roughness values of the as-sprayed abradable coatings.

Abradable Coating	Ra (μm)	Rz (μm)	Rq (μm)
AlSi-Poly	4.44 ± 0.64	25.24 ± 3.17	5.59 ± 0.76
AlSi-hBN-Poly	4.06 ± 0.81	22.64 ± 4.84	5.14 ± 1.14

4.3.2. Tribological Analysis

4.3.2.1. Coating Wear Investigation

The two distinct abradable coatings were employed under two tribological testing methodologies, ball-on-flat and ball-on-disk. The coefficient of friction over sliding cycles for both abradable coatings is illustrated in Figure 4.6. The coatings demonstrate stable and equivalent CoF throughout the 5000 cycles in both tribological assessments. While all tests maintained constant CoF levels around 0.3, the AlSi-hBN-Poly coating under the ball-on-flat tests exhibited a slightly higher amount of fluctuations when compared to AlSi-Poly coating, which presented a stable frictional coefficient on all repeats.

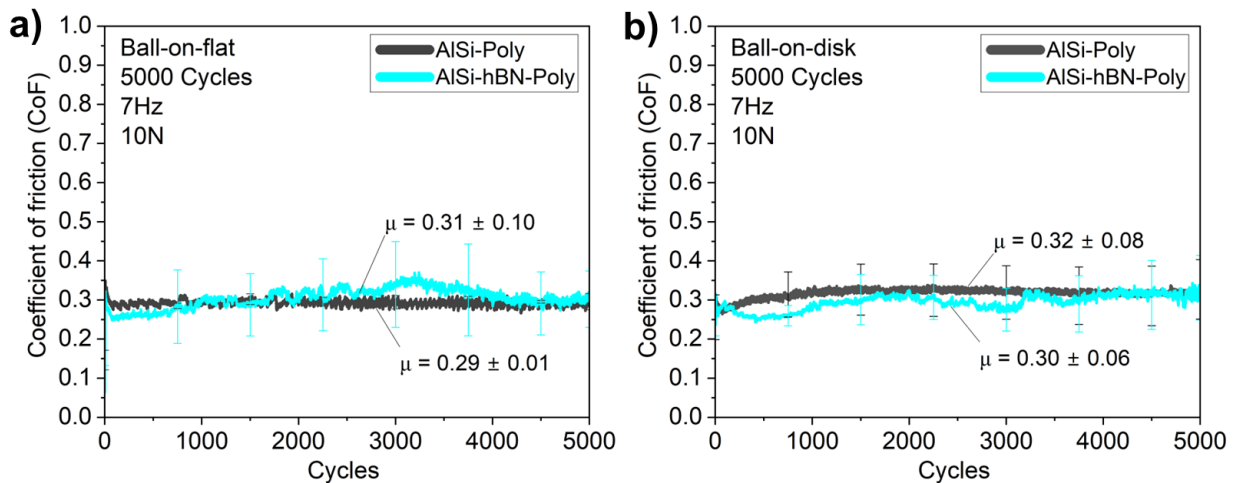


Figure 4.6. Friction coefficient results of the aluminum-silicon abradable coatings under different tribological test conditions; a) Ball-on-flat test; b) Ball-on-disk test.

Figure 4.7 and Figure 4.8 show the wear tracks of both abradable coatings generated using the ball-on-flat and ball-on-disk tests, respectively. In both sliding conditions, AlSi-Poly exhibits significantly lower wear volume than AlSi-hBN-Poly coating, considering the wear depth and width measured by the optical images in Figure 4.7b and c, Figure 4.8b and c. AlSi-Poly exhibited a maximum wear depth of approximately 60 μm in the ball-on-flat test and 22 μm in the ball-on-disk test (Figure 4.7d and Figure 4.8e). In contrast, AlSi-hBN-Poly demonstrated more substantial wear depths, reaching 227 μm in the ball-on-flat test and 158 μm in the ball-on-disk test. To

quantify the disparity, in the ball-on-flat assessment, the wear depth of the AlSi-hBN-Poly abrasible coating was approximately 3.8 times greater than that of the AlSi-Poly coating. Furthermore, in the context of ball-on-disk tests, this ratio between the abrasible coatings is even higher, reaching about 7.2 times higher wear depth for AlSi-hBN-Poly than AlSi-Poly. In addition to the greater wear depth, the coating containing hBN also presented higher wear width in both sliding test conditions, mainly observed in the top surfaces' images of both coatings after testing (Figure 4.7b and c, Figure 4.8b, and c).

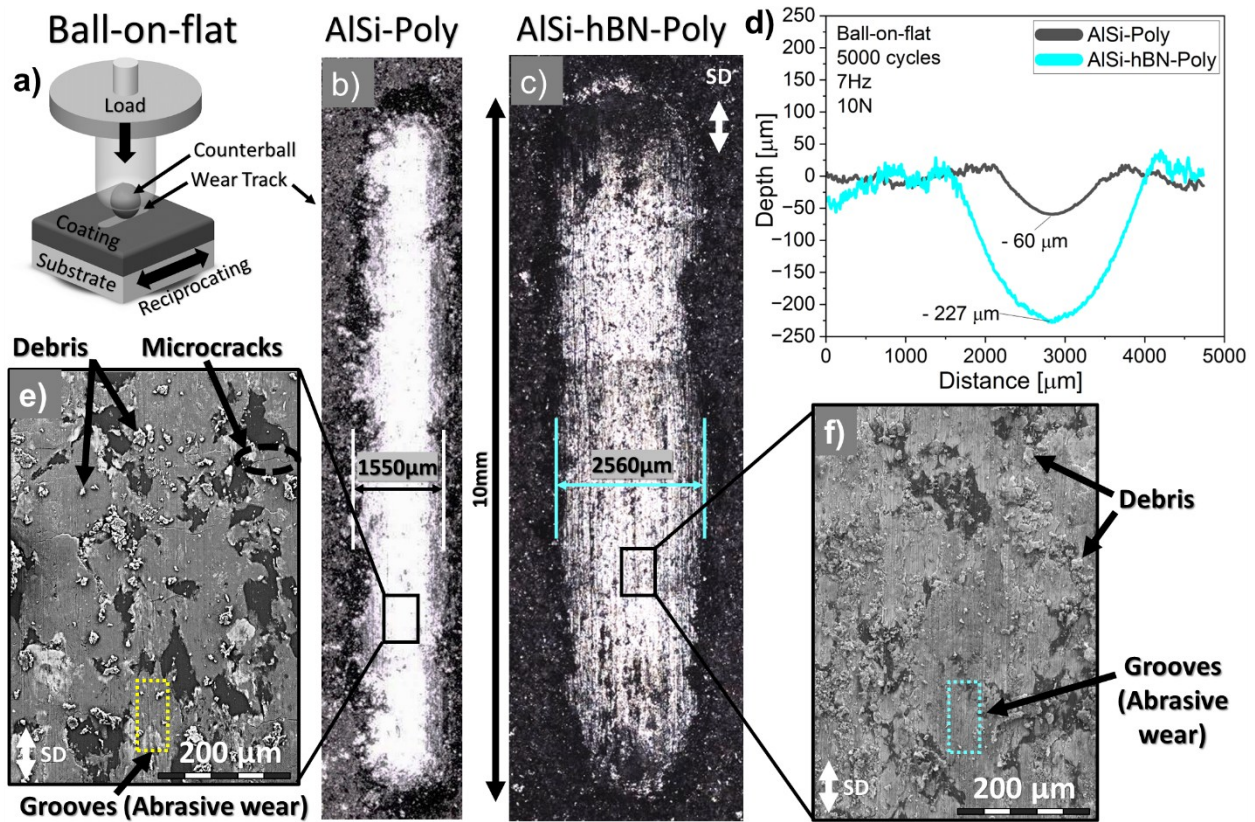


Figure 4.7. Wear track images of both abrasible coatings after 5000 cycles on the ball-on-flat test; a) Schematic representation of the ball-on-flat test; b) Full wear track of the AlSi-Poly coating; c) Full wear track of the AlSi-hBN-Poly coating; d) Wear profile of both abrasible coatings; e) Top surface SEM image of the AlSi-Poly wear track; f) Top surface SEM image of the AlSi-hBN-Poly wear track.

As evident from Figure 4.7e and f, Figure 4.8d and f, both abrasible materials exhibited smeared layers with predominantly abrasive wear mechanisms in both testing conditions, characterized by the formation of numerous grooves parallel to the direction of motion. In Figure 4.7e, AlSi-Poly exhibited some microcracks within the AlSi matrix, oriented perpendicular to the sliding direction. These microcracks could be attributed to the brittleness of the smeared layer resulting from work hardening and aluminum oxidation during the reciprocating sliding movement [173,174].

On the other hand, evidence of microcracks was not observed in AlSi-hBN-Poly coating. Furthermore, the AlSi-hBN-Poly coating exhibited an increased generation of debris compared to the AlSi-Poly coating. The increased debris formation is in good agreement with the wear volume for the AlSi-hBN-Poly coating. This phenomenon is visible in both tribological assessments, as illustrated in Figure 4.7e and f, Figure 4.8d and f. The increased debris generation observed in the AlSi-hBN-Poly coating is a consequence of the repetitive sliding motion executed over a surface containing a substantial dislocator phase as hBN. Specifically, the presence of hBN within the AlSi matrix in the AlSi-hBN-Poly coating microstructure resulted in an intrinsic porosity, which may facilitate the abrasive wear and formation of small debris during the sliding motion.

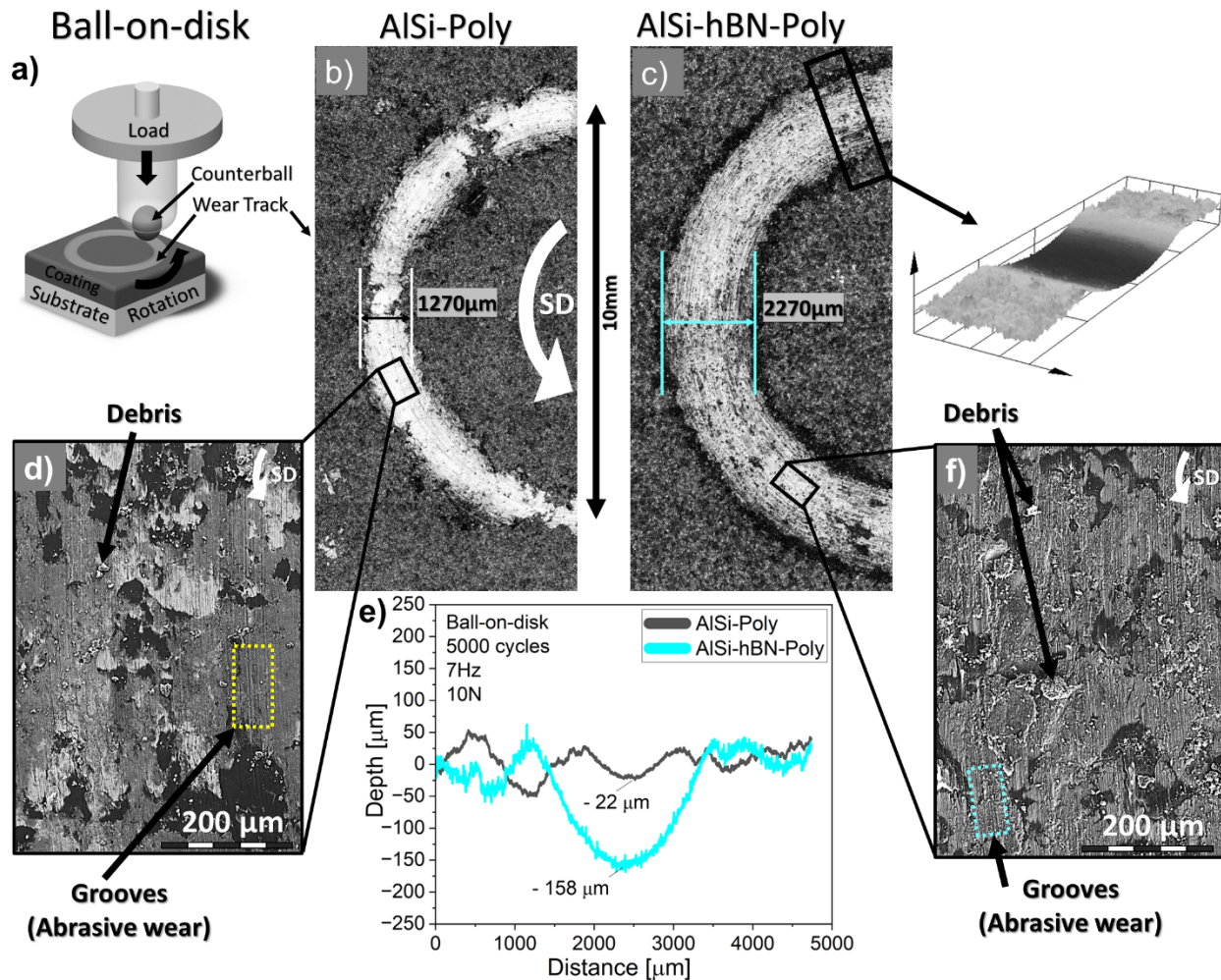


Figure 4.8. Wear track images of both abradable coatings after 5000 cycles on the ball-on-disk test; a) Schematic representation of the ball-on-disk test; b) Top view of AlSi-Poly wear track; c) Top and 3D view of AlSi-hBN-Poly wear track; d) Top surface SEM image of the AlSi-Poly wear track; e) Wear profile of both abradable coatings; f) Top surface SEM image of the AlSi-hBN-Poly wear track.

4.3.2.2. Counterball Performance Investigation

The Ti6Al4V counterballs used on both sliding tests and coatings were investigated in terms of wear and adhesive transfer. Figure 4.9 shows EDS mapping of the top surface of the counterballs used against both abradable coatings. All counterballs exhibited negligible wear, as evidenced by the absence of visible wear scars on their surfaces. However, the formation of a transfer film can be clearly seen on all tested samples. The adhesive transfer was predominantly aluminum from the abradable coating to the counterball with a slight trace of oxides on the top surface (see Figure 4.9).

The counterballs used against AlSi-hBN-Poly coating showed higher adhesive transfer than the ones used over AlSi-Poly coating. This correlates well with the larger number of debris formed on the coating containing hBN. In addition, it is important to highlight the lower percentage of polyester in AlSi-hBN-Poly coating, which could have contributed to the higher amount of metallic transfer (i.e. the aluminum-silicon matrix). This trend was observed on both sliding tests, the reciprocating ball-on-flat and the unidirectional ball-on-disk.

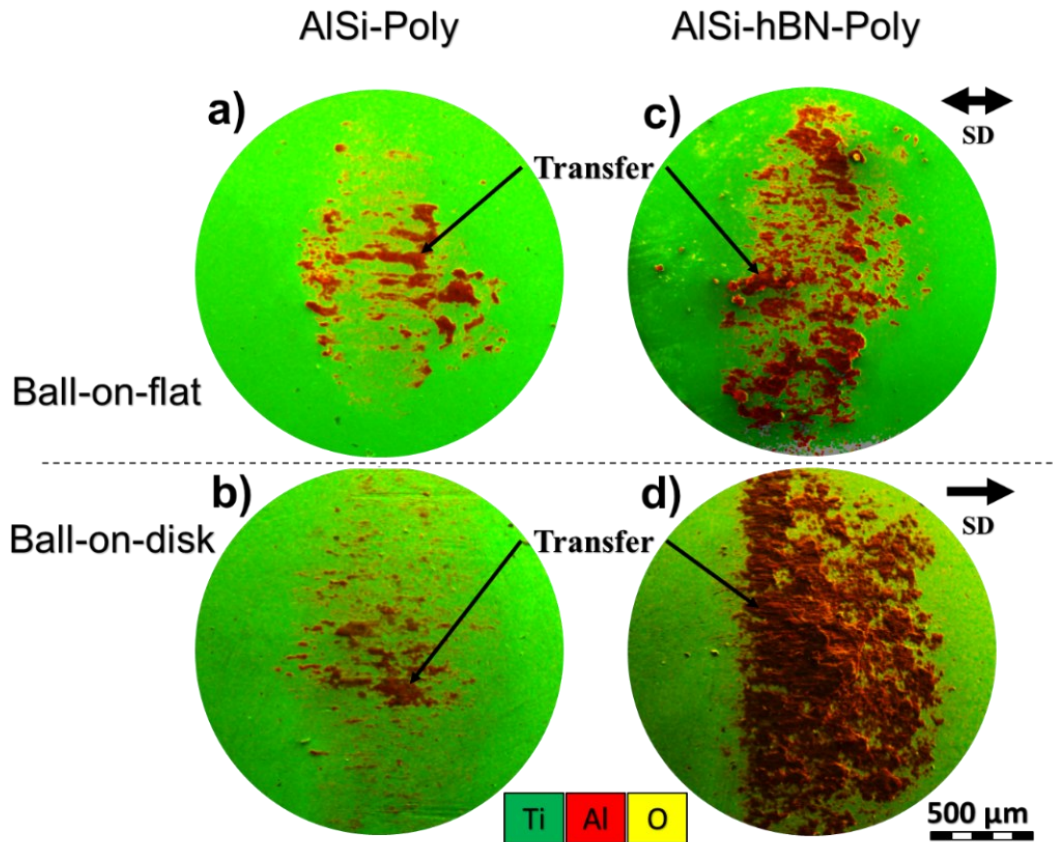


Figure 4.9. EDS analysis of the adhesive transfer film formed on Ti6Al4V counterballs after tribological tests on abradable coatings; a) Ball-on-flat and AlSi-Poly; b) Ball-on-disk and AlSi-Poly; c) Ball-on-flat and AlSi-hBN-Poly; d) Ball-on-disk and AlSi-hBN-Poly.

It should be noted that real gas turbine applications may involve different modes and wear mechanisms, which may not be fully assessed through conventional tribological methodology, especially in terms of debris effects and adhesive transfer. Therefore, the subsequent section discusses the coatings' abrasability assessment results, providing a more realistic representation of their performance in practical application scenarios.

4.3.3. Abradability Performance

4.3.3.1. Coating Abradability Investigation

Abradability testing was performed on both abradable coatings using the custom-build rig, and a consistent groove formation was observed along the direction of motion in all sample repeats. Figure 4.10 shows the photographs of post-rubbed specimens, accompanied by wear track profiles obtained through confocal microscopy for each abradable coating. Inspection of the images in Figure 4.10 reveals that the AlSi-hBN-Poly coating displays a rougher wear track characterized by deeper grooves when contrasted with the AlSi-Poly coating. Supporting this observation, Table 4.5 provides roughness measurements for both abradable coatings regarding Ra and Rz values. The results highlight higher roughness values for the AlSi-hBN-Poly coating ($Ra = 52.47 \pm 0.70 \mu\text{m}$) in comparison to the AlSi-Poly coating ($Ra = 29.14 \pm 0.58 \mu\text{m}$), corroborating the visually observed differences in wear track characteristics.

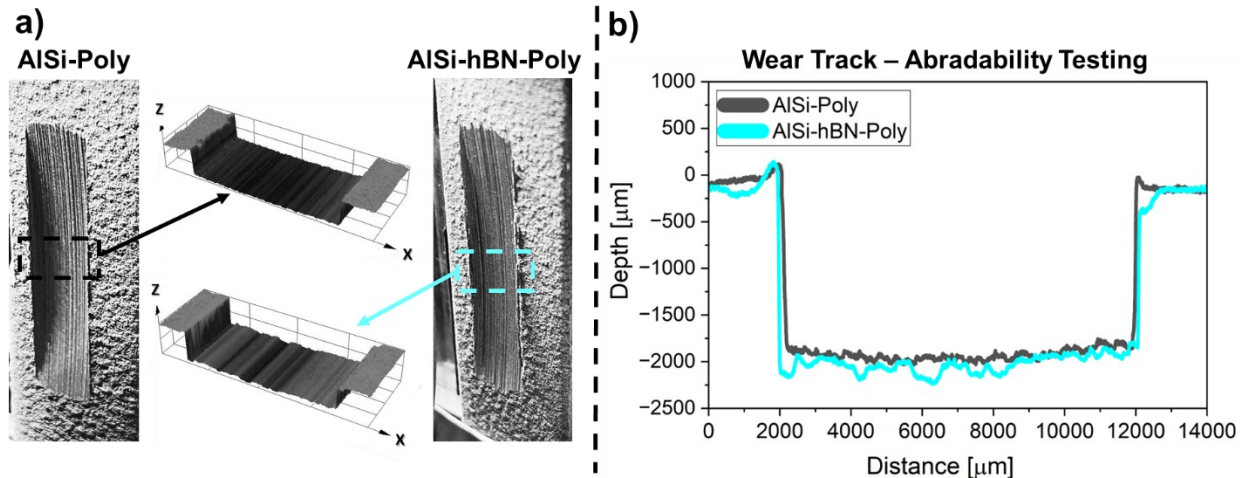


Figure 4.10. Wear track of the coatings performed on the abradable test rig; a) Photographs and 3D optical images of AlSi-Poly and AlSi-hBN-Poly coatings; b) Wear track profile of the abradable coatings extracted from 3D optical images.

Table 4.5. Roughness measurements of the wear track of the abradable coatings after rubbing test.

Wear Track Roughness – Abradability Test			
Abradable Coating	Ra (μm)	Rz (μm)	Rq (μm)
AlSi-Poly	29.14 ± 0.58	342.93 ± 17.71	38.07 ± 0.72
AlSi-hBN-Poly	52.47 ± 0.70	411.81 ± 17.58	64.26 ± 1.00

The grooving formation observed in Figure 4.10 after the abradability testing can be assimilated to the abrasive wear mechanism [175]. The rougher scar appearance on abradable coatings can be well correlated to the larger reaction forces observed on abradable tests, blade speed, and incursion rate [17]. This is consistent with previous studies correlating the reaction forces with the smoother aspects of rubbed samples [146,161].

Figure 4.11 shows the normal and tangential reaction forces as a function of rubbing depth. The reaction forces are crucial for abradable materials during engine operation, and minimal rubbing reaction forces are desired in order to protect the blade [36]. It is essential to mention that the graph presents data collected up to an incursion depth of 1.5 mm, even though the abradability tests were performed until reaching 2 mm. The reaction forces for the AlSi-Poly coating are relatively constant as a function of the incursion depth (see Figure 4.11b and Figure 4.11c), while AlSi-hBN-Poly coating showed a higher amount of fluctuations (see Figure 4.11d and Figure 4.11e). Nevertheless, the AlSi-hBN-Poly coating exhibited higher reaction forces than that of AlSi-poly coating. Compared to the AlSi-Poly coating, the AlSi-hBN-Poly coating showed a remarkable 268% increase in maximum normal reaction force, with values of 156 N and 447 N, respectively. Likewise, there was a corresponding increase of 273% in tangential reaction force for the AlSi-hBN-Poly coating. The higher reaction forces observed for AlSi-hBN-Poly coating are mainly attributed to the lower polyester fraction. Interestingly, the presence of hBN did not seem to favour reducing reaction forces. The reaction forces are also in agreement with results obtained for the post-rubbing specimens, with rougher surfaces associated with higher normal and tangential forces. This result suggests that the addition of hBN to AlSi-hBN-Poly did not provide better abradability when compared to AlSi-Poly coating.

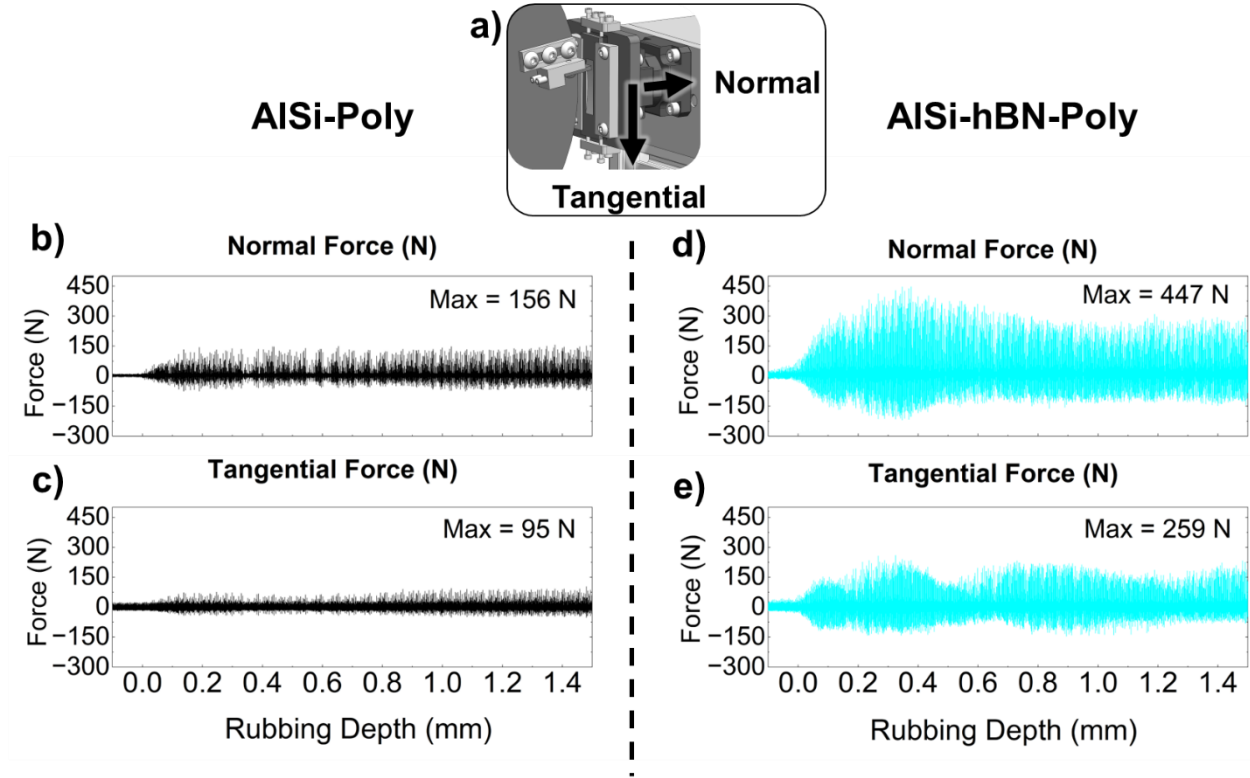


Figure 4.11. Reaction forces along the rubbing depth for the abradable coatings; a) Schematic representation of the reaction forces directions; b) Normal force for AlSi-Poly; c) Tangential force for AlSi-Poly; d) Normal force for AlSi-hBN-Poly; e) Tangential force for AlSi-hBN-Poly.

The rubbing temperature as a function of rubbing depth was also monitored during the test and shown in Figure 4.12a. For both abradables, the rubbing temperature increases as a function of rubbing depth. However, the rubbing temperature obtained for AlSi-hBN-poly increases at a higher rate when compared to the AlSi-poly coating. This trend correlates well with the reaction forces, as shown in Figure 4.11. Despite the differences in thermal conductivity and the applied rubbing forces for each coating, it is noteworthy to mention that neither of the abradable coatings achieved a temperature steady state at a 2 mm incursion depth. Similar investigations have explored the rubbing temperature in abradable coatings [87,161]. Irissou et al [31] observed higher rubbing temperatures associated with higher friction forces and harder materials. Moreover, due to the higher reaction forces, the AlSi-hBN-Poly coating exhibited elevated rubbing temperatures, reaching a peak of 53 °C at the maximum incursion depth of 2 mm. Figure 4.12b summarizes the maximum reaction forces and maximum temperature of both coatings under abradability tests.

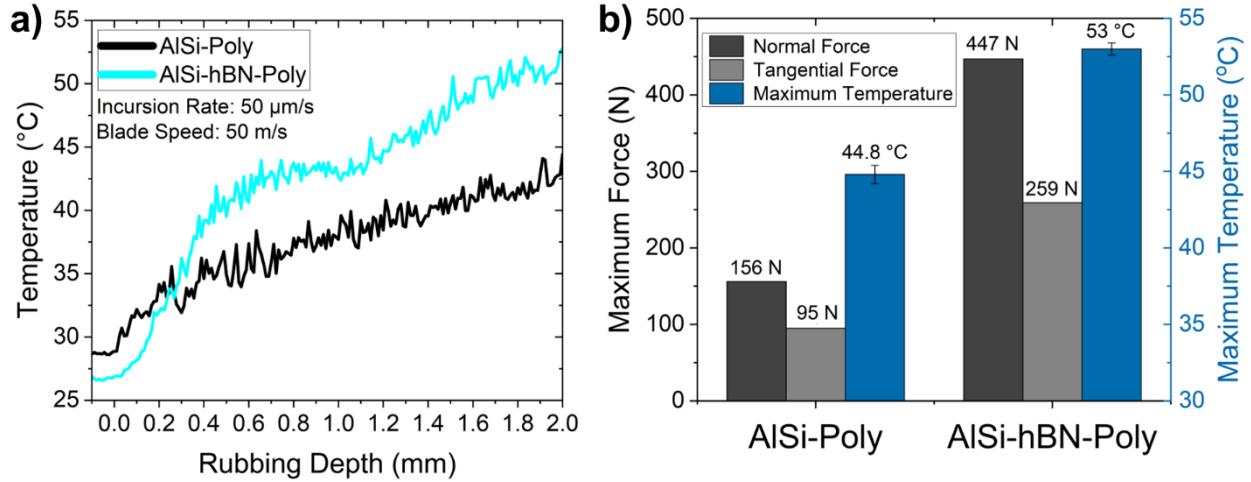


Figure 4.12 a) Evolution of the maximum surface rubbing temperature along incursion depth during abrasability tests; b) A bar graph of the maximum reaction forces and maximum surface rubbing temperature of the abrasable coatings during abrasability tests.

4.3.3.2. Blade Performance Investigation

To elucidate the blade performance against the abrasable coatings, the top surfaces of the blades were examined in terms of blade wear and adhesive transfer. Figure 4.13 shows the post-rubbed titanium blade tips of each tested material through photographs of the blades, SEM/EDS mapping analysis, and images from confocal microscopy. Similar to the results from the tribological testing, no wear was observed on the counterfaces, and adhesive transfer film formation was observed for both tested materials, predominantly aluminum from the abrasable coating to the blade. However, in the abrasability tests, the distinction in the amount of transfer observed between both coatings was relatively lower and challenging to discern (Figure 4.13). Figure 4.13b shows a spread of adhesive transfer film formation over the blade tip used against the AlSi-Poly coating. In contrast, in Figure 4.13e and Figure 4.13f, a slightly higher number of elevated prows of aluminum material can be observed on the titanium blade used against the AlSi-hBN-Poly coating. The prow formation on the blade tip can result in the ploughing phenomenon, which involves a lateral plastic flow caused by the prows penetrating the coating, leading to grooving [175]. This observation aligns with the rougher scar appearance observed on the AlSi-hBN-Poly coating.

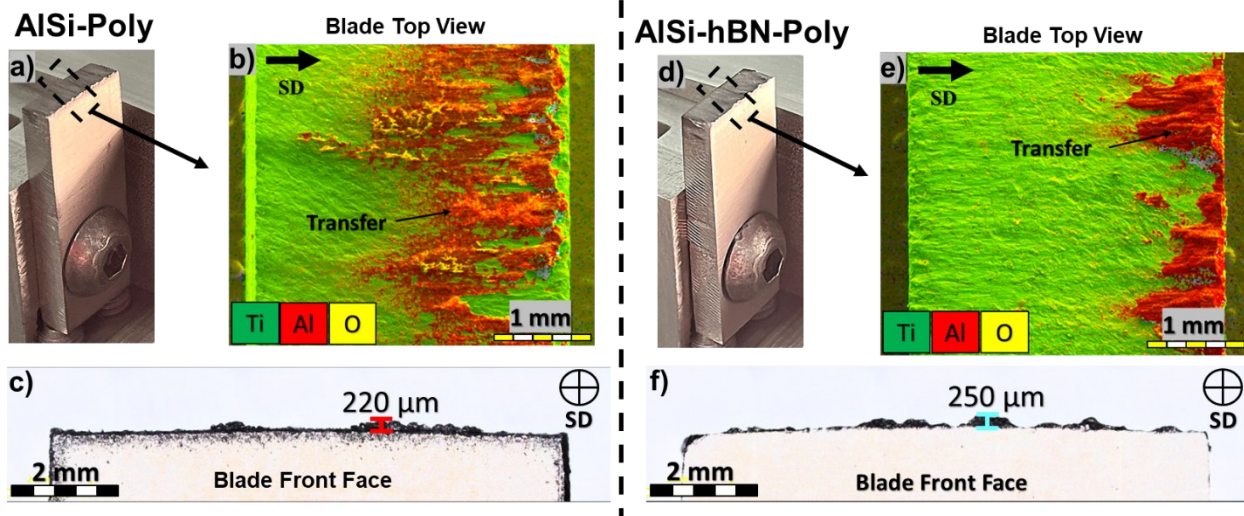


Figure 4.13. Transfer film analyses of the Ti6Al4V blade tips used on the abrasability test; a and d) Photo of the blade tip after testing AISi-Poly and AISi-hBN-Poly coating, respectively; b and e) EDS analysis of the top surface of the blade tip on AISi-Poly and AISi-hBN-Poly testing respectively; c and f) Microscopical image of the front view of the blade tip after testing AISi-Poly and AISi-hBN-Poly respectively.

4.3.4. Interfacial Phenomena

Based on the observations from the tribological analyses of the coatings, both abradable coatings tested exhibit similar frictional coefficients (Figure 4.6) when evaluated using the ball-on-flat and ball-on-disk. However, the wear depth and width observed on AISi-hBN-Poly coating were significantly higher when compared to AISi-Poly coating, leading to a wear volume difference between these coatings of approximately 6 times on ball-on-flat (3.4 mm^3 versus 0.6 mm^3) and 10 times on the ball-on-disk condition (7.2 mm^3 versus 0.7 mm^3), as can be seen in Figure 4.7 and Figure 4.8. This difference may be associated with the lower particle cohesion introduced by the presence of hBN trapped within the AISi particles (Figure 4e), which contributes to the increased sliding wear. The higher wear volume observed in the AISi-hBN-Poly coating led to a higher amount of particle liberation (i.e., debris formation) during the sliding contact. The reduced cohesion of the AISi-hBN-Poly coating is likely linked to the lubricating properties of hBN, which aids in the partition and subsequent mobility of AISi particles during sliding interactions. Furthermore, reversely, the wear disparity between coatings is attributed to the substantial third-body abrasion caused by the increased number of debris and adhesive transfer observed on AISi-hBN-Poly coating. This is also consistent with the slightly higher fluctuation of the CoF curve observed in Figure 4.6 in both tribological assessments, ball-on-flat and ball-on-disk configurations.

Ex situ analysis of the counterball (Figure 4.9) revealed no wear when sliding against both abradable coatings. However, the sliding tests indicated the formation of a transfer film

predominantly composed of aluminum from the abrasible coating to the counterball material. Notably, counterballs used against AlSi-hBN-Poly coating exhibited higher adhesive transfer film, which may be attributed to the more significant amount of debris formed during the 5000 sliding cycles. This trend was consistently observed in both sliding tests, including the reciprocating ball-on-flat and the unidirectional ball-on-disk configurations. However, this phenomenon becomes notably pronounced in the ball-on-disk configuration (Figure 4.9d), where the circular and unidirectional movement may likely enhance the entrapment of debris. This continuous presence of aluminum debris between the interacting surfaces increases the likelihood of adherence of aluminum on the titanium alloy counterball. A schematic showing a summary of the main interfacial phenomena observed on tribological and abrasability tests are presented in Figure 4.14.

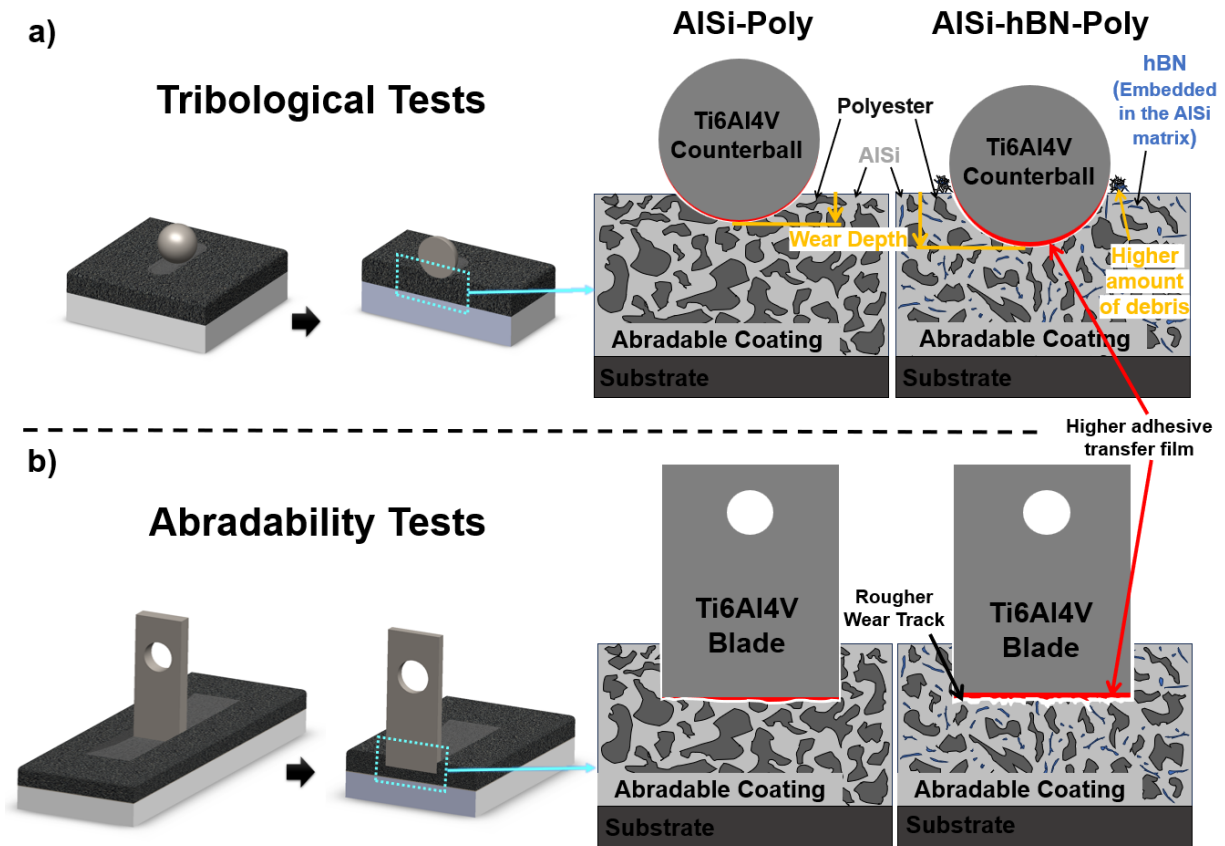


Figure 4.14. Schematic summary of the wear behaviour observed on tribological and abrasability assessment to evaluate the abrasible coatings; a) Reciprocating ball-on-flat testing of AlSi-Poly and AlSi-hBN-Poly wear tracks and counterballs; b) Abradability testing of AlSi-Poly and AlSi-hBN-Poly wear tracks and blades.

It is worth mentioning that each assessment technique (tribological and abrasability test) relied on different mechanical inputs, and consequently, different outputs were observed. While tribological analyses were based on the sliding movement of counterballs over the coating, the abrasability relied on constant shocks of the passing blade provided by the rotating parts and the linear incursion movement. This can be seen in Figure 4.2 and Figure 4.3d. Consequently, different wear mechanisms were observed between the two coatings, with and without hBN (Figure 14). With regards to the effect of hBN on the coating wear, hBN particles are brittle and, therefore,

break readily, initiating cracks and releasing debris [39]. Additionally, according to Xue et al [176] and Ghasripour et al. [39], the primary wear mechanism of aluminum-silicon hexagonal boron nitride (AlSi-hBN) is micro-rupture, driven by cracks originating from the breakage of hBN. On the other hand, polyester is tougher and has a comparatively higher damping capacity than hBN; thus, polyester particles are prone to initiate micro-rupture only under severe concentrating loadings as those caused by the shocks of the rotating blade in the case of abrasability tests [39]. These effects collectively underscore the complex role of hBN in optimizing the performance of abrasable coatings for high-performance applications.

In terms of the abrasability evaluation (i.e. rig testing), the wear tracks of both abrasable coatings reveal a smooth cutting pattern with no apparent fractured surfaces, accompanied by a distinct grooving formation indicative of the predominant abrasive wear mechanism, as illustrated in Figure 4.10. However, rig testing revealed a more desirable abrasability for AlSi-Poly than that of AlSi-hBN-Poly coating, with the first coating presenting a smoother rubbing wear track based on visual inspections and roughness measurements (Figure 4.10 and Table 4.5). These results align well with the material's characteristics, such as lower hardness and higher area fraction of filler materials obtained in the AlSi-Poly coating (Figure 4.5). Furthermore, the addition of 6%hBN to the AlSi-hBN-Poly coating did not seem to have a significant effect on the abrasability testing, with hardness identified as the predominant factor determining the difference in abrasability between the abrasable coatings tested. The inverse correlation between hardness and abrasability performance has been previously discussed in the literature [25,103]. In addition, Irissou et al. [8] emphasize the occurrence of rougher and irregular rub grooves on harder materials.

In terms of the reaction forces evaluation during the rubbing test, the rougher scar appearance on the wear track correlates well with the larger reaction forces and higher rubbing temperatures observed in the AlSi-hBN-Poly abrasable coating, compared to Table 4.5 and Figure 4.12b. A similar association between forces and the smoother aspects of rubbed samples was discussed by [146,161]. Besides the difference observed in reaction forces, as well as rubbing temperatures between the coatings, both abrasables exhibited equivalent normal/tangential forces ratio, approximately 0.6. This observation aligns well with the results from the sliding wear tests, where both abrasables showed equivalent friction coefficients (Figure 4.6). However, when comparing the friction forces obtained from the abrasable rig and the tribological testing, which are very sensitive to the blade cutting area [177], a considerable difference in forces is expected, since the area of interaction is also significantly different. This can be explained using the Adhesion Theory of Friction proposed by Bowden and Tabor [178], as illustrated in Equation 1.

$$F = A \cdot s \quad (\text{Equation 4.1})$$

where, F is the friction force (N), A is the real area of contact, and s represents the force required to shear the metallic junctions. In this study, the area of interaction in the rubbing tests is determined as 31.8 mm² from the blade's cutting area, and in tribological assessments, 0.02 mm² from the counterball stress over the coating plane calculated using Hertzian theory [179,180].

Thus, according to Equation 1, due to the considerably larger contact area in rubbing tests, a corresponding increase in friction force measurements is anticipated in tests using the abrasible test rig. This assumption is grounded in the constancy of shear stress in both conditions, given that the material tested remains consistent, and shear stress predominantly depends on the material properties. However, it should be noted that there may have been other factors contributing to the differences in friction (e.g. differences in strain rates, flow of debris particles, vertical vs. horizontal sample orientation, etc.) since this is a complex phenomenon.

Counterintuitively to the friction behaviour, there is a divergence in the wear behaviour between tribological and abrasibility assessment. The coating with a higher wear in ball-on-disk and ball-on-flat tests (AlSi-hBN-Poly) exhibited lower abrasibility (Figure 4.7, Figure 4.8, and Figure 4.12). It may be linked to the challenges tribological assessments face in ejecting debris particles, while in abrasibility testing, particle debris is easily expelled from the wear track due to factors like high blade tip speed and intermittent rubbing motions. Hu et al [181] emphasize that the wear profile of the AlSi coating is significantly influenced by the peeled-off wear debris during sliding contact. In addition, numerous studies have discussed the behaviour of released particles and their impact on coating wear [15,175], as well as the adhesive transfer to the counter element [32,163].

In terms of adhesive transfer behaviour, the abrasibility testing results are in alignment with the sliding testing, showing no apparent wear on the blade, while showcasing adhesive transfer film formation on its top surface, principally comprising aluminum migrating from the abrasible coating to the blade, as can be seen by comparing Figure 4.9 and Figure 4.13. A slight difference in transfer behaviour can be noted between the blades performed against the abrasible coatings, as shown in Figure 4.12. This distinction may be attributed to the contrasting area fraction of filler materials, and consequently, the aluminum-silicon matrix distinct content between the coatings (Figure 4.5). Furthermore, introducing hBN in the AlSi-hBN-Poly coating did not significantly impact the adhesive transfer. Titanium blades performed against the AlSi-Poly coating exhibit a widespread adhesive transfer film, while for the AlSi-hBN-Poly coating with a higher content of AlSi matrix, the blades displayed slightly more elevated prows (Figure 4.13). The presence of prows may contribute to the ploughing phenomenon, causing lateral plastic flow and grooving formation [175], which aligns with the observed rougher scar appearance on AlSi-hBN-Poly observed in Figure 4.10.

4.4. Conclusions

The primary objective of this study was to assess and compare two abradable coatings, AlSi-Poly and AlSi-hBN-Poly. This evaluation allows us to get an understanding of the effect of different fillers, particularly the hBN as a solid lubricant. Furthermore, the study systematically contrasted outcomes derived from two sliding test conditions and the abradability assessment, designed to closely mimic real aircraft turbine conditions. In pursuit of advancing the understanding and development of innovative abradable coatings, this work underscored the following key insights:

- Both thermally sprayed abradable coatings displayed uniform filler distribution and similar as-sprayed surface roughness. The AlSi-hBN-Poly showed hBN uniformly embedded within the AlSi matrix, lower total filler content and higher HR15Y hardness than the AlSi-Poly coating.
- The tribological analyses showed similar frictional coefficients for both abradable coatings and a considerably higher wear volume on the AlSi-hBN-Poly coating. The wear volume discrepancy was attributed to the increased formation of debris resulting from the presence of hBN in its microstructure, and higher adhesive transfer film observed on AlSi-hBN-Poly coating.
- Abradability assessments revealed a predominant abrasive wear mechanism for both abradable coatings, showing a smooth cutting with a distinct grooving formation. The AlSi-Poly coating exhibited slightly higher abradability characteristics than AlSi-hBN-Poly, as evidenced by reaction force measurements, visual inspections, and wear track roughness measurements. Negligible blade wear and adhesive transfer film were observed during the testing of both abradable coatings.

Effect of Mo and Cr on Abradability and Tribological Performance of AlSi-Based Abradable Coatings ⁵

Abstract

Abradable coatings have historically been utilized as sealing materials to enhance aerospace engine efficiency by minimizing the gap between stationary and rotating components in the low-pressure compressor stage. During potential blade-abradable interaction, the abradable material assumes a sacrificial role, thereby preventing the blade from structural damage. While extensive research has been devoted to developing corrosion-resistant abradable systems, ensuring their optimal abradability and tribological performance is crucial. Thus, this study aims to investigate two thermally sprayed aluminum-silicon-based (AlSi) coatings in terms of their tribological and abradability performance. While both coatings contain polyester, one incorporates a small concentration of molybdenum (Mo) and chromium (Cr). These coatings are named as AlSi-Poly and AlSi-MoCr, respectively. Both abradable coatings were investigated in terms of HR15Y hardness, microstructure, surface roughness, and wear. The wear performance of both coatings was evaluated through tribological studies, including ball-on-disk and ball-on-flat, and subsequently compared with abradability tests conducted using a custom-built abradable rig designed to closely simulate the blade-abradable interaction. The coating characterization revealed equivalent results for both abradable materials in terms of hardness, surface roughness, and filler material distribution. The tribological assessment showed an equivalent frictional coefficient and wear rates between the coatings, and no apparent damage to the Ti6Al4V counterballs was observed. However, slight differences in wear mechanisms were observed between the testing setups. The abradability evaluation of both coatings showed comparable wear mechanisms, including longitudinal grooves and smearing, with comparable wear track roughness, reaction forces and rubbing temperatures. Although no evident blade wear was observed, the blade used against AlSi-MoCr exhibited slightly more spread aluminum transfer. Overall, the consistent results across different TRL approaches, including tribological and abradability performance evaluations, support the equivalence of both coatings as effective abradable materials. The inclusion of Mo and Cr in the AlSi matrix showed minimal impact on wear performance, further validating their use in advanced applications.

Keywords: Abradable Coating; Abradability Test; Thermal Spray; Tribology; Wear.

⁵ This chapter has been published in *Wear*.

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5.1. Introduction

The continuous pursuit of higher efficiency and lower environmental impact in aircraft engines has driven significant advancements in the development of advanced materials for clearance control [4,7,8]. One of the key innovations in this area is the use of abradable seal systems, which have contributed to optimizing modern aero-engine performance [39,182]. These sacrificial materials are strategically employed within gas turbine engines to minimize the clearance between stationary and rotating parts, enhancing engine efficiency and operational safety [7,97]. In case of contact between rotating and stationary components, the abradable material serves as the sacrificial layer, thereby protecting critical structural components such as the blades [17,88]. This capability not only prevents potentially catastrophic structural failures but also enables tighter clearances that are less sensitive to common issues like a shroud, rotor misalignment or casing out-of-roundness [16,46].

The manufacturing of metallic abradable materials is typically achieved through thermal spray processes, such as atmospheric plasma spraying (APS), which is widely favoured for its versatility and effectiveness [21]. Thermal spraying involves the deposition of metallic or non-metallic materials onto a substrate by propelling them at high speeds and temperatures. The incident material plastically deforms upon impact, flattening and adhering to the substrate to form a coating layer [21,22]. APS, in particular, is highly regarded for its ability to produce coatings with the necessary properties for abradable applications, including a consistent microstructure [17,23], low hardness [25] and low residual stresses [24], which facilitates smooth interaction with blade tips without causing significant wear or damage to the counter element [17].

Achieving the desired balance of properties in abradable coatings is a complex challenge. These coatings must not only possess good abrasability performance but also exhibit high bonding strength, resistance to solid particle erosion, and corrosion resistance [13,17]. Additionally, the performance of abradable materials is further influenced by their chemical composition and microstructure, which can vary significantly depending on the specific application [25]. Typically, abradable coatings are composed of three distinct phases: a matrix that provides structural integrity, a solid lubricant or dislocator phase that promotes crack initiation and propagation, and controlled porosity that facilitates energy dissipation during interaction with blade tips [13,183]. For instance, metallic abradable coatings tailored for low-temperature environments, such as those found in the low-pressure compressor area of aero-engines, are typically composed of aluminum-silicon (AlSi) alloys. These coatings are designed to operate at temperatures below 450°C, where they exhibit optimal performance characteristics [19,20].

Numerous studies have explored the incorporation of various solid lubricants or dislocator phases into AlSi-based coatings, including hexagonal boron nitride (hBN) [4,96], molybdenum disulphide (MoS₂) and graphite [98,99]. However, enhancing the AlSi matrix can offer further improvements in wear performance, such as by incorporating additional elements like

Molybdenum (Mo) [184,185], Chromium (Cr) [184,185], Nickel (Ni) [186,187], Strontium (Sr) [188], and Zinc (Zn) [184]. Mo and Cr, in particular, stand out for their excellent corrosion-resistant properties and may significantly enhance the durability of Al-based alloys in wear environments [185,189].

Additionally, elements such as Mo and Cr have been extensively applied to steel [190,191] and nickel-based alloys [192,193] across several other applications. Chromium, in particular, plays a strong role in maintaining the alloy's passivity, while molybdenum typically stabilizes the passive film [189,193]. Hashimoto et al. [194] state that adding a small amount of molybdenum combined with the presence of chromium in the alloy can be remarkably beneficial, especially by reducing the current density. However, ensuring that abrasible alloys enhanced with corrosion-resistant elements can withstand harsh operational environments while maintaining their essential abrasible properties is vital for preserving the efficiency, reliability, and safety of aero-engine components [7,13].

Bertuol et al. [4] demonstrated that the AlSi-based coating containing only polyester exhibited superior tribological and abrasibility performance compared to the AlSi-based coating with incorporated hBN and reduced polyester content. On the other hand, Arendarchuck et al. [187] showed that an AlSi-based coating with a higher polyester content and the addition of Ni maintained equivalent tribological performance while enhancing erosion resistance relative to the AlSi-based coating without nickel. Moreover, studies by Liu et al. [25] and Boddenberg et al. [120] revealed that varying the area fractions of fillers and altering compositions may affect the wear performance. These evaluations support the importance of varying compositions and filler content to enhance the performance of AlSi-based abrasible coatings.

The wear mechanisms involved in the interaction between the composite elements of abrasible coatings and aero-engine blades are difficult to comprehensively define [7,13]. These mechanisms can include cutting, abrasion, smearing, material transfer, grooving, melting, cracking, and formation of tribofilms [7,13,26,27]. Some researchers have explored the blade-abrasible interaction using simplified setups such as scratch tests [102], pin-on-disk [137,142], and single-pass pendulum scratch tests [88]. However, these approaches often fall short of accurately representing the conditions within an aero-engine, leading to studies at lower Technology Readiness Levels (TRL). To address these limitations, advanced methods have been developed to assess the abrasible materials under closer application-relevant conditions, particularly to reach higher TRLs [2,3,28]. For instance, custom-made abrasible test rigs are employed to closely simulate the interaction between abrasible coatings and blade tips, providing more precise insights into their wear behaviour [28,30].

Thus, this study aims to evaluate the effects of Mo and Cr in minor fractions on the wear behaviour of two AlSi-Polyester-based abrasible coatings under tribological and abrasibility conditions. The primary focus is to investigate how these promising corrosion-resistant elements influence the abrasibility performance of AlSi-based coatings interacting against Ti6Al4V blades,

particularly under simulated low-pressure compressor conditions. The study also seeks to identify connections across different TRLs in terms of wear mechanisms. Specifically, the performance of these coatings has been evaluated using ball-on-flat and ball-on-disk methods (TRL-3), which are then compared with results from abrasability tests (TRL-4), providing a more comprehensive understanding of the coatings' behaviour and paving the way for more efficient and reliable aero-engine designs in the future.

5.2. Materials and Methods

5.2.1. Coating Preparation

AlSi-polyester feedstock was used as the baseline material. This powder has been widely used in the aerospace industry for clearance control applications within gas turbine engines. It contains polyester as a filler material. The second AlSi-based powder, referred to as AlSi-MoCr-polyester, incorporates additional materials such as molybdenum and chromium. These elements were selected as additives to the AlSi matrix due to their promising corrosive properties [61,195,196]. However, only a small percentage of each was added, aiming not to significantly affect the tribological and abrasability performance of the coating.

The characterization of AlSi-Poly and AlSi-MoCr feedstocks, as illustrated in Figure 5.1, was conducted using laser diffraction (LD) analysis, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS). In both feedstocks, the method employed for powder manufacturing was blending, and irregular-rounded particle morphologies were obtained. The AlSi-Poly powder exhibited a median particle size (Dv50) for volume distribution of 59 μm , whereas the AlSi-MoCr powder displayed a Dv50 of 66 μm .

It is worth noting that a detailed analysis of AlSi-Poly was previously conducted and discussed in Bertuol et al. [4]. The present study builds upon using AlSi-Poly as a reference and extends it to further explore the material's properties and performance.

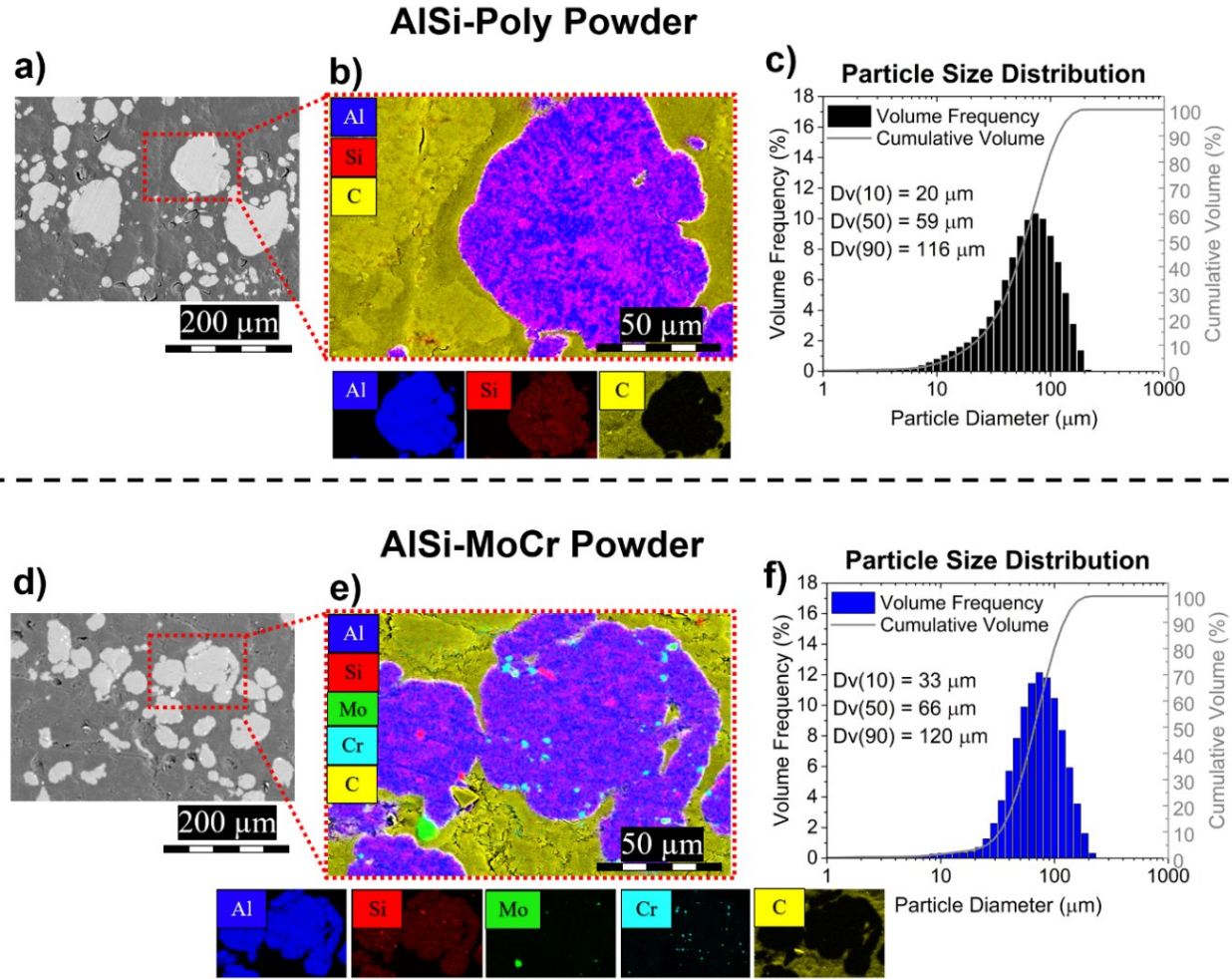


Figure 5.1. Powder particle characterization of the AlSi abrasible powders; a) low-magnification SEM image of AlSi-Poly powder; b) EDS mapping analysis of AlSi-poly powder; c) particle size distribution of the AlSi-Poly powder; d) low-magnification SEM image of AlSi-MoCr powder; e) EDS mapping analysis of AlSi-MoCr powder; f) particle size distribution of the AlSi-MoCr powder.

SAE 304 stainless steel was chosen as substrate material, which is commonly used in the static structures of aircraft engines, and plates of 25.4 x 150 x 4.75 mm were selected in order to facilitate deposition and further characterizations. To ensure a better interlocking in the coating-substrate interface, the substrate surfaces were grit blasted with #80 grit alumina particles to reach a surface roughness (R_a) of $5.6 \pm 1.0 \mu\text{m}$, followed by cleaning with compressed air to remove residues.

The deposition was carried out using a radial injection 3MB plasma gun by Atmospheric Plasma Spraying (APS). The operation parameters were recommended by the powder supplier and can be seen in Table 5.1. Both abrasible powders were deposited using the same parameters. The plasma spray gun was attached to a stationary robot assembly (HP-20, Motoman, Yaskawa Electric Corp., Waukegan, IL, USA) to ensure a uniform stand-off distance and velocity. A total of 50

passes were conducted to develop a coating thickness exceeding 4 mm. A schematic of the thermal spray deposition process and the aluminum-based coatings can be seen in Figure 5.2.

Table 5.1. The plasma spray parameters used to thermally spray AlSi-Poly and AlSi-MoCr abrasable coatings.

Process	Atmospheric Plasma Spray (APS)
Gun	3MB
Nozzle	GP
Linear Velocity	1 m/s
Stand-off Distance (SoD)	90 mm
Current	500 A
Voltage	66 V
Powder Feed Rate	30 g/min
Argon Flow Rate	100 l/min
Hydrogen Flow Rate	2.8 l/min

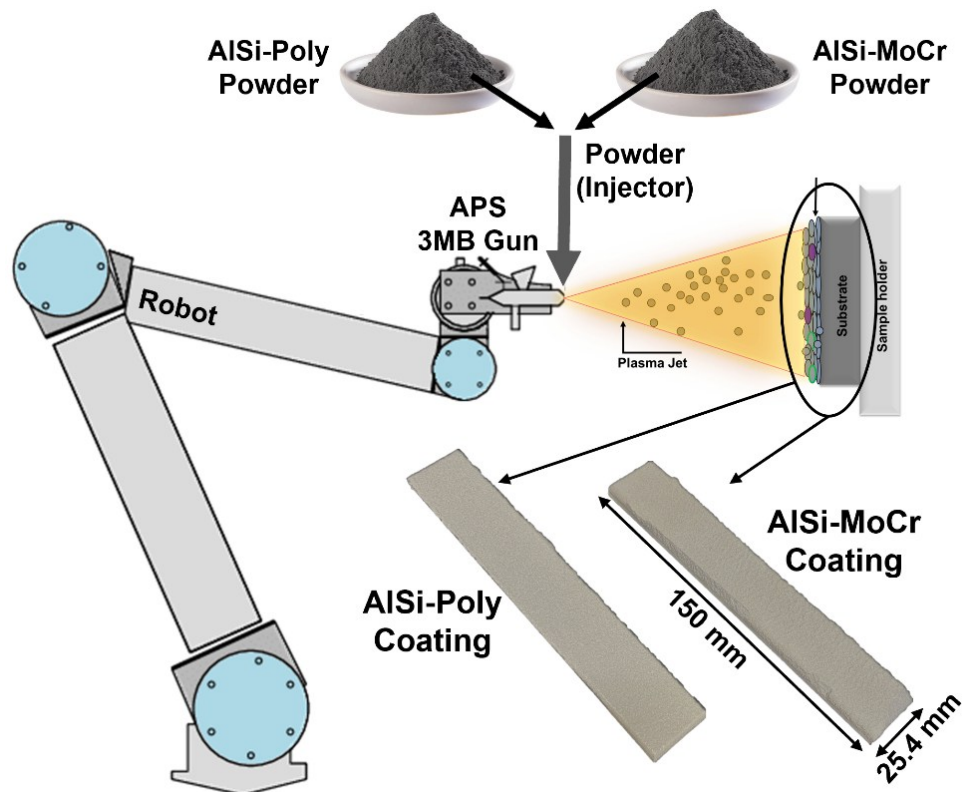


Figure 5.2. Schematic of the atmospheric plasma spray and abrasable materials.

5.2.2. Coating Characterization

The as-sprayed samples were cut to 25.4 x 25.4 mm and investigated in terms of roughness and Rockwell HR15Y hardness. The as-sprayed samples were tested from diverse positions on the sprayed plates to account for potential non-uniformity in coating deposition. First, on the cut samples, roughness analyses were performed with the aid of a confocal laser microscope (LEXT OLS 4100, Olympus Corporation), focusing particularly on parameters such as average roughness (Ra) and maximum peak-to-valley height roughness (Rz). Second, the hardness of the as-sprayed coatings was investigated by the Rockwell HR15Y hardness scale using a 12.7 mm steel ball. At least 20 indentations were made for average hardness measurements.

Additionally, the sprayed specimens were cross-sectioned using a high-speed abrasive cutting machine (Struers, Canada). These sections were then mounted by vacuum impregnation using cold epoxy resin (ANAMET, Canada) and left to cure at room temperature for a minimum of 24 hours to ensure complete hardening of the epoxy. Following mounting, the samples underwent grinding with abrasive papers ranging from 360 to 1200 grits, followed by polishing using water-based diamond suspensions of 9, 3, and 1 μm sequentially. Final polishing was employed using a 0.04 μm colloidal silica suspension. Grinding and polishing were performed using an automatic grinding-polishing machine (Struers, Canada). Subsequently, the samples were cleaned with water and dried. Metallographic analysis of the polished surfaces was conducted using the confocal laser microscope, and SEM coupled with EDS.

5.2.3. Tribological Testing

As fundamental studies, two sliding tests were employed to investigate the cyclical interaction of the counter element against the abradable materials. This approach focused on evaluating fundamental aspects of the tribological interaction, such as adhesive transfer, friction coefficient, and the wear mechanisms of both coatings.

The two configurations of sliding wear tests were performed on a tribometer (Anton Paar TRB³, TriTec SA, Switzerland) located in the Tribology Laboratory at Concordia University, Canada. First, a ball-on-flat setup with reciprocating motion, and second, a ball-on-disk setup with rotational motion. The testing methodologies are illustrated in Figure 5.3. The tests were performed on 25.4 x 25.4 mm as-sprayed samples under controlled environmental conditions, at room temperature with a relative humidity of around 20%, and each test condition was repeated three times.

The tribological tests were conducted under a constant load of 10 N and a frequency of 7 Hz (equivalent to a sliding speed of 0.22 m/s); these parameters were determined based on the

equipment's capabilities, aiming to get the highest sliding speed on both tests. On the ball-on-flat testing condition, the test was performed with a stroke length of 10 mm, while for the ball-on-disk, a wear diameter of 10 mm was chosen. Both tests were performed until they reached a total of 5000 sliding cycles.

Ti6Al4V counterballs with 6.35 mm diameter were selected to replicate engine-relevant conditions when interacting with the abradable coatings. The counterballs present a mirror-finished surface with a hardness of $HV_{200} = 331.7 \pm 4.5$. Additionally, due to the comparable coating compositions and testing conditions, a maximum Hertzian contact pressure of 96 MPa [4] can be considered for all tribological investigations of both thermally sprayed aluminum-silicon abradable coatings, as calculated considering Poisson's ratio (0.23) [112] and elastic modulus (2.08 GPa) [102]. The most relevant parameters and information used in the tribological investigation are summarized in Table 5.2.

Ex-situ analyses of the worn samples and counterballs were also conducted. The wear profiles were extracted using the confocal microscope, with at least 10 cross-sectional profiles acquired and averaged at three different positions across the wear track to get more reliable results. Furthermore, the coefficient of friction (CoF) along the sliding cycles of each repeat was directly obtained from the tribometer and subsequently averaged and plotted with error bars.

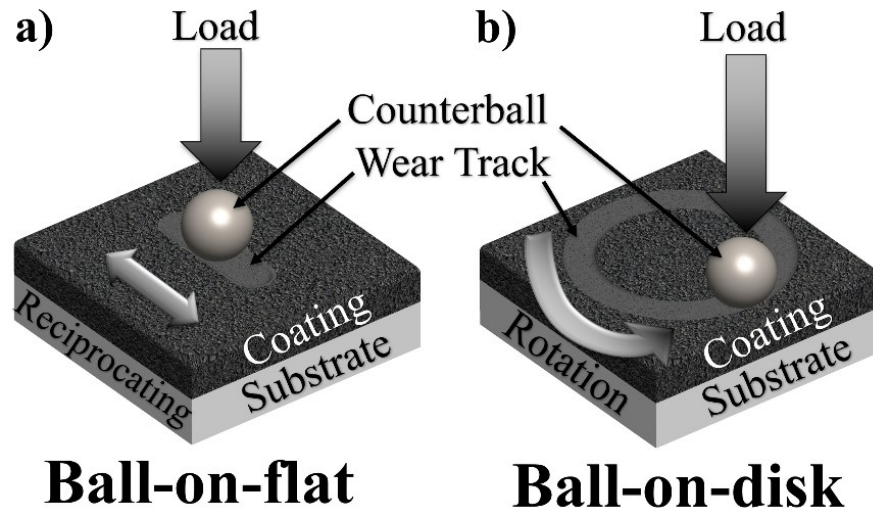


Figure 5.3. Schematic images of the tribological tests performed; a) ball-on-flat; b) ball-on-disk.

Table 5.2. Primary information and parameters used on ball-on-flat and ball-on-disk assessment.

	Ball-on-flat	Ball-on-disk
Tribometer	Anton Paar TRB ³	
Counterball Material	Ti6Al4V	
Counterball Size	Ø 6.35mm	
Counterball Hardness (HV₂₀₀)	331.7 ± 4.5	
Abradable Sample Size	25.4 x 25.4 mm	
Test conditions	Room temperature and 20% humidity	
Normal Load	10 N	
Sliding Cycles	5000 cycles	
Sliding Amplitude	10 mm	-
Wear Track Arc Length	-	31.4 mm
Frequency	7 Hz	
Sliding Speed	0.22 m/s	
Hertzian Contact Pressure	96 MPa	

Based on the area of the wear track obtained by the wear profile, the wear rate (mm³/Nm) of each abradable coating could be calculated by Equation 1.

$$Wear\ Rate = \frac{A * s}{F * L} \frac{(mm^3)}{(Nm)} \quad (Equation\ 5.1)$$

where A = cross-section area of the wear track (mm²), s = length of the wear track (mm), F = applied load (N), and L = total sliding distance (m) obtained by considering the number of sliding cycles.

5.2.4. Abradability

5.2.4.1. Abradable Test Rig

The abradable test rig, developed at Concordia University, was specifically designed to simulate the rubbing process of an aero-engine system on a smaller scale. Details about the abradable test rig can be seen elsewhere [3,4]. In short, the rig offers the flexibility to conduct

experiments under various parameters, including incursion rates, incursion depth, and rotational speed. Additionally, the rig enhances TRL scalability for industrial applications, ensuring that promising materials are identified and evaluated effectively for broader implementation.

Overall, the abradable rig consists of a blade mounted on a rotating disk paired with an abradable specimen under investigation. An incursion motion is introduced via a stepper motor, facilitating interaction between the abradable material and the dummy blade. Figure 5.4 presents photographs and a schematic of the abradable test rig; more technical details and capabilities can be found in [3,4].

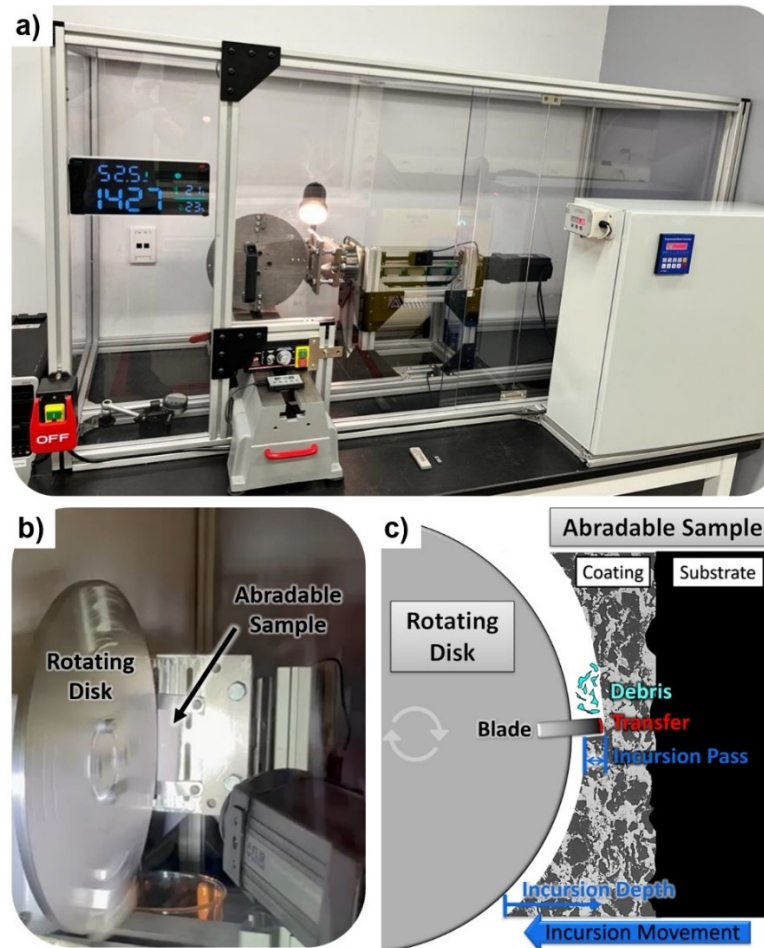


Figure 5.4. Abradable test rig; a) overview of the abradable test rig; b) close view of the abradable sample holder and rotating disk; c) Schematic representation of the abradability test.

5.2.4.2. Abradability testing

Aiming to establish connections across different TRLs and gain a more comprehensive understanding of coating performance under varying conditions, abradability tests were conducted to simulate the operational conditions of aero-engine systems. These results were then compared

with those obtained from the earlier tribological tests, providing critical insights into the coatings' behaviour across fundamental and applied contexts.

The abratable performance of the coatings was evaluated under the test conditions specified in Table 5.3. Blade tips with a simplified geometry were manufactured to replicate the rotor blade-casing interaction typical in aircraft applications. In this study, grade 5 titanium alloy (Ti6Al4V annealed) was chosen as the blade material, and the blade geometry was set at 10 x 25 x 3.18 mm, yielding a thickness-to-chord ratio of 0.32. The tests were conducted at a constant incursion rate of 50 $\mu\text{m/s}$ until reaching a maximum depth of 2 mm. The rotatory disc carrying the blades rotated at 3600 rpm, resulting in a maximum linear speed of 50 m/s at the blade tip. This setup translated to an incursion per revolution of 0.83 $\mu\text{m/pass}$. The tests were performed on samples with as-sprayed surfaces and in a controlled environment at room temperature with a relative humidity maintained around 20%.

The abrasability assessment involves both indirect and direct outputs provided by the abratable test rig. Indirect outputs are associated with ex-situ analyses of the rubbed surfaces and blades, such as utilizing SEM, EDS, and a confocal microscope. This analysis focuses on observing the wear mechanisms of the rubbed samples, material transfer between the abratable coatings and blades, as well as blade wear. Direct outputs include real-time measurements such as reaction forces (normal and tangential) exerted on the abratable material by the blade-abratable interaction, as well as localized temperatures generated due to frictional heating, named in this study as rubbing temperature.

Table 5.3. Abradability testing parameters used for both abratable coatings.

Abradability Testing	
Blade Geometry	Flat (Simplified geometry)
Blade Material	Ti6Al4V (Grade 5)
Blade Size	10 x 25 x 3.18 mm
Blade Thickness-to-chord Ratio	0.32
Blade Speed	50 m/s
Disk Rotation	3600 rpm
Incursion Rate	50 $\mu\text{m/s}$
Incursion per Pass	0.83 $\mu\text{m/pass}$
Incursion Depth	2 mm
Abradable Sample Geometry	25 x 76 mm (Flat sample)
Testing Temperature	Room Temperature
Relative Humidity	~ 20%

5.2.1. Statistical Analysis

Statistical analysis was conducted to quantitatively evaluate the variability and significance of the tribological and abrasability results. In the tribological tests, the primary focus was on the wear rate and its associated dispersion among the two coating systems, while in the abrasability tests, the normal and tangential reaction forces were analyzed to assess material response consistency under controlled incursion conditions. Repeats were performed to ensure statistical reliability and allow for meaningful comparison.

Data were processed in Microsoft Excel, where descriptive statistics (mean and standard deviation) were first obtained for all measured parameters. Subsequently, independent t-tests assuming equal variances were performed with a significance level of $\alpha = 0.05$ to determine whether differences among coatings were statistically significant relative to the baseline AlSi-Poly. In addition, Cohen's d was calculated to estimate the effect size, providing a measure of the magnitude and practical relevance of observed differences. This statistical framework supported the interpretation of coating performance trends with quantitative confidence, reinforcing the robustness of the experimental results across the different TRL stages investigated in this study.

5.3. Results

5.3.1. Coating Microstructure Analyses

The cross-sections of AlSi-Poly and AlSi-MoCr coatings were examined and are shown in Figure 5.5. Both thermally sprayed abrasable coatings exhibited coating thicknesses exceeding 4 mm, with a uniform distribution of polyester within the aluminum-silicon matrix throughout the entire coating thickness, as illustrated in Figure 5.5a and Figure 5.5f. Moreover, both coatings predominantly exhibit an AlSi metallic matrix visible as light gray regions, interspersed with pores and polyester that appear as dark gray regions. The distinction between pores and polymer is challenging to identify due to their similar contrast to the secondary fillers in SEM images [25,187]. At higher magnifications, the AlSi-MoCr coating reveals the presence of Mo and Cr within the AlSi matrix, identifiable by the white areas highlighted in Figure 5.5e.

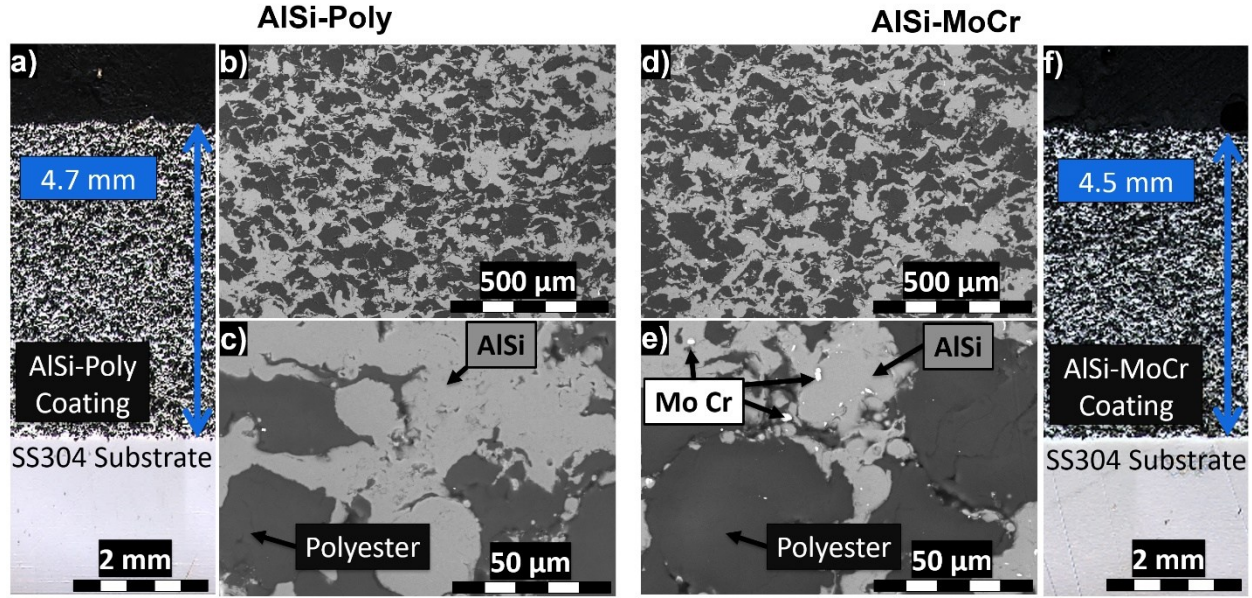


Figure 5.5. Microstructural characterization of the abradable coatings at lower and higher magnifications; a) Cross-section image of the AlSi-Poly coating obtained by confocal microscope; b) Cross-section SEM image of AlSi-Poly coating at lower magnification; c) Cross-section SEM image of AlSi-Poly coating at higher magnification; d) Cross-section SEM image of AlSi-MoCr coating at lower magnification; e) Cross-section SEM image of AlSi-MoCr coating at higher magnification; f) Cross-section image of the AlSi-MoCr coating obtained by confocal microscope.

Although both powders initially contain a similar polyester content, their compositions can change during the thermal spraying process. To assess these changes, the area fraction of the filler was estimated using SEM images and processed with ImageJ software. Figure 5.6a presents a detailed analysis of the filler material area fraction and HR15Y hardness measurements for each coating. The average area fraction for AlSi-Poly is slightly higher compared to AlSi-MoCr coatings. However, despite this apparent difference, the variation is not statistically significant when considering the error bars. Similarly, both coatings exhibit equivalent HR15Y hardness values, falling within comparable error ranges. AlSi-Poly displays $60 \pm 4.2\%$ filler material with a hardness of approximately 70 ± 2.7 HR15Y, while AlSi-MoCr shows $55 \pm 2.6\%$ filler material and a macrohardness of 68 ± 3.5 HR15Y.

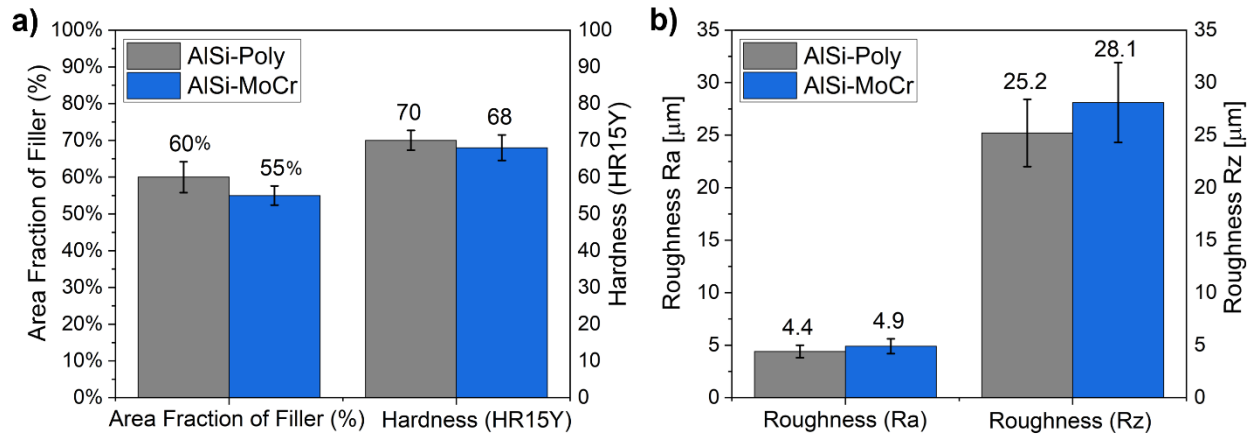


Figure 5.6. a) Area fraction of filler materials and HR15Y hardness of the abrasible coatings; b) As-sprayed coating surface roughness in terms of Ra and Rz.

Surface roughness measurements for each coating in the as-sprayed condition are presented in Figure 5.6b. Both the AlSi-Poly and AlSi-MoCr coatings displayed comparable Ra and Rz values when considering the error bars, reflecting the identical plasma-spray conditions applied during their deposition. The consistent roughness values indicate that the addition of Mo and Cr in the AlSi-MoCr coating did not substantially alter the surface roughness characteristics compared to the AlSi-Poly coating, which contains only polyester as the filler material.

5.3.2. Tribological Analysis

5.3.2.1. Coating Performance Assessment

The tribological performance of the abrasible coatings was evaluated using two distinct testing methodologies: ball-on-flat and ball-on-disk, respectively. These methods simulate different contact conditions, allowing for a comprehensive assessment of the coatings' frictional and wear characteristics. As shown in Figure 5.7a and Figure 5.7b the coefficient of friction (CoF) for both coatings was consistently measured at approximately 0.3 throughout the 5000 sliding cycles in both testing configurations. This consistency in CoF values indicates that the coatings maintain stable frictional behaviour under prolonged sliding conditions and support their equivalence and surface integrity all over the tested cycles.

The wear profile analysis further complements these findings (see Figure 5.7c and Figure 5.7d). Under the ball-on-flat configuration, the coatings exhibited a maximum wear depth of approximately 60 μm , while the ball-on-disk setup resulted in a maximum wear depth of 28 μm . The notable difference in wear depth between the two configurations is primarily due to the variation in debris release efficiency under each sliding condition. This variation arises from the different sliding movements, reciprocating versus unidirectional.

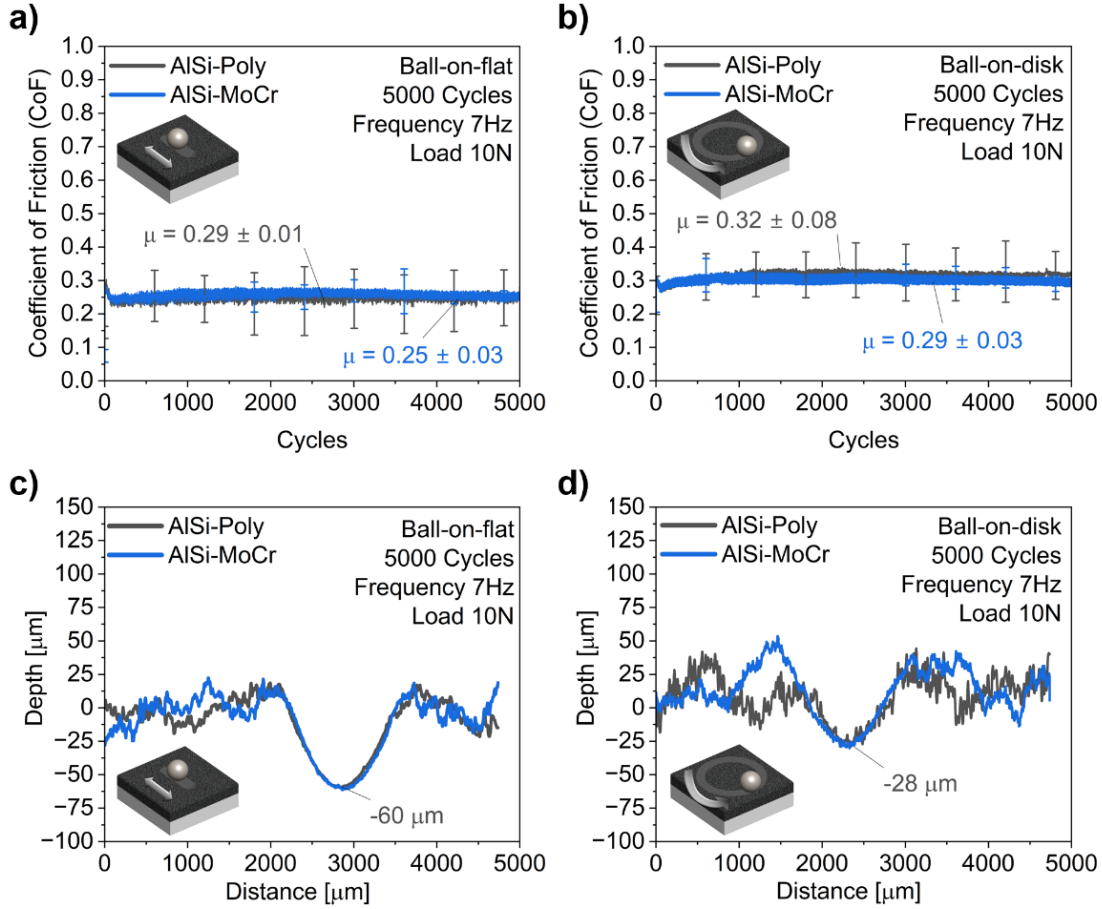


Figure 5.7. Tribological assessment of the AlSi-based coatings; a) coefficient of friction on ball-on-flat test; b) coefficient of friction on ball-on-disk test; c) wear profile on ball-on-flat test; d) wear profile on ball-on-disk test.

Figure 5.8a and Figure 5.8b provides confocal microscopy images of the wear tracks from the ball-on-flat tests. As depicted in the figure, the wear track widths for the AlSi-Poly and AlSi-MoCr coatings were measured at around $1550 \mu\text{m}$ and $1335 \mu\text{m}$, respectively, showing only a slight variation. This minor variation suggests that the inclusion of Mo and Cr does not significantly affect the wear resistance of the coatings. Consistent results were observed in the ball-on-disk tests, as shown in Figure 5.8c and Figure 5.8d. The wear track widths were measured at $1270 \mu\text{m}$ for the AlSi-Poly coating and $1490 \mu\text{m}$ for the AlSi-MoCr coating. These measurements further confirm the minimal impact of Mo and Cr on the coatings' wear performance. AlSi-Poly wear track images (Figure 5.8a and Figure 5.8c) have been adapted from our previous work.

Wear rates for the AlSi-Poly and AlSi-MoCr coatings tested at both conditions are shown in Figure 5.8e. In the ball-on-disk setup, AlSi-Poly demonstrated a marginally lower wear rate average of $42 \pm 7.45 \times 10^{-5} \text{ mm}^3/\text{Nm}$, compared to AlSi-MoCr, which exhibited a wear rate of $58.5 \pm 17.44 \times 10^{-5} \text{ mm}^3/\text{Nm}$. Despite this numerical difference, the variation between them is not statistically significant ($p = 0.345$) when accounting for the variability observed across repetitions. See Table 5.4. Similarly, the ball-on-flat tests showed comparable wear rates for both coatings.

AlSi-Poly exhibited a wear rate of $57.4 \pm 13.84 \times 10^{-5} \text{ mm}^3/\text{Nm}$, while AlSi-MoCr showed a wear rate of $59.3 \pm 14.87 \times 10^{-5} \text{ mm}^3/\text{Nm}$. Here again, the coatings are statistically indistinguishable ($p = 0.909$), confirming their comparable performance. Overall, these results indicate that Mo and Cr in the AlSi-based coating minimally impact the wear performance under both conditions.

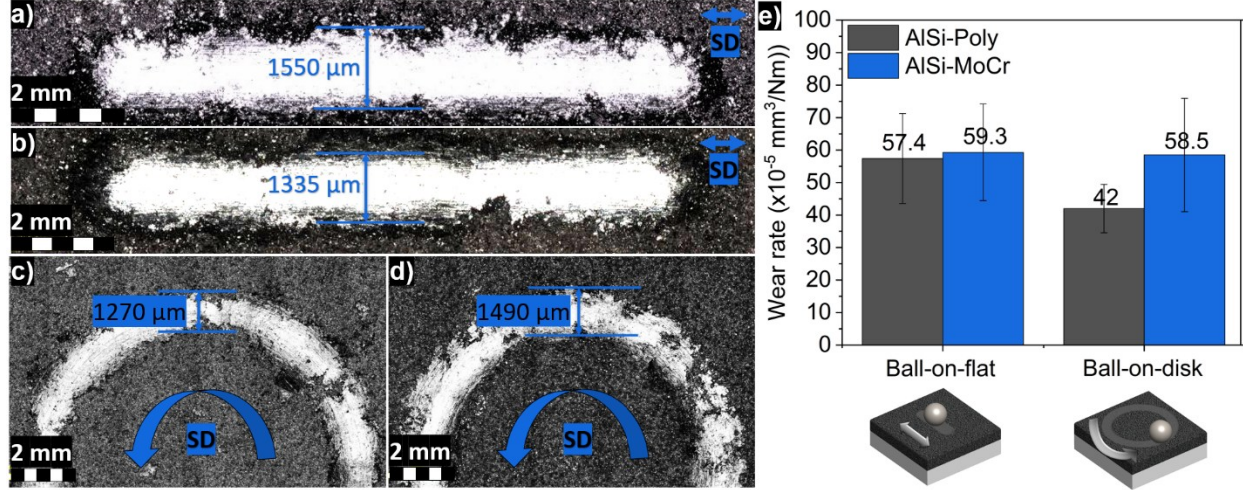


Figure 5.8. Wear track images of AlSi-Poly and AlSi-MoCr after 5000 cycles on (a and b) ball-on-flat test and (c and d) ball-on-disk test; e) Wear rate of both abradable coatings.

Table 5.4. Statistical comparison between AlSi-MoCr and the baseline (AlSi-Poly) for tribological wear rate performance, showing p -values, effect sizes (Cohen's d), and significance interpretation.

Material Comparison	Test Type	p-value	Cohen's d	Statistical Conclusion Regarding Wear Rate Values
AlSi-MoCr vs AlSi-Poly	Ball-on-flat	0.909	0.13	No statistically significant difference ($p > 0.05$); negligible effect size, confirming equivalent wear behavior
AlSi-MoCr vs AlSi-Poly	Ball-on-disk	0.345	1.22	No statistically significant difference ($p > 0.05$); moderate-to-large effect size suggesting a possible practical difference, though within experimental variability

The wear tracks of the abradable coatings were also investigated in terms of wear mechanism by SEM, EDS mapping and point analysis, as can be seen in Figure 5.9 and Figure 5.10. In the ball-on-flat condition (Figure 5.9), the top view SEM images indicated an accumulation of loose debris all over the wear track on both abradable coatings. The presence of such debris highlights the dynamic nature of the sliding wear process, wherein aluminum and polyester particles are detached from the coating surface and dispersed around the wear track (Figure 5.9a and Figure 5.9d). Moreover, the top view images clearly showed the formation of

cracks perpendicular to the sliding movement; these cracks are indicative of stresses during the reciprocating motion [138,197].

Despite the similarities in wear mechanisms observed in both the AlSi-Poly and AlSi-MoCr coatings, the AlSi-MoCr coating demonstrated a more pronounced formation of smeared material, as illustrated in Figure 5.9d. Additionally, neither coating exhibited strong signs of ploughing or densification, supporting that both coatings presented equivalent wear mechanisms without significant differences in subsurface deformation.

The EDS mapping and point analysis, as shown in Figure 5.9c and Figure 5.9f, consistently revealed a uniform layer of oxygen across the wear tracks of both coatings. This consistent presence of oxygen indicates a strong oxidation process on the surfaces exposed to sliding wear. The oxidation may be attributed to the combination of atmospheric oxygen interacting with the high frictional heat generated during the tests, which enhances the reactivity of the surface and promotes the formation of an oxide layer on the aluminum-based coatings [198,199].

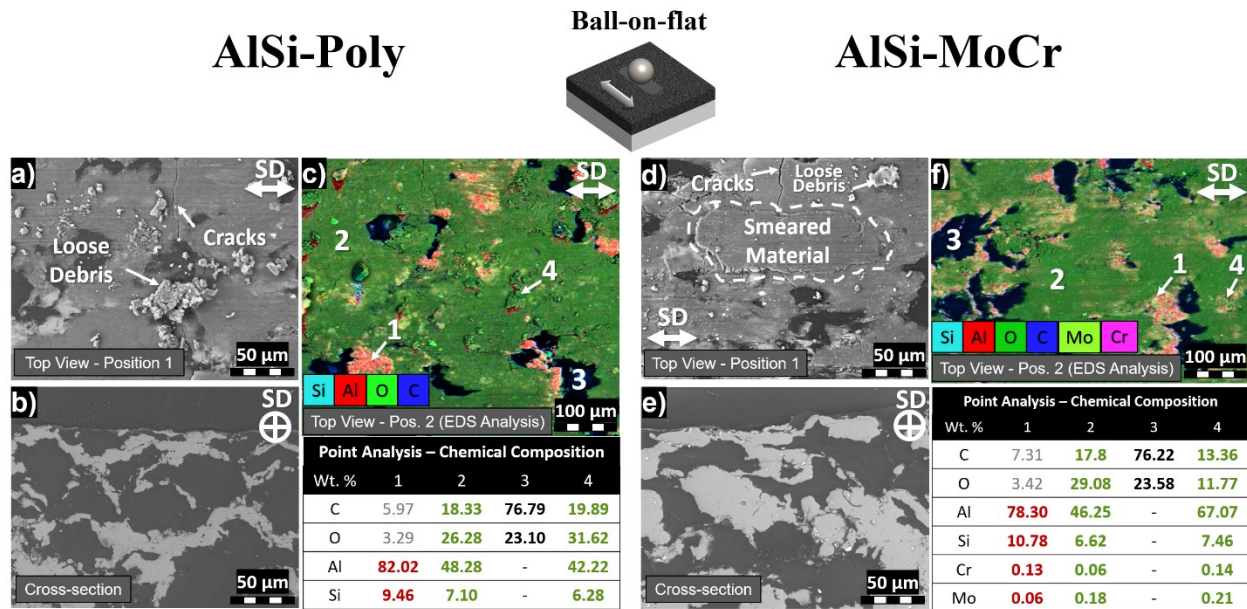


Figure 5.9. Wear track characterization of the abrasible coatings after ball-on-flat tests; a-c) AlSi-Poly; d-f) AlSi-MoCr; a and d) top view of the wear track; b and e) cross-section of the wear track; c and f) EDS mapping and point analysis of the wear track.

Similarly, AlSi-Poly and AlSi-MoCr under ball-on-disk tests were also investigated in terms of wear mechanism, as can be seen in Figure 5.10. The main findings included more distinct abrasive marks (Figure 5.10a and Figure 5.10d) and tribofilm formation (Figure 5.10b and Figure 5.10e) on both coatings, with no significant differences observed between them.

While the wear mechanisms were largely similar between the AlSi-Poly and AlSi-MoCr coatings, the ball-on-disk tests revealed a higher incidence of superficial microcrack formation, particularly in the AlSi-MoCr coating (Figure 5.10d). Furthermore, consistent with the findings

from the ball-on-flat tests, neither coating exhibited signs of ploughing or densification in the ball-on-disk configuration, and the EDS mapping and point analysis (Figure 5.10c and f) also revealed a large layer of oxygen across the wear tracks after ball-on-disk tests.

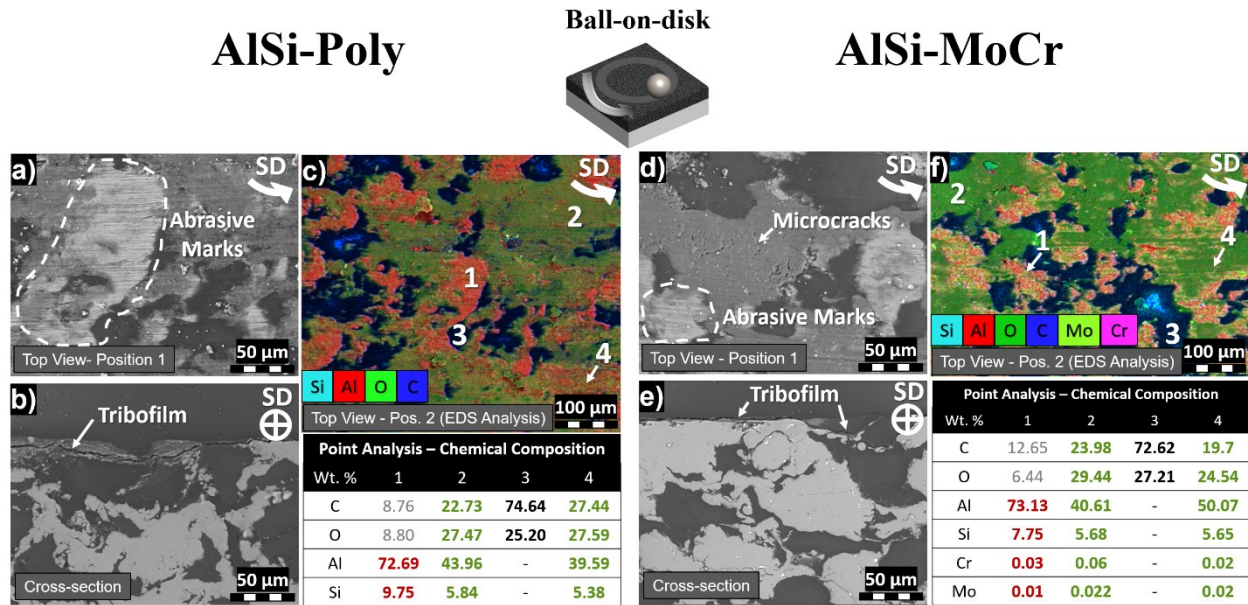


Figure 5.10. Wear track characterization of the abrasible coatings after ball-on-disk tests; a-c) AlSi-Poly; d-f) AlSi-MoCr; a and d) top view of the wear track; b and e) cross-section of the wear track; c and f) EDS mapping and point analysis of the wear track.

5.3.2.2. Counterball Performance Assessment

The Ti6Al4V counterballs used against both AlSi-based coatings were thoroughly analyzed to assess wear and adhesive transfer characteristics. Figure 5.11 presents the SEM and EDS mapping of the top surface of the counterballs after testing in the ball-on-flat and ball-on-disk configurations. Images of AlSi-Poly counterballs were adapted from the literature [4].

The analysis revealed no significant wear on the counterballs, as indicated by the absence of visible wear scars on their surfaces. This lack of wear was consistent across all counterballs, regardless of the tribological configuration or the type of abrasible coating tested. Consistently, there were no traces of Ti in the EDS mapping of the wear tracks presented previously in Figure 5.9 and Figure 5.10. Overall, the presence of Mo and Cr in the AlSi-MoCr coating did not lead to any noticeable changes in counterball wear, nor did the testing methodology, ball-on-flat or ball-on-disk.

Regarding adhesive transfer film, Figure 5.11 clearly shows the deposition of an aluminum layer on the surface of the counterballs for all tested samples. The adhesive transfer primarily consisted of aluminum from the abrasible coatings, with a minor presence of oxides,

indicating a strong interaction between the coating material and the counterball. The levels of adhesive transfer were equivalent for counterballs tested against both AlSi-Poly and AlSi-MoCr coatings. This equivalence in adhesive transfer and counterball wear across both abradable coatings highlights that the small chemical composition difference does not significantly influence the mechanical or adhesive behaviour during sliding interactions. In other words, the transfer characteristics are primarily governed by the base AlSi composition, and the promising corrosion-resistant elements do not induce any detectable change in the overall tribological performance, even considering previously discussed results.

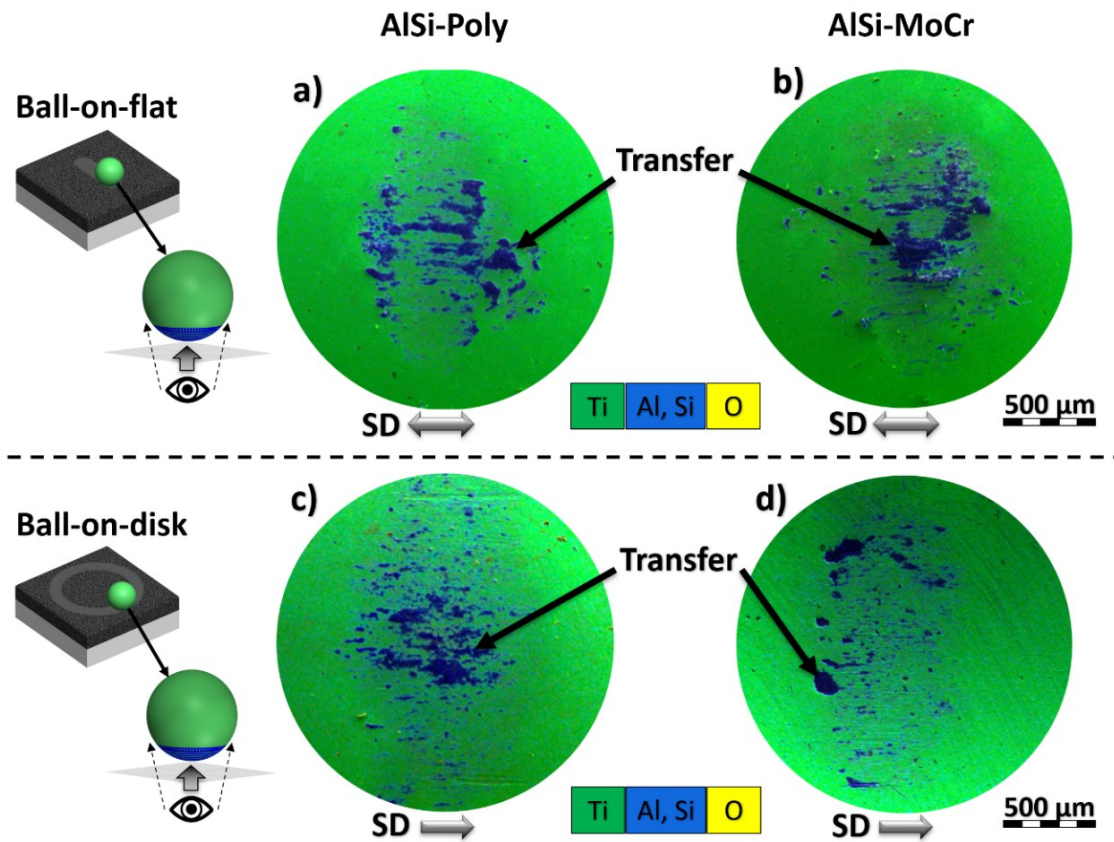


Figure 5.11. Counterball characterization after tribological tests by EDS mapping; a) ball-on-flat test against AlSi-Poly; b) ball-on-flat test against AlSi-MoCr; c) ball-on-disk test against AlSi-Poly; d) ball-on-disk test against AlSi-MoCr.

It is important to note that real gas turbine applications may encompass various operational modes and wear mechanisms that conventional tribological methodologies may not fully capture, particularly concerning debris effects and adhesive transfer. Therefore, the subsequent section discusses the coatings' abrasability assessment results, aiming to provide a more comprehensive evaluation of their performance in closer practical application scenarios at higher TRL.

5.3.3. Abradability Performance

5.3.3.1. Coating Performance Assessment

AlSi-Poly and AlSi-MoCr coatings were subjected to abradability testing, revealing a consistent pattern of groove formation along the direction of motion in both coatings across all repetitions. Figure 5.12 demonstrates that both the AlSi-based coatings exhibit visually similar results in terms of groove formation, incursion depth, and surface roughness. Furthermore, the edges of the wear tracks exhibit elevated prow, which could be attributed to plastic deformation caused by the blades' incursion into the coatings. This similarity on wear mechanism can be attributed to both abradable coatings' nearly identical chemical composition. The minor addition of Mo and Cr in the AlSi-MoCr coating did not significantly impact the visual appearance of the wear track, particularly regarding groove formation. The groove patterns observed after abradability testing are well-documented in the literature and are typically associated with abrasive wear mechanisms [27,175].

This equivalence in wear characteristics is further supported by the roughness values highlighted in the wear track profile in Figure 5.12c, where the AlSi-Poly coating exhibited an average roughness (R_a) of $29.1 \pm 0.6 \mu\text{m}$, compared to $28.3 \pm 1.0 \mu\text{m}$ for the AlSi-MoCr coating. Considering the standard error, both coatings presented roughness values within a similar range of approximately $29 \mu\text{m}$. However, the wear track roughness values were significantly higher compared to the initial as-sprayed roughness measurements taken before the rubbing test, as shown in Figure 5.6b. This considerable increase in roughness is attributed to the longitudinal grooves created by the blade-abradable interactions, which intensifies the surface texture of the coatings after abradability tests.

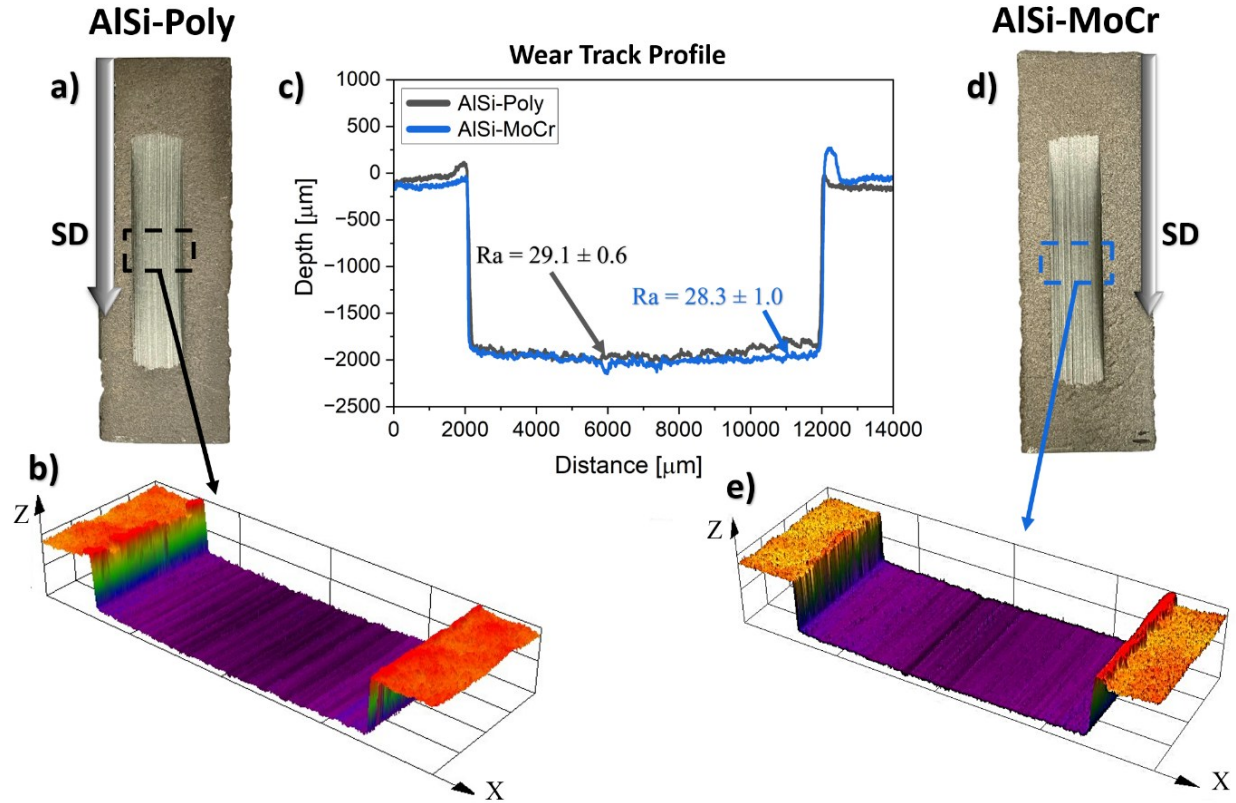


Figure 5.12. Wear track of the AlSi-based coatings after abrasability test; a-d) photographs of AlSi-Poly and AlSi-MoCr, respectively; b and e) 3D optical images of the wear track; c) wear track profile of the abrasable coatings including the R_a of the wear track.

As shown in Figure 5.13, both AlSi-based coatings (AlSi-Poly and AlSi-MoCr) exhibited smeared layers of the aluminum matrix with predominant abrasive wear marks characterized by the formation of numerous longitudinal grooves aligned with the direction of motion. According to the literature [103,146], the smeared regions observed in both coatings further indicate the occurrence of localized plastic deformation, which is a typical response of the aluminum matrix under such testing conditions

A detailed comparison of the wear tracks revealed that both coatings demonstrated equivalent smooth rubbing surfaces with no cracks and comparable smeared regions. Moreover, the absence of Ti traces in the EDS analysis (Figure 5.13b and Figure 5.13d) on the wear tracks provided additional insights, confirming no adhesive transfer of material from the TiAl4V blade to the AlSi-based coatings. The results suggest that Mo and Cr in the AlSi-MoCr coating introduces no notable deviations in the wear mechanisms or the surface characteristics when compared to the AlSi-Poly coating. Both coatings exhibited similar responses to the abrasability tests, with comparable wear patterns and no evidence of blade material transfer to the coating.

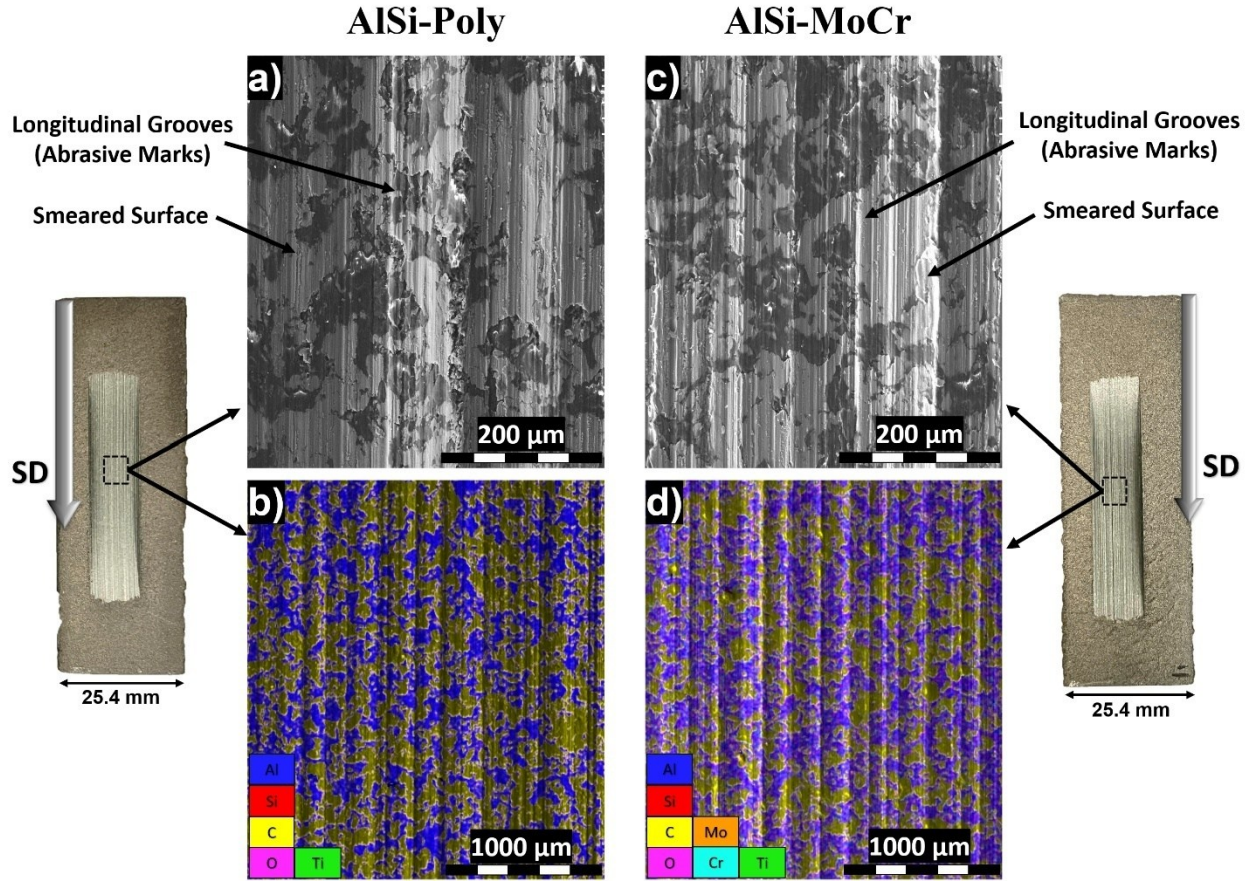


Figure 5.13. SEM and EDS mapping of the wear track of AlSi-based coatings after abrasability tests; a and b) AlSi-Poly; c and d) AlSi-MoCr; a and c) top view of the wear track; b and d) EDS mapping of the top surface.

5.3.3.2. Blade Performance Assessment

To assess the blade performance against the abradable coatings, the top and front surfaces of the Ti6Al4V blades were characterized using photographs, EDS mapping analysis, and confocal microscopy. Figure 5.14 presents a detailed characterization of the blades used in the abrasability tests, focusing on adhesive transfer behaviour and blade wear. The AlSi-Poly images of the blades (Figure 5.14) have been replotted for comparison with our previous work [3,4].

Regarding adhesive transfer, Figure 5.14c and Figure 5.14g illustrate the deposition of aluminum and carbon on the top surface of the blades for both tested samples. The adhesive transfer film primarily consists of aluminum, which was expected considering the high aluminum concentration in the abradable coatings. Interestingly, traces of carbon were also detected on the top surfaces of both blades, indicating a transfer from the dislocator phase (polyester) to the blade. The distinction in the amount of adhesive transfer observed between both coatings was relatively lower, with a slightly higher spread of transfer film over the blade used against AlSi-Poly, as can be seen comparing Figure 5.14c and Figure 5.14g. Additionally, for both coatings, elevated prows

of aluminum material were observed on the titanium blades, primarily localized at the region where the initial blade-abradable interaction occurred. AlSi-Poly showed slightly greater prows, as can be seen in Figure 5.14d and Figure 5.14h.

In terms of blade wear, the top surface characterization showed no significant wear on the blades used against either AlSi-based coatings, as indicated by the absence of visible wear marks. This observation is consistent with the tribological results, which similarly showed no wear on the counterball materials, regardless of the presence of Mo and Cr in the coating.

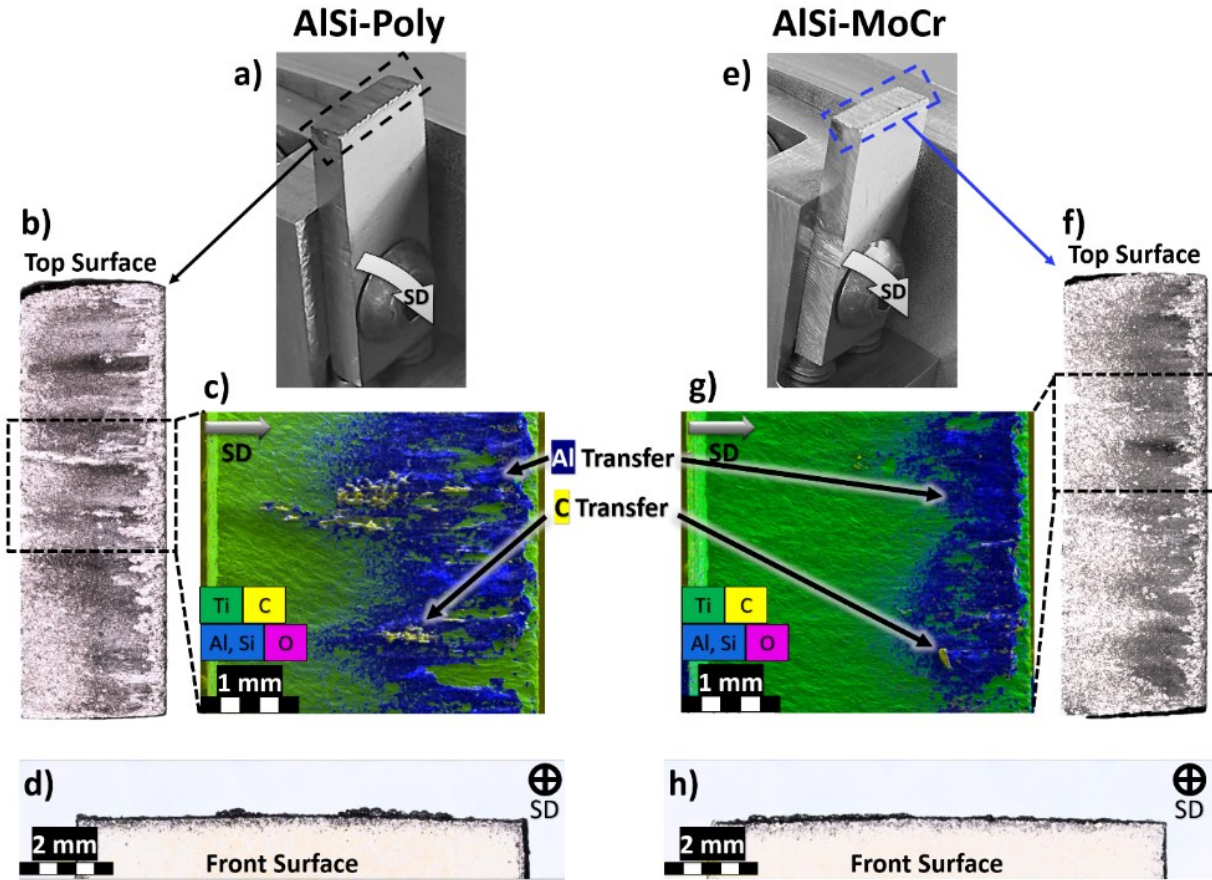


Figure 5.14. Ti6Al4V blade characterization after abrasability test; a and e) photos of the blades used on AlSi-Poly and AlSi-MoCr testing; b and f) microscopical images of the top surface of the blades; c and g) EDS mapping of the blades; d and h) microscopical images of the front surface of the blades.

5.3.3.3. Reaction Forces and Temperature Investigation

Figure 5.15 presents the maximum normal and tangential reaction forces for both AlSi-Poly and AlSi-MoCr coatings during abrasability tests. These reaction forces are critical in assessing the performance of abradable materials, as lower reaction forces are essential to minimize damage to compressor blades during engine operation [36]. The results reveal slightly higher average normal and tangential forces for the AlSi-MoCr coating than for AlSi-Poly. Specifically, the normal force for AlSi-Poly was recorded at 119.6 ± 35.7 N, while AlSi-MoCr exhibited 132.1 ± 51.9 N. For tangential forces, AlSi-Poly demonstrated 67.1 ± 24.2 N, compared to 79.3 ± 25.9 N for AlSi-MoCr. Although AlSi-MoCr exhibited slightly higher mean reaction forces, the two coatings show no statistically significant differences ($p = 0.749$ for normal and $p = 0.583$ for tangential forces), with small to medium effect sizes (Cohen's $d = 0.28$ and 0.49 , respectively). This confirms that both materials are statistically equivalent in terms of abrasability forces, and observed differences fall within the range of experimental variability, as illustrated in Figure 5.15a. and summarized in Table 5.5. Additionally, the tangential forces for both coatings were consistently about 60% of their respective normal forces.

The results presented in terms of reaction forces are consistent with findings from the literature, where the authors normally correlate the forces with the rougher scar appearance of the wear track, as well as the blade speed and incursion rate [17,146,161]. In this study, all of those results and input parameters were maintained consistently across both coatings, with and without Mo and Cr, leading to comparable results.

From Figure 5.15c to Figure 5.15f, the variation in reaction forces as a function of incursion depth for both coatings is depicted. The results show that AlSi-Poly and AlSi-MoCr exhibit relatively constant reaction force behaviour throughout the incursion depth. While some fluctuations were observed, these were expected due to the inherent inhomogeneity of the coating and localized variations during wear [117]. The intensity and variation of these impulses are often associated with the coating's hardness [31]. However, the fluctuations were minimal in this case, indicating that both coatings provided a stable interaction with the blade without significant intermittent braking. Despite the overall uniformity, the maximum normal forces were observed early in the incursion process. AlSi-Poly reached its peak normal force of 118.1 N at a depth of 0.77 mm, while AlSi-MoCr peaked at 103.2 N at 0.17 mm. The maximum tangential forces were recorded at greater incursion depths, with AlSi-Poly reaching 53.9 N at 1.56 mm and AlSi-MoCr at 1.88 mm. These results suggest that deeper and longer wear tracks may lead to higher tangential forces since the friction may be greater at greater incursion depths [87].

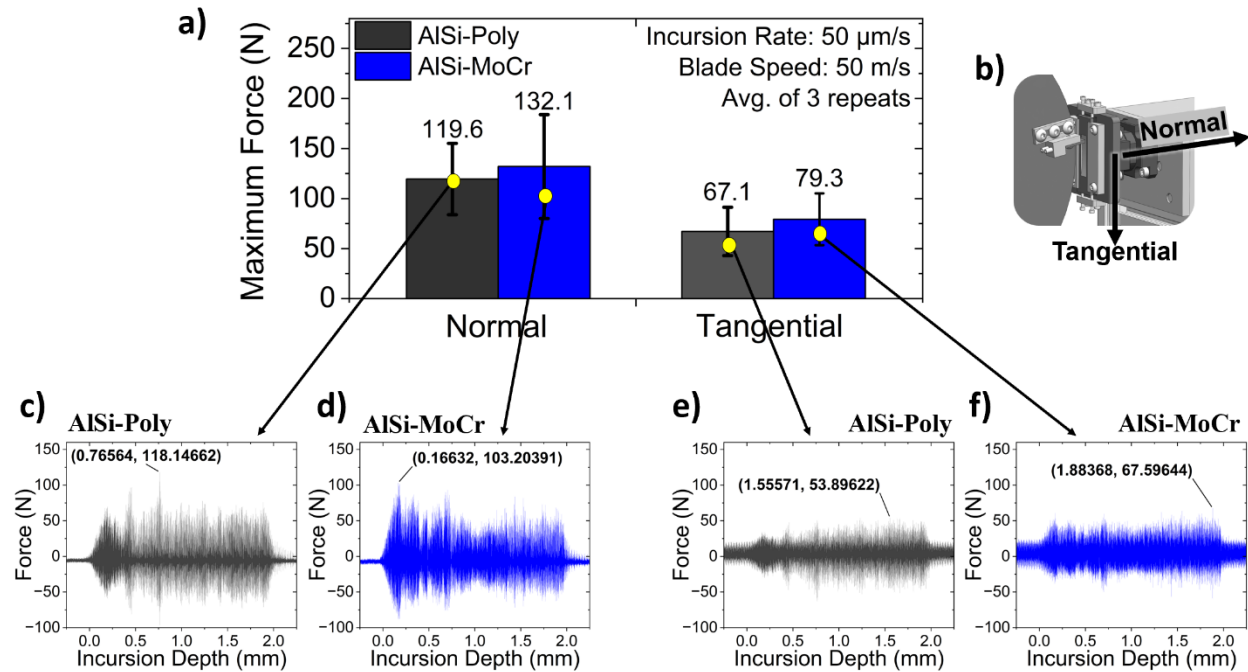


Figure 5.15. Normal and tangential forces during the abrasability tests; a) maximum reaction forces of AlSi-Poly and AlSi-MoCr; b) schematic of the reaction force directions on abrasability test; c) normal force for AlSi-Poly; d) normal force for AlSi-MoCr; e) tangential force for AlSi-Poly; f) tangential force for AlSi-MoCr.

Table 5.5. Statistical comparison between AlSi-MoCr and the baseline (AlSi-Poly) for abrasability reaction forces, showing *p*-values, effect sizes (Cohen's *d*), and significance interpretation.

Material Comparison	Force Type	<i>p</i> -value	Cohen's <i>d</i>	Statistical Conclusion Regarding Reaction Forces
AlSi-MoCr vs AlSi-Poly	Normal	0.749	0.28	No statistically significant difference; small effect size; materials are statistically equivalent
AlSi-MoCr vs AlSi-Poly	Tangential	0.583	0.49	No statistically significant difference; medium effect size; potential practical difference statistically-wise

Moreover, the surface rubbing temperature was closely monitored during the abrasability tests, as shown in Figure 5.16. Figure 5.16a presents the average maximum temperatures recorded across all tests, including multiple repetitions. The data reveal that the AlSi-Poly coating reached an average maximum rubbing temperature of $47.6 \pm 5.3^\circ\text{C}$, while the AlSi-MoCr coating exhibited a slightly higher average temperature of $49.3 \pm 5.86^\circ\text{C}$. However, when considering the error bars, the temperature profiles of both coatings are statistically equivalent. This result is consistent with

the earlier findings on reaction forces and wear analysis, further supporting the conclusion that both coatings exhibit similar abrasability performance.

In terms of the evolution of surface rubbing temperature along the incursion depth, the results in Figure 5.16b show that both coatings experienced a rapid temperature increase at the start of the rubbing test, reaching approximately 45°C within the first 0.25 mm incursion depth. The temperature then continued to rise with some fluctuations, ultimately peaking at the end of the incursion movement. It is noteworthy that the blade-abradable interaction concluded upon reaching a 2 mm incursion depth, where the temperature promptly drops, reaching about 35°C within 30 seconds, with AlSi-MoCr ending with a slightly higher temperature, consistent with its marginally higher peak temperature during the test.

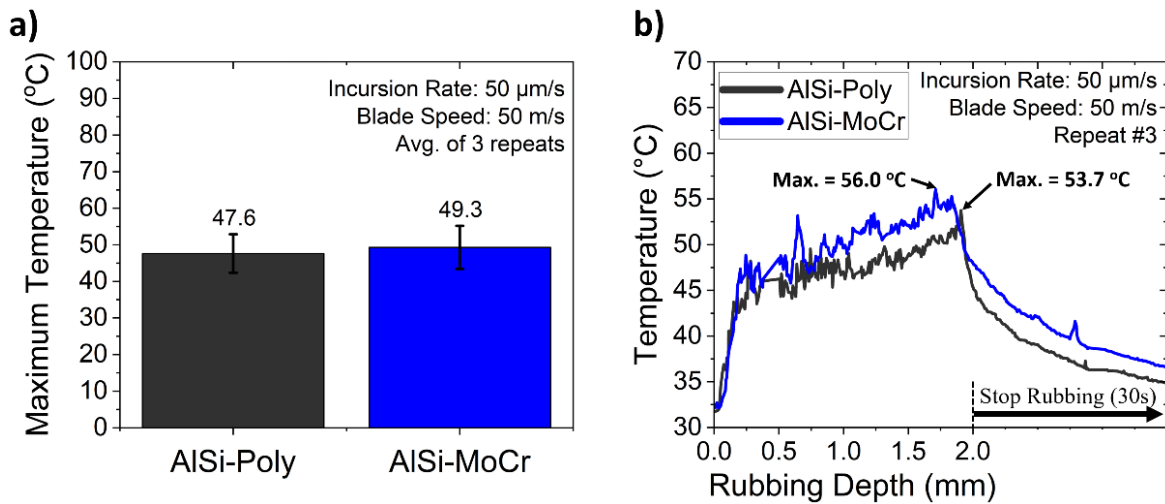


Figure 5.16. Maximum surface rubbing temperature of both AlSi-based coatings; a) averaged maximum temperature of all repetitions; b) evolution of the temperature along the incursion depth of repeat number 3.

5.4. Discussion

5.4.1. Coating Characterization

The AlSi-Poly and AlSi-MoCr coatings share several notable similarities. First of all, regarding coating microstructure, both coatings exhibit similar coating characteristics in terms of thickness and microstructure, with both showing a predominant AlSi matrix uniformly interspersed with polymer (Figure 5.5). Similar findings have been observed in other studies with comparable aluminum-based coatings [25,101,103]. In this study, despite the addition of Mo and Cr in the AlSi-MoCr coating, there are no significant differences in filler material area fraction, hardness, or surface roughness compared to the AlSi-Poly coating (Figure 5.6). These findings suggest that the inclusion of Mo and Cr does not substantially alter the coatings' overall characteristics, also highlighting the effectiveness of the APS technique in producing equivalent coating microstructures, which was anticipated given the use of identical spraying parameters and comparable chemical compositions presented in Table 5.1 and Figure 5.1 respectively. For example, Liu et al [25] sprayed five aluminum-based abrasible coatings with comparable compositions and spraying conditions, resulting in microstructures equivalent to those presented in this study in Figure 5.5.

5.4.2. Tribological Evaluation

Regarding friction measurements, the CoF for both coatings consistently remained around 0.3 across both testing methods (ball-on-flat and ball-on-disk), as presented in Figure 5.7. CoF within the same range was also found and discussed in the literature on comparable AlSi abrasible coatings [101,116,200]. Additionally, the stable CoF curves observed in all tests indicate a consistent sliding performance throughout the entire test cycle, regardless of the type of sliding movement (whether reciprocating or unidirectional rotational), and irrespective of the inclusion of Mo and Cr in the second coating.

On the other hand, regarding wear evaluation, the findings in Figure 5.7 suggest that while both coatings exhibit similar wear profiles, the wear mechanism might be influenced by the testing configuration. In ball-on-flat testing, there was a more pronounced formation of smeared material, perpendicular cracks, and an accumulation of loose debris across the wear track for both abrasible coatings (Figure 5.9). The ball-on-disk configuration revealed more evident abrasive marks (Figure 5.10a and Figure 5.10d) and tribofilm formation (Figure 5.10b and Figure 5.10e) on both coatings, with no significant differences between them.

Additionally, a reduced wear depth was observed in the ball-on-disk tests for both coatings (Figure 5.7), which may be attributed to the difference in sliding motion and the protective

effect of tribofilm formation. The continuous rotational motion in ball-on-disk testing likely facilitates the formation of the tribofilms through a combination of debris formation and difficulty in releasing them out from the wear track. These results align with findings in the literature that associate released particles with the wear mechanism and final wear profile [15,181]. This may also explain the reduced number of loose debris observed in the ball-on-disk test (Figure 5.10) compared to the ball-on-flat results presented in Figure 5.9.

The analysis of the Ti6Al4V counterballs used against both AlSi-Poly and AlSi-MoCr coatings reveals that the presence of Mo and Cr in the AlSi-MoCr coating has little effect on the counterball wear and adhesive transfer behaviour. Typically, studies associate the presence of wear scars on the counter element as indicative of damage [88,161]. However, in this study, no visible wear scars were observed, and its absence across all tests suggests no significant damage to the counterballs, whether in ball-on-flat or ball-on-disk configurations. Conversely, evident adhesive transfer films were observed on all counterballs, primarily composed of aluminum and a minor presence of oxides (Figure 5.11). This outcome was anticipated due to the strong frictional interaction between the aluminum-based coating and the titanium-based counterball material. Wu et al. [201] highlight the strong chemical bonding between Ti6Al4V and a commercial aluminum alloy driven by frictional motion.

Overall, the observations of all tribological results suggest that the inclusion of Mo and Cr does not notably impact the wear performance, neither the AlSi-based coatings nor their respective tested counterballs. However, the performance was slightly influenced by the different tribological configurations tested.

5.4.3. Abradability Investigation

In terms of wear track investigation, both coatings revealed the presence of longitudinal grooves aligned with the motion direction (Figure 5.13), with equivalent wear track roughness (Figure 5.12). This observation is consistent with findings from previous studies, which also associated similar wear grooves with abrasive wear mechanisms [7,103,132]. Furthermore, the presence of transferred material and prows on the blade (Figure 5.14) is likely contributing to the groove formation observed on the abradable coatings. The literature [4,175] discusses how these prows on blades can displace coating material below and to the sides, inducing a ploughing phenomenon that results in longitudinal grooves on the coating surface. This interaction between adhesive transfer and abrasive wear mechanisms highlights the complex nature of wear processes in these coatings, where both material transfer and mechanical deformation play significant roles. The observed groove formation suggests a synergistic effect between adhesive transfer and abrasive action.

Moreover, smeared metallic surfaces were also observed in the SEM images of both coatings (Figure 5.13), consistent with findings reported by other research groups [103,132,146]. This smearing mechanism indicates that material may become trapped between the blade and coating surface during interactions, subsequently spreading across the wear track before eventually being released. This process can lead to a buildup of force and temperature [132]. Additionally, this phenomenon may have influenced the adhesive transfer behaviour observed on the blade (Figure 5.14), reinforcing the complex interplay between material transfer and mechanical wear mechanisms.

In the investigation of material transfer during wear testing of both abrasable coatings, the analysis revealed no detectable transfer of material from the Ti6Al4V blades to the coatings, as evidenced by the absence of titanium traces in the EDS mapping analysis (Figure 5.13). This indicates that, in terms of chemical composition, the wear track of the coating remained largely consistent with the original coating microstructure, showing no significant degradation or alteration after the test. However, a substantial amount of aluminum was detected on the surface of the blades (Figure 5.14), indicating that material was transferred from the abrasable coatings and deposited onto the blade surfaces during the rubbing process. This aluminum deposition is likely driven by the high frictional temperatures generated during the rubbing interactions, as supported by previous studies [168,176]. Several other studies have similarly documented the adhesive transfer of material from abrasable coatings to blade surfaces under comparable conditions [32,163]. Similarly to the tribological investigation of this study, the counter element also presented a considerable amount of transfer material, as can be noticed by comparing Figure 5.11 and Figure 5.14.

The absence of titanium transfer, coupled with significant aluminum deposition, suggests that the interaction is primarily driven by the adhesion of coating material to the blade rather than a reciprocal material exchange. This observation aligns with the notion that the coating material, under the influence of elevated temperatures and mechanical forces, is more prone to transfer to the blade, potentially affecting the wear mechanism and the overall performance of the coating after repetitive cycles. These findings collectively suggest that the wear behaviour of the abrasable coatings is governed by a combination of abrasive and adhesive mechanisms, with the observed groove formation, smeared surfaces and material transfer being the key mechanisms observed in this study, regardless of the addition of Mo and Cr in the AlSi matrix.

When compared to the tribological results, both performance evaluations showed no significant wear on the Ti6Al4V counter elements. SEM analysis revealed no visible wear scars on the counterballs (Figure 5.11) and blades (Figure 5.14) after testing. This consistency across both evaluations suggests that the interaction between the coating and the counter element is primarily destructive to the coating rather than the counter material, preserving the integrity of the counter element, a key characteristic of an effective abrasable material [7,164,202]. Notably, this

preservation of the counter material occurred regardless of the addition of MoCr or the specific testing method employed.

Additionally, the reaction forces are also in agreement with the results obtained for the post-rubbing specimens. Typically, higher normal and tangential forces correlate with higher coating hardness, which often leads to rougher wear track surfaces [4,25,103]. However, in this study, both the AlSi-Poly and AlSi-MoCr coatings exhibited similar hardness levels (Figure 5.6) and comparable wear track roughness (Figure 5.12). Consequently, as expected, no significant differences were observed in the reaction forces (Figure 5.15) between the two coatings. The slight variations in maximum force values and peak locations are within the same range and do not suggest a meaningful difference between the coatings tested. This result suggests that adding MoCr to the AlSi-based coating had little influence on the abrasability performance under the tested conditions. Overall, the reaction forces outcome reinforces the idea that adding a minor concentration of Mo and Cr does not markedly alter the mechanical behaviour of the coating, maintaining a performance level comparable to AlSi-Poly coating.

Previous studies have extensively explored surface rubbing temperatures in abrasable coatings, linking temperatures to friction forces [87,161] and coating hardness [31,161]. In the current study, since both AlSi-Poly and AlSi-MoCr coatings displayed comparable hardness and frictional forces, it is unsurprising that no significant differences in rubbing temperatures were observed. Moreover, the minimal addition of Mo and Cr to the AlSi-MoCr coating is unlikely to have considerably altered the thermal conductivity, which explains the near-identical temperature profiles observed in both coatings.

5.5. Conclusions

This study provides a comprehensive evaluation of the AlSi-MoCr abrasable coating, comparing it with AlSi-Poly, with a focus on coating characterization and mechanical wear resistance. It also explores the connections between different TRLs by assessing wear mechanisms through tribological and abrasability performance tests. To enhance the comprehensiveness and drive the development of next-generation abrasable coatings, this study highlights the following key insights:

- Besides the minor differences in chemical composition, both coatings exhibited a uniform distribution of polyester, consistent hardness, equivalent as-sprayed surface roughness, and similar area fractions of filler materials when deposited with identical APS parameters.
- Tribological evaluations demonstrated that AlSi-Poly and AlSi-MoCr had equivalent wear rates and CoF, with adhesive wear transfer to the Ti6Al4V counterball for both ball-on-flat and ball-on-disk test conditions. Moreover, no apparent damage to the counterballs was observed. Although minor differences in the wear mechanisms were observed between the testing setups, the overall tribological performance between coatings was consistent.
- Abrasability performance assessments revealed the presence of longitudinal grooves and smearing on both coatings, with comparable wear track roughness and prow formation on the blade tips. These features were consistent across both coatings, although the AlSi-MoCr coating exhibited more widespread adhesive transfer of aluminum onto the titanium blades. Despite this, no damage to the blade was observed in either case. The study also identified equivalences between the two coatings in terms of reaction forces and rubbing temperatures during testing.
- The similarities between tribological and abrasability results rely on the observation of adhesive transfer material with no apparent wear to the counter element against both tested coatings.

The consistency in results at different TRLs studies, tribological and abrasability performance of the coating, reinforces the reliability of applying AlSi-based coatings as abrasable materials, with minimal impact from the inclusion of Mo and Cr in the AlSi matrix.

Assessment of AlSi-Based Abradable Coatings with hBN and MoCr Additives for Aerospace Conditions: A Novel High-Temperature Rig Approach ⁶

Abstract

Abradable coatings are crucial for enhancing gas turbine efficiency and enabling sustainable aviation by reducing fuel consumption and protecting rotor components during blade-casing interactions. However, assessing their performance under relevant speed and temperature conditions remains challenging due to the cost and complexity of custom-built abradable rigs. This study addresses these challenges by upgrading an existing abradable test rig with a high-temperature module, supporting scalable materials testing under extreme gas turbine and hydrogen-compatible turbine conditions. It also evaluates the abradability performance of three thermally sprayed AlSi-based coatings at 300°C. (1) AlSi-Poly, with 40 wt% polyester as a baseline; (2) AlSi-MoCr, with similar polyester content plus small additions of molybdenum (Mo) and chromium (Cr); and (3) AlSi-hBN-Poly, with 6 wt% hexagonal boron nitride (hBN) and 20 wt% polyester. The inclusion of hBN, an eco-friendly solid lubricant, and MoCr, recognized for corrosion resistance, reflects growing interest in materials designed for energy-efficient turbines and Industry 4.0 aerospace systems. Abradability tests showed that AlSi-Poly and AlSi-MoCr outperformed AlSi-hBN-Poly at both temperatures based on lower reaction forces. All coatings exhibited reduced forces at 300°C due to thermal softening. AlSi-Poly and AlSi-MoCr demonstrated comparable abradability, with smoother wear tracks at room temperature that worsened at 300°C, along with increased dynamic interaction coefficient (F_t/F_n). In contrast, AlSi-hBN-Poly stood out for its thermal stability, higher roughness, and the lowest F_t/F_n . These findings also highlight the relevance of the high-temperature abradable rig as a cost-effective platform for pre-screening aerospace abrasives under application-relevant conditions, bridging fundamental research and engine testing.

Keywords: Abradable Coatings, Gas Turbine Efficiency, High-Temperature Testing, Thermal Spray, Tribology.

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6.1. Introduction

The drive for enhanced efficiency and reduced environmental impact in modern gas turbine engines has intensified the need for advanced materials capable of operating under extreme conditions while enabling tighter rotor-stator clearances [7,8]. These clearances, critical for minimizing aerodynamic losses and improving fuel economy, depend heavily on the performance of abradable systems, which are based on abradable sacrificial materials specifically engineered to protect rotor blades during blade-casing interactions [13,97]. By providing a controlled sacrificial layer, abradables not only preserve blade integrity but also reduce high-pressure air leakage [9,10]. For instance, a clearance of approximately 0.13 mm between rotor blades and the casing can lead to an increase in fuel consumption of up to 0.5% [203,204].

The effectiveness of an abradable coating is defined by its ability to achieve a delicate balance: it must be sufficiently soft to abrade cleanly under blade contact while remaining robust against erosion [187,205], oxidation [5,185], and thermal degradation [95,101]. Among the coatings employed today, thermally sprayed aluminum-silicon-based systems reinforced with polyester phases dominate low-pressure compressor (LPC) applications, where operating temperatures remain below 450 °C [19,61]. These materials typically utilize a triphasic architecture consisting of a metallic matrix for structural stability, a polymeric phase as a filler to increase abradability combined with porosity and controlled failure, and, in some cases, solid lubricants such as hexagonal boron nitride (hBN) to facilitate crack propagation and reduce friction [13,183].

However, the thermomechanical stability of such coatings remains a significant challenge. While polyester additives enhance abradability by promoting mechanical energy absorption, they are highly susceptible to thermal softening at elevated temperatures, leading to performance degradation [104,105]. In contrast, the incorporation of hBN, a green solid lubricant, offers improvements in thermal stability and lubrication but introduces microstructural heterogeneities that may affect the wear mechanisms and morphology [4,100]. Thus, the wear track morphology and resulting surface roughness serve as key indicators of coating performance, linking material response to abradability efficiency. Smooth, shallow tracks typically indicate efficient material removal through controlled plastic deformation, minimizing energy dissipation and blade damage [206,207]. In contrast, rough, heterogeneous wear tracks often reflect unstable contact conditions, higher frictional forces, and the onset of material failure modes [17,25]. Consequently, the association between wear track roughness and abradability performance offers crucial insights into underlying wear mechanisms. Ductile wear, characterized by material smearing and continuous grooves, is usually desirable for abradables as it is associated with high energy absorption and controlled material removal. Brittle fracture mechanisms, leading to crack propagation, particle pull-out, and big debris formation, are highly undesirable as they can trigger coating delamination and severe blade wear [7,80,208,209].

Understanding these wear mechanisms under operational thermal conditions is essential, as the material's ductile-brittle transition can significantly influence abradable performance

[107,108]. Martinet et al. (2020) [105] emphasize the profound effect of temperature on coating behavior, the authors highlight the increased role of polymer softening at elevated temperatures, which shifts the wear regime from ductile-dominant to mixed or brittle-dominant behaviors. Additionally, Liu et al (2024) [106] observed increased adhesive transfer between the AlSi-based coating and the blade at high operating temperature. Despite these findings, there is a lack of systematic comparative studies exploring the high-temperature behavior of AlSi-based abrasible coatings, particularly those with polyester and modified with molybdenum (Mo), chromium (Cr), and hBN, leading to a gap in scientific understanding of compositional impacts on high-temperature performance.

Addressing this gap requires experimental approaches that mimic aeroengine operating conditions [2]. However, while full-scale engine tests provide the most accurate results, their high costs and proprietary industrial protocols often limit accessibility and hinder broader knowledge dissemination [3,14]. Conversely, conventional laboratory tests like pin-on-disk or scratch tests fall short of capturing the complex, high-speed dynamics of rotor-casing interactions [88,142]. This economic and technical barrier restrains innovation, particularly for researchers aiming to bridge fundamental material science with industrial applications.

To overcome these challenges, this study introduces a novel, cost-effective high-temperature abrasible test rig designed to simulate elevated aeroengine temperature conditions while providing actionable insights for both material optimization and Technology Readiness Level (TRL) progression. Besides its limitation in terms of blade speed, this work is based on the work of Bertuol et al. (2024) [3], where it is integrated a modular heating system capable of sustaining surface temperatures up to 350 °C, enabling controlled simulation of LPC-stage environments while simultaneously measuring key tribological parameters such as normal (F_n) and tangential (F_t) reaction forces, and dynamic frictional behavior.

The novelty of this work lies in (i) the development and validation of a high-temperature abrasible rig to bridge the gap between laboratory-scale assessments and application-relevant conditions, providing a scalable pre-screening tool for material qualification, and (ii) elucidating the temperature-dependent tribological behavior of three next-generation AlSi-based coatings: a baseline AlSi-Polyester (AlSi-Poly), a MoCr-doped variant (AlSi-MoCr), and an hBN-enhanced formulation (AlSi-hBN-Poly). While previous works have shown promising low-temperature abrasibility performance of the AlSi-based coatings, with MoCr [5], and hBN [4] additives, no work to date has combined these aspects under elevated thermal loads. Thus, this study advances the state of the art by addressing a key gap in the literature: the lack of direct, comparative abrasibility testing of AlSi-based abrasible coatings, especially under application-relevant high-temperature conditions. By analyzing wear track morphology, blade wear, reaction force profiles, and dynamic interaction coefficients (F_t/F_n), this study provides new insights into how compositional variations influence abrasibility, thermal stability, and performance consistency at elevated temperatures. The findings contribute directly to the advancement of robust, high-performance abrasible coatings for future gas turbine engines operating under increasingly demanding thermal and mechanical regimes.

6.2. Materials and Methods

The research methodology of this study is systematically divided into three key phases: (1) the abrasible materials and properties, (2) the abrasible test rig and its upgrade in terms of design and implementation of a high-temperature module, and (3) the evaluation of the abrasibility performance of the coatings under simulated extreme aircraft operating conditions. A schematic overview illustrating the workflow and interconnected phases of this research is presented in Figure 6.1.

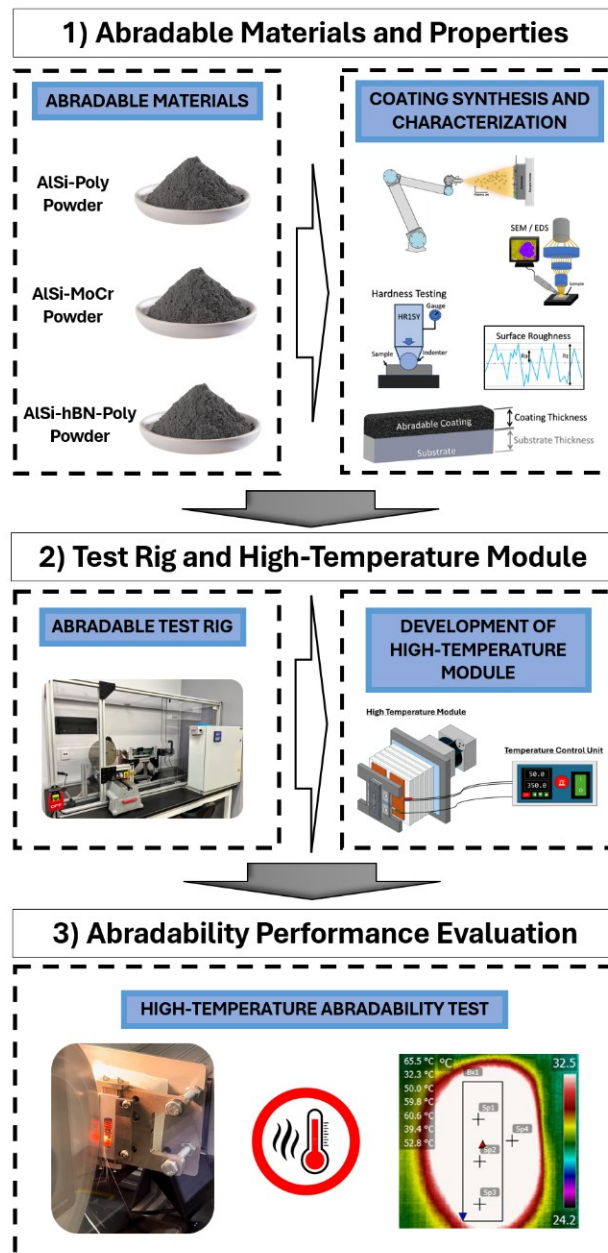


Figure 6.1. Schematic overview of the research methodology.

6.2.1. Abradable Materials and Properties

This study investigates three aluminum-based abradable materials: AlSi-Poly, AlSi-MoCr, and AlSi-hBN-Poly. The first material, AlSi-Poly, serves as the baseline material and is widely utilized in the aerospace industry for clearance control in gas turbine engines. It contains 40 wt.% polyester as a filler material. The second abradable material, AlSi-MoCr, incorporates minor fractions of molybdenum and chromium as additives to the AlSi matrix, chosen for their corrosion-resistant properties [61,195,196]. The third material, AlSi-hBN-Poly, incorporates 20 wt.% polyester and 6 wt.% hexagonal boron nitride (hBN), a solid lubricant chosen for its excellent thermal stability and tribological performance. The 6 wt.% hBN concentration was determined based on industry standards and commercial literature [20]. The reduction in polyester content, compared to the baseline, aims to prevent an excessive total filler volume, which could compromise the erosion–abradability balance critical to abradable functionality. Moreover, as polyester has limited thermal resistance, the substitution with hBN may support improved high-temperature stability. This composition was designed to explore whether hBN could partially replace polyester while maintaining effective abradability under elevated temperatures. While this formulation introduces simultaneous changes in polyester and hBN content, the comparative analysis and discussions in this study consider these factors.

A comprehensive analysis of the AlSi-Poly, AlSi-MoCr, and AlSi-hBN-Poly coatings has been previously investigated in [5] and [4]. To ensure consistency and facilitate comparative analysis, all samples were subjected to identical thermal spray deposition and characterization procedures. Table 6.1 summarizes the key characteristics of the tested coatings, with each dataset linked to the previously published reference sprayed over stainless-steel substrates.

Table 6.1. Overview of the abradable coatings' properties.

Abradable Material	Powder Size Distribution [Dv(50)]	Area Fraction of Filler (%)	Coating Hardness (HR15Y)	Coating Roughness (Ra in μm)	Coating Thickness (mm)	Ref.
AlSi-Poly	59	60 ± 4.2	70 ± 2.7	4.44 ± 0.64	4.7	[4]
AlSi-MoCr	66	55 ± 2.6	68 ± 3.5	4.89 ± 0.74	4.5	[5]
AlSi-hBN-Poly	71	34.6 ± 2.1	83.8 ± 1.3	4.06 ± 0.81	3.1	[4]

6.2.2. Abradable Test Rig

The cost-effective abradable test rig was conceptualized, designed, and manufactured at Concordia University to replicate the blade-abradable interaction process typical of aero-engine systems, but on a smaller and more controlled laboratory scale. The rig was specifically engineered to simulate the operational conditions encountered in gas turbine engines, enabling the evaluation of abradable coatings under application-relevant scenarios. Its design focuses on providing a versatile, reliable, and cost-efficient platform for pre-screening and optimizing abradable materials, thereby reducing the time and expenses associated with traditional high-speed testing methods.

The rig's ability to simulate key parameters such as blade tip velocity, incursion rates, and interfacial temperatures makes it a valuable tool for advancing research in abradable coating performance and wear mechanisms. Especially allowing the identification of promising materials and optimizing their properties before progressing to more complex and expensive TRL testing.

A comprehensive description of the rig's development, including its design principles, construction, and validation process, has been documented in detail elsewhere [3].

6.2.3. Development of the High-Temperature Module

As a complement to the existing abradable test rig, a high-temperature module was designed to heat the abradable coating sample up to 350 °C, aiming to simulate more realistically the range of operating conditions experienced in an aircraft engine at the low-pressure compressor stage [105,117,210]. Figure 6.2 presents the abradable test rig with the high-temperature module attached.

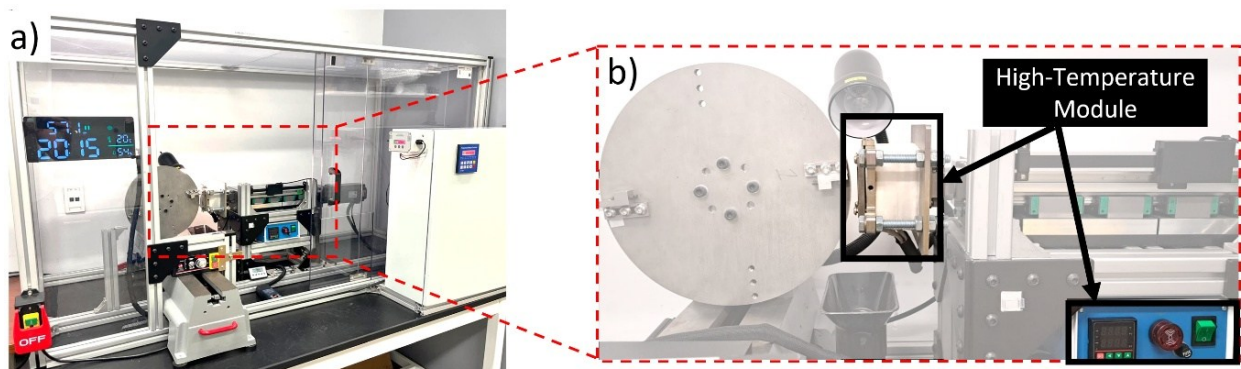


Figure 6.2. Abradable test rig with the high-temperature module attachment; a) Overview of the cost-effective abradable test rig; b) Close-view of the abradable rig highlighting the high-temperature module.

To ensure consistent heating of the abradable sample, four alumina ceramic heating elements (70x30 mm, 110 V, 66 ohm) were attached to the backside of the sample holder, as illustrated in Figure 6.3a. These heating elements were integrated with a temperature control unit comprising a REX-C100 PID temperature controller, a solid-state relay (SSR 40DA), a wiring board, a button switch, an indicator light, and a safety buzzer for overheat protection (Figure 6.3c).

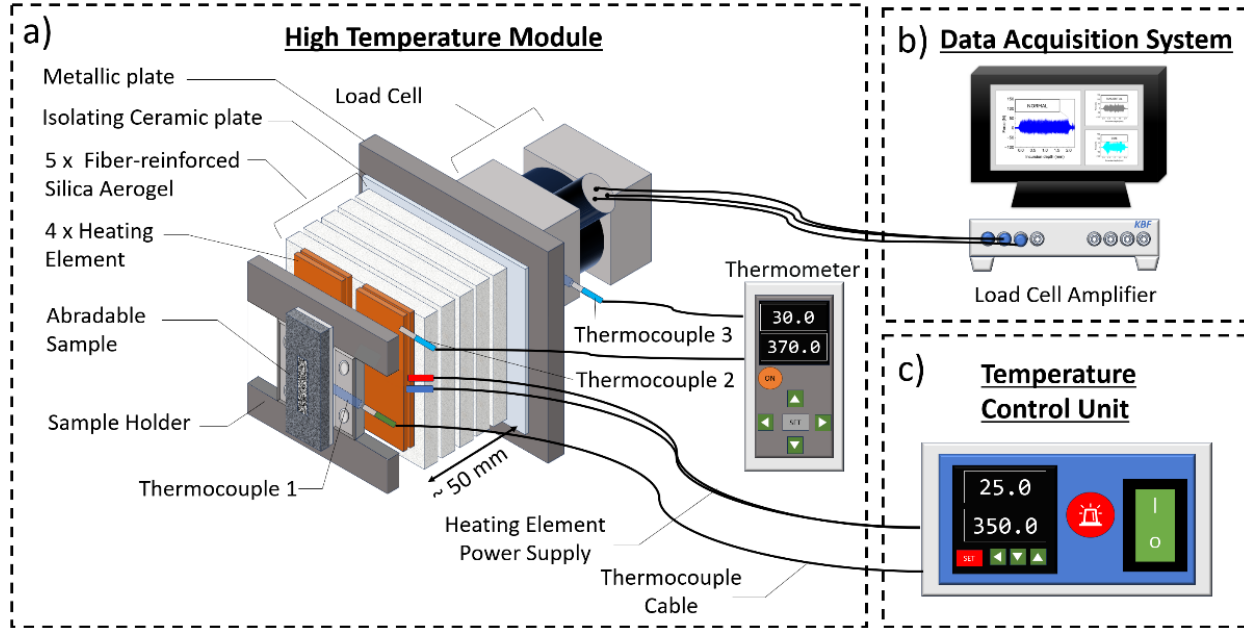


Figure 6.3. Schematic of the high-temperature module developed for the abradable test rig; a) High-temperature module assembly schematic; b) Data acquisition system schematic; c) Temperature control unit schematic.

In addition, the temperature monitoring across the setup was critical to ensuring consistent pre-heating conditions. Thus, three type-K thermocouples were strategically positioned around the sample holder. The first thermocouple was embedded inside the holder, as close as possible to the coating sample, to provide accurate feedback to the temperature control unit. A second was placed between the sample holder and heating elements to enable auxiliary system monitoring. The third thermocouple was positioned near the load cell to verify that it remained within its safe operating limit of 120 °C [149], ensuring that its functionality and accuracy were not compromised by excessive heat.

Additionally, an A320 ThermoVision infrared camera (FLIR Systems, MA) was mounted approximately 0.3 m from the sample to provide full-field surface temperature visualization. The thermal camera served two key purposes: monitoring surface temperatures during the heating phase and allowing real-time tracking of thermal fluctuations during blade-coating interactions. It features a detection range of 0–350 °C, ± 2 °C accuracy, and a 12 ms response time, with a dynamically updated reference ensuring reliable temperature measurements [3,150]. These data were time-synchronized with the incursion process to accurately correlate surface temperature with rubbing depth. Although the system captures the overall interfacial temperature influenced by

frictional heating, key parameters such as emissivity, distance, and accuracy must be calibrated prior to testing.

For thermal insulation, a combination of five layers of fibre-reinforced silica aerogel (90x90x10 mm each) and a thin insulating ceramic plate was employed. Silica aerogel was chosen due to its superior insulating properties (heat flow rate: 0.047 W at 24 °C [211]), which reduces heat transfer, allowing for minimal thermal interference with adjacent components [212,213]. Additionally, all components were strapped using high-temperature tape and fastened with four bolts between the sample holder and the metallic plate connected to the load cell, providing a solid mechanical connection. The separation distance between the heating plates and the metallic plate was carefully optimized through preliminary experiments. A 50 mm gap (i.e. equal to five layers of fibre-reinforced silica aerogel) was determined to be the ideal balance between minimizing heat transfer and maintaining system stability, ensuring that heating transfer or vibration did not affect the accuracy of the force measurements.

6.2.4. Abradability Performance Evaluation

To evaluate the performance of abradable coatings under conditions simulating real-world aero-engine environments, a systematic testing approach was employed using the abradable test rig. The evaluation was divided into two distinct testing regimes: room temperature (25 ± 10 °C) and high surface temperature (300 ± 25 °C). This dual-temperature approach was designed to assess coating performance across thermal conditions representative of gas turbine engine operations.

Room temperature abradability tests (RT), previously published in [5] and [4], provided baseline data for comparative analysis. In this study, three repeats of high-temperature abradability tests (HT) were performed to extend the evaluation, focusing on comparing results with existing RT literature. Additionally, two extra repeats were performed at RT for AlSi-hBN-Poly in order to enhance the quality of the results and keep a similar methodology. Table 6.2 outlines the testing matrix for all evaluated conditions.

Table 6.2. Test conditions for room and high-temperature abradability evaluation.

Abradable	Blade	Blade Speed	Incursion Rate	Incursion Depth	Operating Temperature	Ref
AlSi-Poly	Ti6Al4V Grade 5 Annealed (10x25x3.18mm)	50 m/s	50 μ m/s (0.83 μ m/pass)	2 mm	RT	[5]
					300 $\pm$ 25 °C	
AlSi-MoCr					RT	[4]
					300 $\pm$ 25 °C	
AlSi-hBN-Poly					RT	[5]
					300 $\pm$ 25 °C	

To ensure consistency, all testing parameters, such as blade speed (50 m/s), incursion rate (50 $\mu\text{m/s}$), and incursion depth (2 mm), were maintained across both temperature regimes, with temperature as the special variable. This approach enables a direct comparison of coating performance under different initial thermal conditions.

The incursion rate of 50 $\mu\text{m/s}$ was selected to replicate gradual blade-casing interference within the typical clearance-tightening events, ensuring controlled and progressive wear. Similar incursion rates can also be found in the literature [25,88,117]. This rate also minimizes abrupt mechanical impacts, enabling clearer interpretation of force evolution and surface responses.

The surface testing temperature of 300 ± 25 °C was selected based on the maximum operational temperature limits of AlSi-based abradable coatings in actual engine conditions, as documented in [20]. This temperature range is representative of the thermal environment in the low-pressure compressor (LPC) stage, where AlSi-based coatings are commonly applied [143]. Testing at this temperature evaluates the coatings' ability to maintain structural integrity, abradability, and wear resistance under thermally demanding conditions, which is critical for their reliability in aerospace applications. The ± 25 °C margin accounts for localized thermal gradients across the contact surface and natural fluctuations during real-time operation.

To replicate the rotor blade-casing interaction, blade tips with a simplified geometry were water jet cut using grade 5 titanium alloy (Ti6Al4V annealed). The choice of Ti6Al4V alloy reflects the standard material used in LPC blade manufacturing, ensuring relevance to industry practice. The blade dimensions were set to 10 x 25 x 3.18 mm, resulting in a thickness-to-chord ratio of 0.32. The rotating disc, carrying one blade, operated at 3600 rpm, resulting in an incursion of 0.83 μm per pass.

The time of heating exposure of each sample involves two distinct phases: (i) a pre-heating period and (ii) the rubbing interaction. First, the sample was uniformly heated to the target surface temperature of 300 °C using the integrated high-temperature module. This heating phase lasted only a few minutes until a stable and homogeneous temperature distribution across the sample surface was achieved. Second, the rubbing phase was conducted by initiating a controlled incursion of the blade into the coating. Given a total incursion depth of 2 mm and a constant incursion rate of 50 $\mu\text{m/s}$, each test lasted approximately 40 seconds. As each specimen underwent a single thermal cycle and was exposed to a temperature below the degradation limit of the coating materials, no thermal fatigue or significant thermal degradation effects were expected during the evaluation.

The abradability assessment was conducted using both direct and indirect outputs from the test rig. Direct outputs included real-time measurements of reaction forces (normal and tangential) given during the blade-abradable interaction, as well as localized temperatures caused by the frictional heating, referred to as rubbing temperature. Indirect outputs involved ex-situ analyses of the rubbed surfaces and blades using confocal microscopy, scanning electron

microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS), including top surface imaging, cross-sections and side views. These analyses focused on characterizing wear mechanisms, wear track profiles and roughness, material transfer between the coatings and blades, and blade wear.

Additionally, this study methodology is subject to several key assumptions and limitations. First, testing was conducted using a single blade with a simplified flat geometry and fixed operational parameters. While this approach is well-suited for material-level investigations, it may limit the generalization of wear mechanisms across different engine blade geometries and operating profiles. Second, although the test rig replicates high-temperature and blade-abradable contact conditions, it operates in a controlled laboratory-scale environment. As such, it does not fully reproduce the complex multi-axial stress states, dynamic loading, and long-term cyclic effects encountered in real engine service conditions.

6.2.1. Statistical Analysis

A systematic statistical analysis was conducted to quantitatively assess the variability and significance of the abrasability reaction forces, focusing on both the normal and tangential components measured during blade–abrasable interactions. The analysis comprised two stages: (i) comparison of each coating against the baseline under identical test conditions, and (ii) evaluation of each coating’s behavior at RT and 300 °C to assess the statistical influence of operating temperature. All tests included at least two to three repetitions per material and condition. Although this represents a relatively small sample size for statistical analysis, the results provide valuable insights into emerging trends and enable a meaningful comparative assessment across coating compositions and temperature regimes.

Raw force data were first processed in Microsoft Excel to compute descriptive statistics (mean and standard deviation), providing an initial evaluation of performance variability. Independent two-sample t-tests assuming equal variances were then applied using a significance level of $\alpha = 0.05$. In addition to the p-values, Cohen’s d effect sizes were calculated to quantify the magnitude and practical relevance of observed differences, allowing differentiation between statistically significant and practically meaningful trends.

This statistical framework supported a detailed interpretation of abrasability performance, facilitating direct comparisons among coatings and temperature regimes. When integrated with the multi-TRL testing methodology, these analyses provide a robust, data-driven foundation for material selection and optimization at a sub-scale evaluation.

6.3. Results

6.3.1. Coating Performance Investigation

Abradability testing of AlSi-Poly, AlSi-MoCr, and AlSi-hBN-Poly coatings revealed consistent groove formation along the direction of motion under both room and high-temperature conditions. Figure 6.4 presents photographs of the post-rubbed specimens, along with top-surface and 3D images of the wear track profiles obtained through confocal microscopy for each coating. The RT results, adapted from previous literature [4,5], are included for comparative analysis with the newly conducted abrasability tests at elevated temperature.

Visual inspection of the samples tested at 300 °C (Figure 6.4d, e, and f) showed wear track characteristics similar to those observed at RT, including comparable appearance, coloration, and the absence of large cracks or significant material detachment. This suggests that the fundamental wear mechanisms, such as abrasive grooving and adhesive transfer, remained present across temperature regimes.

However, while previous RT tests revealed deeper and more pronounced grooves in AlSi-hBN-Poly (Figure 6.4c), the tests at 300 °C exhibited less pronounced differences among the coatings. AlSi-hBN-Poly still showed slightly more pronounced grooves compared to AlSi-Poly (Figure 6.4a) and AlSi-MoCr (Figure 6.4b), but the overall wear behavior was more uniform when compared at 300 °C (Figure 6.4d, e, and f). This indicates that elevated temperatures may have influenced the wear track profile of the abradable materials.

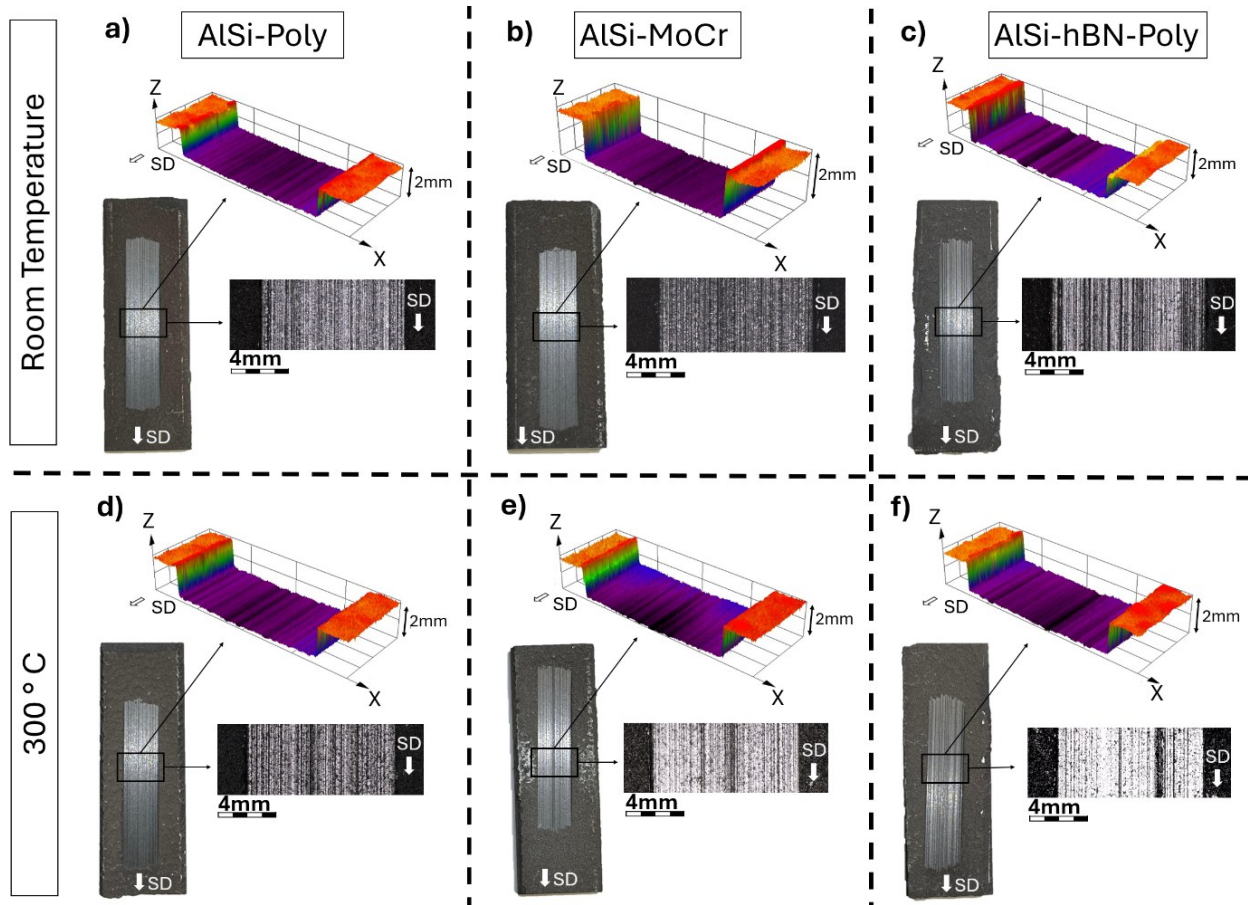


Figure 6.4. Wear track of the abradable coatings after abrasability tests at different operating temperatures; a,b,c) Room temperature; d,e,f) 300 °C.

The wear track profiles and roughness measurements for each tested coating are presented in Figure 6.5 and Figure 6.6, presenting the results from abrasability tests conducted at both room and high temperatures. The data include average roughness (R_a) and maximum peak-to-valley height (R_z) for all three abradable coatings. These results highlight the influence of the operating temperature on the wear track surface integrity of the coatings when submitted to the abrasability tests. Previous studies conducted at room temperature [4,5] demonstrated that AlSi-Poly and AlSi-MoCr exhibited equivalent R_a values and significantly smoother wear tracks compared to AlSi-hBN-Poly (Figure 6.5). As discussed in Bertuol et al [4], the higher surface irregularities observed in AlSi-hBN-Poly at RT are indicative of inferior abrasability performance.

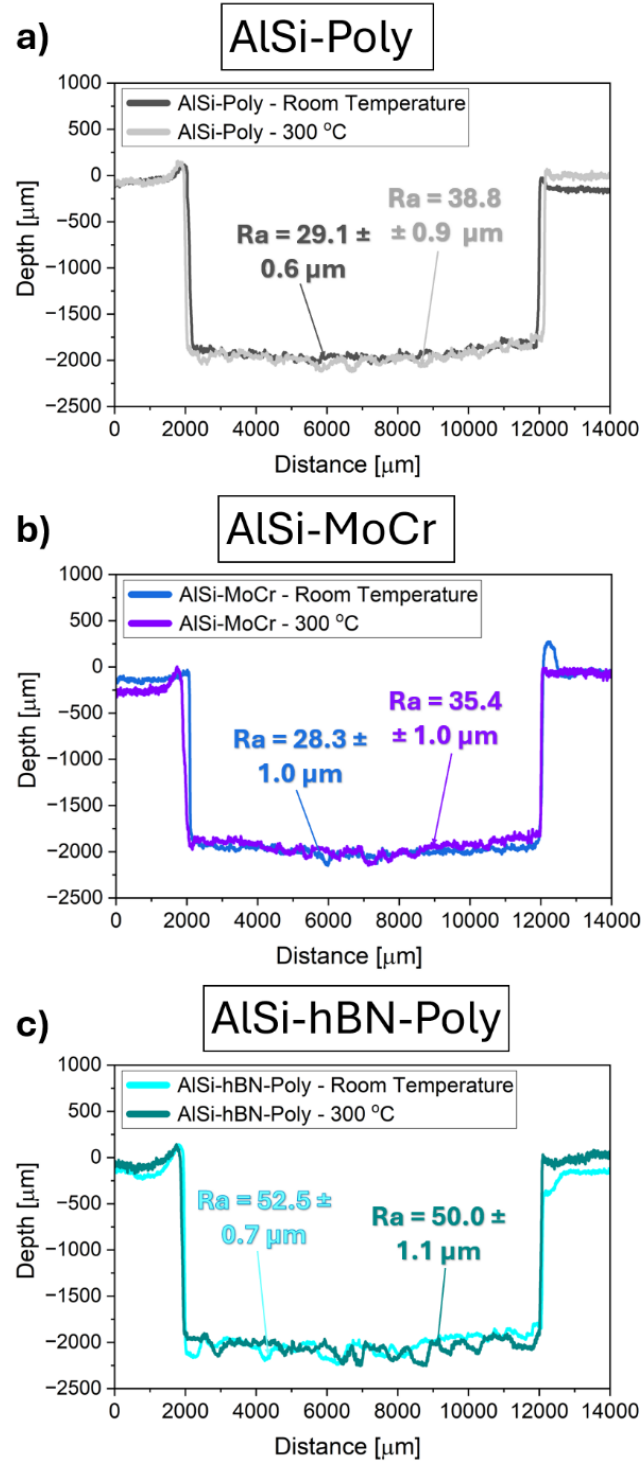


Figure 6.5. Wear track profile of the abrasion-resistant coatings after abrasion tests at room and high temperature; a) AlSi-Poly; b) AlSi-MoCr; c) AlSi-hBN-Poly.

Regarding the roughness measurements after high-temperature abrasion tests, AlSi-Poly and AlSi-MoCr exhibited a notable increase in R_a roughness compared to their room-temperature performance (see Figure 6.6a and b). Specifically, AlSi-Poly showed a 33% increase

in Ra, from $29.1 \pm 0.6 \mu\text{m}$ at RT to $38.8 \pm 0.9 \mu\text{m}$ at 300°C , while AlSi-MoCr exhibited a 25% increase, from $28.3 \pm 1.0 \mu\text{m}$ to $35.4 \pm 1.0 \mu\text{m}$. In contrast, AlSi-hBN-Poly displayed no significant change in Ra, with a slight decrease of 5% from $52.5 \pm 0.7 \mu\text{m}$ at RT to $50.0 \pm 1.1 \mu\text{m}$ at 300°C . This suggests that AlSi-hBN-Poly is less sensitive to the increase in abrasability temperatures, highlighting its greater thermal stability compared to AlSi-Poly and AlSi-MoCr.

In terms of Rz, all coatings showed a slight increase at 300°C , as depicted in Figure 6.6b. The Rz of AlSi-Poly increased from $342.9 \pm 17.7 \mu\text{m}$ at RT to $526.2 \pm 41.2 \mu\text{m}$ at 300°C , while AlSi-MoCr rose from $387.1 \pm 35.4 \mu\text{m}$ to $466.0 \pm 41.3 \mu\text{m}$. AlSi-hBN-Poly also exhibited a marginal increase, from $411.8 \pm 17.6 \mu\text{m}$ to $475.9 \pm 25.6 \mu\text{m}$. These trends indicate that elevated temperatures generally aggravate surface irregularities and deepen wear tracks, particularly for AlSi-Poly and AlSi-MoCr, which demonstrated greater sensitivity to temperature variations during abrasability testing.

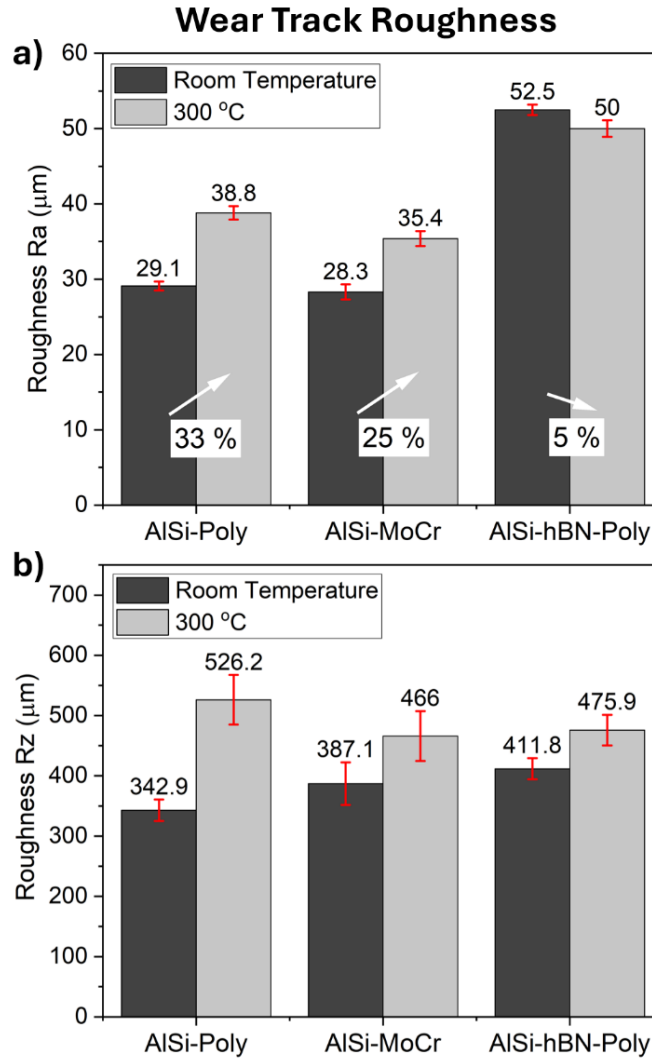


Figure 6.6. Wear track roughness of the abrasible coatings after abrasability tests at room and 300°C ; a) Roughness Ra; b) Roughness Rz.

Figure 6.7 presents SEM and EDS images of the three coatings (AlSi-Poly, AlSi-MoCr, and AlSi-hBN-Poly) tested at both operating temperatures (RT and 300 °C), captured at various magnifications. The wear track images reveal predominant abrasive wear mechanisms, characterized by longitudinal grooves aligned with the direction of motion, as well as smeared layers of the aluminum matrix. This phenomenon aligns with the expected mechanical response of aluminum-based materials under abrasive wear [103,146], where localized plastic deformation occurs and material redistribution are common outcomes.

A comparison of the wear tracks between RT and 300 °C conditions shows equivalent wear mechanisms across all three coatings, with no evidence of cracks and similar smeared regions. Additionally, EDS analysis (Figure 6.7a, d, g, j, m and p) confirmed the absence of titanium (Ti) traces on the wear tracks, indicating no adhesive transfer of material from the Ti6Al4V blade to the AlSi-based coatings. These findings suggest that, even at elevated operating temperatures, no significant variations in the wear track surface were observed. All three coatings demonstrated similar responses to the abrasability tests, with comparable wear patterns and no transfer of blade material to the coatings.

In addition to surface analyses, visual inspections of the substrate–coating interface before and after abrasability tests were also conducted, at both room and high temperatures. The results revealed no evident signs of delamination, cracking, or substrate exposure. Although adhesion strength was not quantitatively measured, the consistent integrity of the coatings across all conditions suggests strong interfacial bonding, regardless of the additive composition tested (MoCr or hBN). These observations support the structural reliability of the coatings under thermal and mechanical loads.

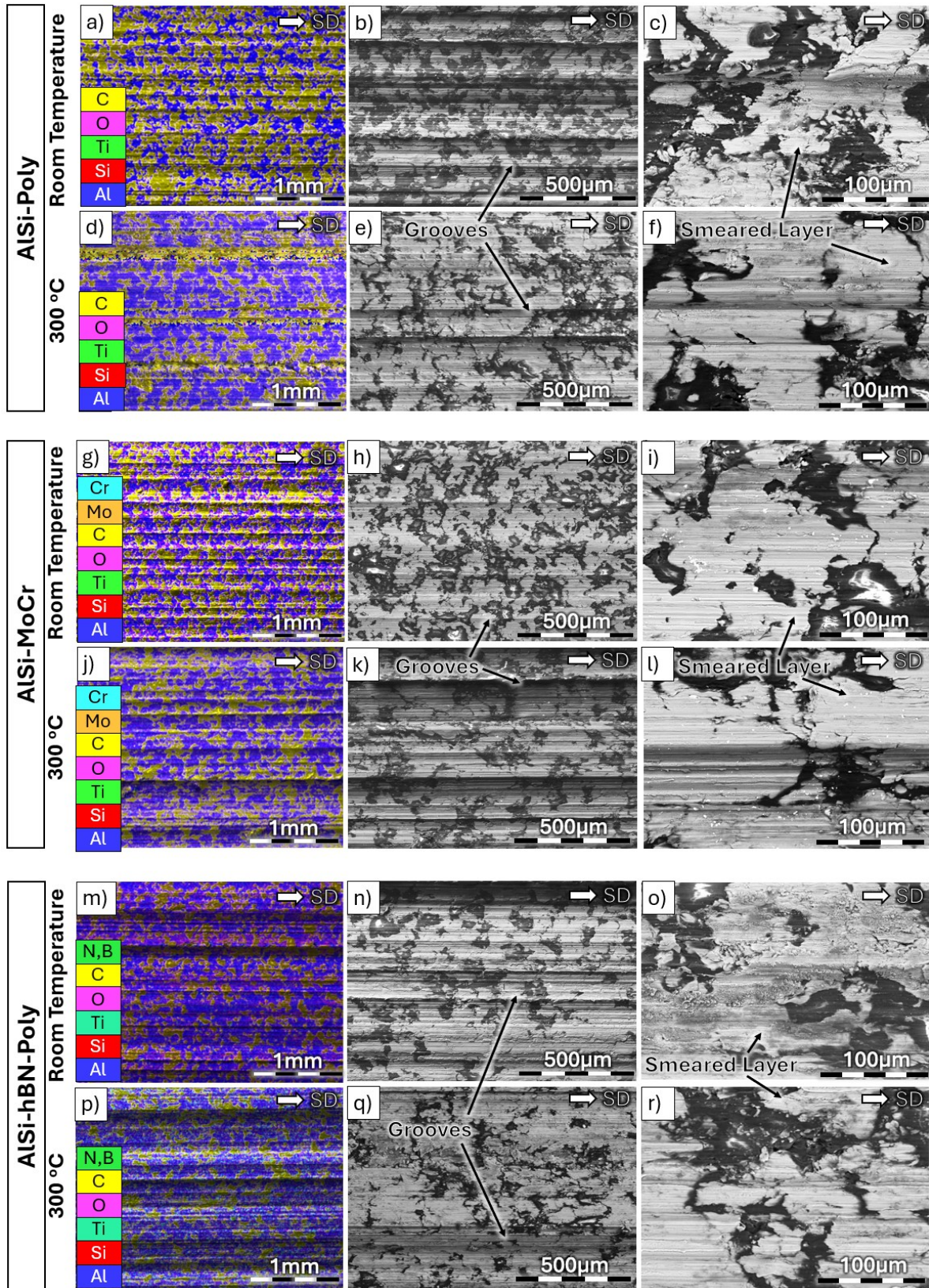


Figure 6.7. SEM images at different magnifications of the rubbed wear tracks of all three abrasion-resistant coatings at different operating temperatures; a-f) AlSi-Poly; g-l) AlSi-MoCr; (m-r) AlSi-hBN-Poly.

6.3.2. Blade Performance Investigation

Figure 6.8 presents the characterization of Ti6Al4V blades after abrasability tests at room temperature and high temperature. The analysis focuses on adhesive transfer behavior, blade wear, and surface modifications. The top surface, front surface, and EDS mapping images of the blades are presented. Room temperature results (Figure 6.8b, c, and d) were reorganized and adapted from previous work [4,5] for comparative analysis with high-temperature tests.

EDS mapping (overlaid on top surface images in Figure 6.8) reveals an adhesive transfer layer deposited on the original titanium material (green). The transfer film primarily consists of aluminum (blue), consistent with the high aluminum content in the abradable coatings. This phenomenon is driven by the adhesive wear mechanism, where material from the softer coating (AlSi-based) transfers to the harder blade (Ti6Al4V) due to frictional forces and localized heating. Traces of carbon (indicative of polyester transfer) were also detected (yellow), more prominently in blades tested against AlSi-Poly and AlSi-MoCr coatings, which have higher initial polyester concentrations compared to AlSi-hBN-Poly.

The amount of adhesive transfer observed at 300 °C was relatively equivalent across all three coatings. However, compared to RT tests, a slightly higher adhesive transfer was noted at elevated temperature. Interestingly, blades tested at 300 °C exhibited longitudinal abrasive marks aligned with the sliding direction, which were absent in RT tests. These marks are attributed to the plastic deformation of polyester transferred from the abradable coatings during earlier rubbing passes, as confirmed by EDS mapping, which associates the marks with carbon. Front surface images and visual inspection further support this observation.

In terms of blade wear, no significant material loss or structural damage was observed on any of the Ti6Al4V blades tested at either room temperature (RT) or 300 °C. This conclusion is supported by the absence of visible surface deformation or valleys in the front surface microscopy images, as well as by the EDS mappings. These observations suggest that the interaction between the blade and the abradable coatings remained within acceptable limits, with wear processes dominated by adhesive transfer and limited abrasive marks. The consistency across all three coatings and both temperature regimes highlights the thermal stability of Ti6Al4V blades at 300 °C and the abradable materials, regardless of the presence of MoCr or hBN in the coatings.

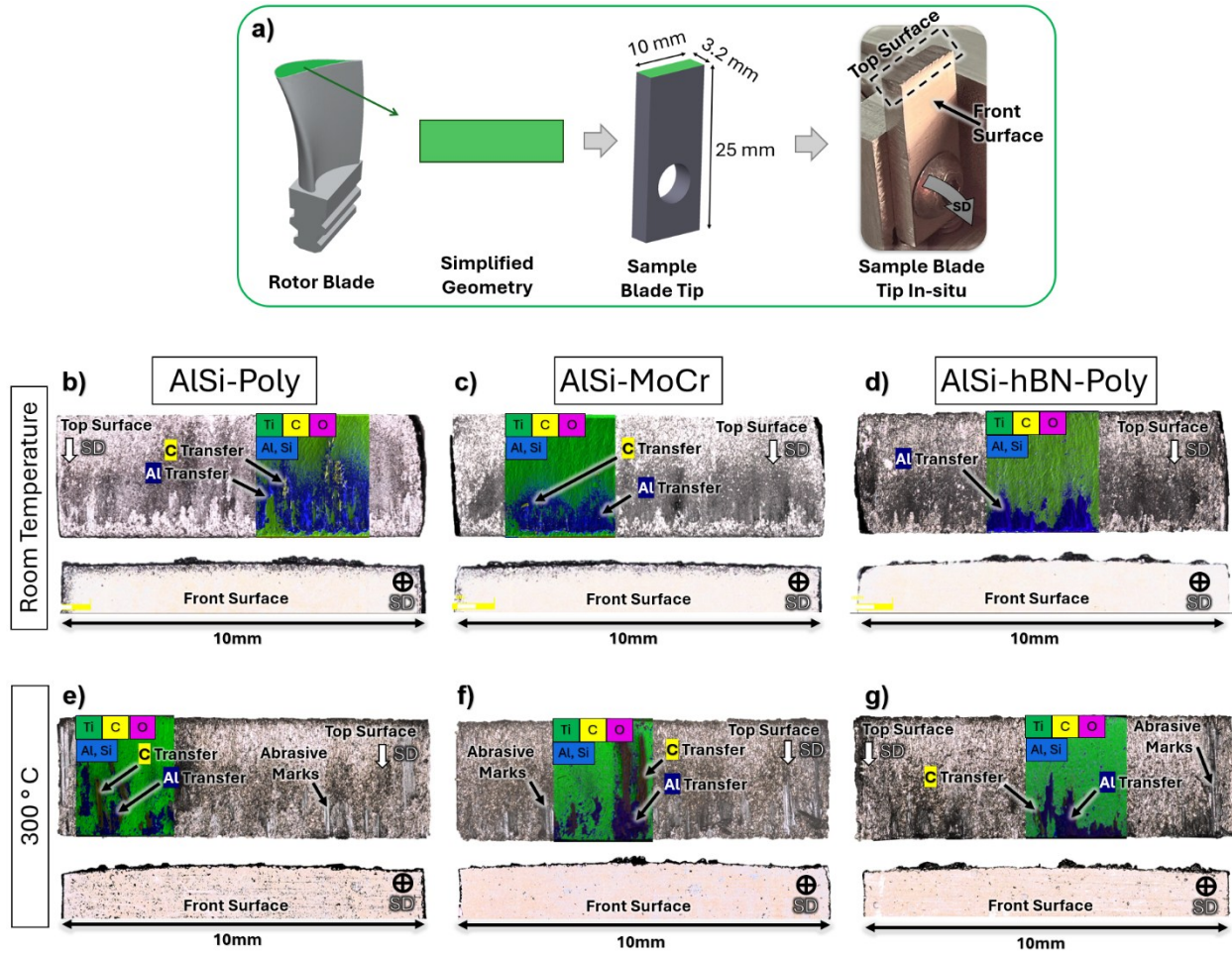


Figure 6.8. Characterization of Ti6Al4V blades after abrasability tests; a) Schematic of blade geometry and image positioning; b-g) Top surface, front surface, and EDS mapping of each blade after abrasability tests under different operational temperatures and coatings.

6.3.3. Reaction Forces and Rubbing Temperature

Figure 6.9 and Figure 6.10 present the reaction forces for AlSi-Poly, AlSi-MoCr, and AlSi-hBN-Poly coatings during abrasability tests at RT and 300 °C. Lower reaction forces are critical for minimizing damage to compressor blades during engine operation [36]. The results show a significant reduction in average normal reaction forces (Figure 6.9a) at 300 °C compared to RT. The ratio of normal forces between RT and 300 °C was 1.9 for AlSi-Poly, 2.2 for AlSi-MoCr, and 3.4 for AlSi-hBN-Poly, indicating reductions of approximately 50% for AlSi-Poly and AlSi-MoCr, and 70% for AlSi-hBN-Poly. These findings show the significant impact of temperature on reducing normal reaction forces (F_n), primarily due to the thermal softening of Al-based abrasable coatings, as supported by previous studies [105,214]. Despite the higher reduction in AlSi-hBN-Poly, the coating still exhibited higher absolute normal forces compared to the other

coatings, which can be associated with the higher initial hardness of AlSi-hBN-Poly and the lower amount of polyester.

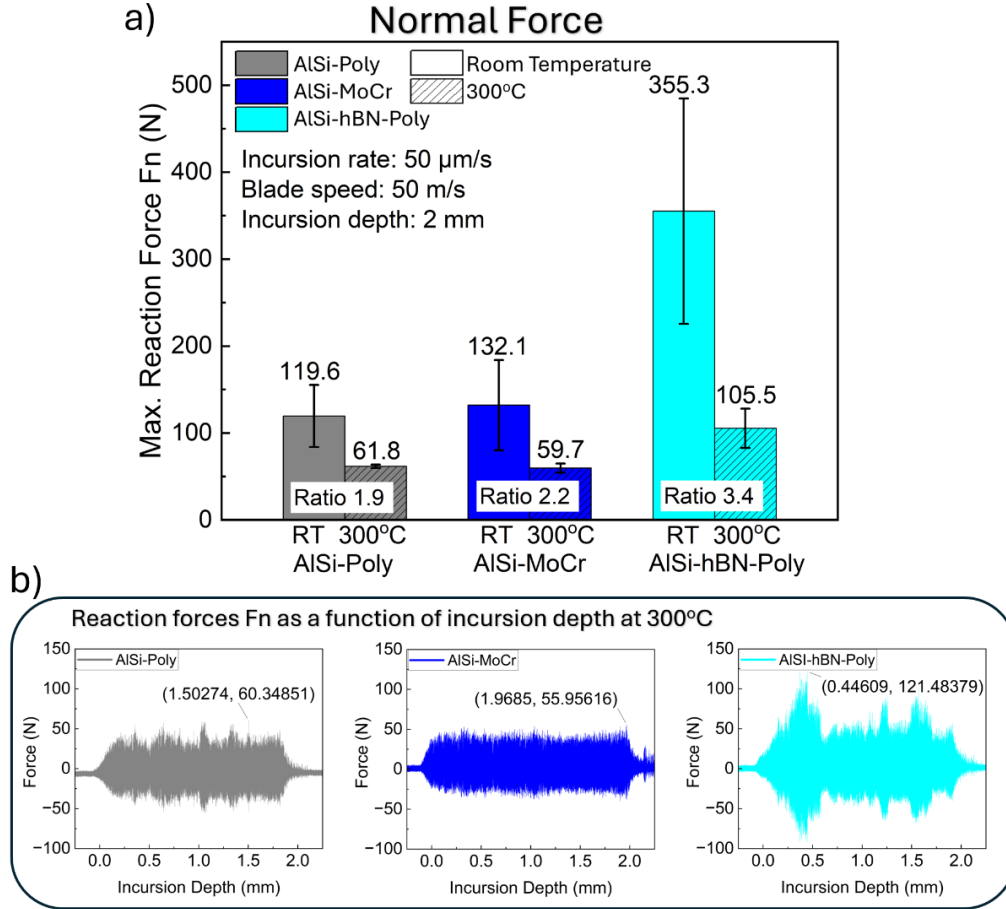


Figure 6.9. Normal reaction forces of the abradable coatings; a) Maximum normal reaction force at RT and 300 °C; b) Normal force impulses as a function of rubbing depth for each abradable coating tested at 300 °C.

For tangential forces (Figure 6.10), AlSi-Poly and AlSi-MoCr showed RT/HT ratios of 1.3 and 1.4, respectively, while AlSi-hBN-Poly had a ratio of 2.7. However, considering the error bars generated from repeated tests suggests that the maximum tangential forces (F_t) for all coatings were equivalent between 300 °C and RT. Moreover, AlSi-hBN-Poly displayed higher absolute tangential forces and greater error bars, particularly at RT, likely due to the higher heterogeneity of the coating and consequent higher force pulse variations across the incursion depth. The higher friction dynamics oscillations observed on AlSi-hBN-Poly at RT were also observed and discussed in a previous study [4].

Figure 6.9b and Figure 6.10b illustrate the reaction force pulses as a function of incursion depth under high-temperature conditions for all three coatings. AlSi-Poly and AlSi-MoCr exhibit relatively stable reaction force behavior throughout the incursion depth, consistent with findings from the literature for both room-temperature [147] and high-temperature [117] testing. However,

AlSi-hBN-Poly shows more pronounced fluctuations, which is expected due to the high heterogeneity of its composite microstructure, which includes metallic (AlSi), polymeric (polyester), and ceramic (hBN) phases, and its higher coating hardness compared to AlSi-Poly and AlSi-MoCr.

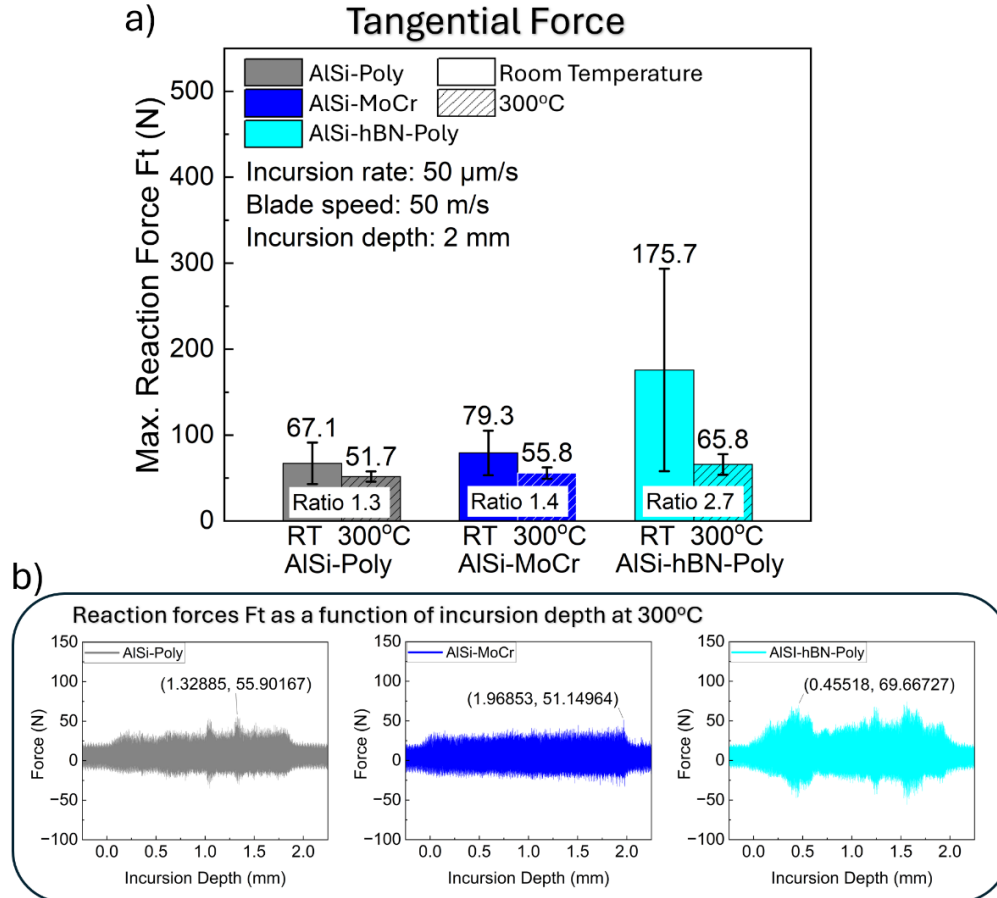


Figure 6.10. Tangential reaction forces of the abradable coatings; a) Maximum tangential reaction force at RT and 300 °C; b) Tangential force impulses as a function of rubbing depth for each abradable coating tested at 300 °C.

To support the interpretation of abradability performance, statistical analyses were performed on the measured reaction forces and presented in Table 6.3 and Table 6.4. The procedure involved two complementary stages: (i) comparison of each coating with the baseline under identical test conditions (Table 6.3), and (ii) assessment of temperature influence through within-coating comparisons between RT and 300 °C (Table 6.4).

Table 6.3 shows that AlSi-MoCr did not differ significantly from AlSi-Poly for either normal or tangential forces at RT and 300 °C ($p = 0.582\text{--}0.749$), with small-to-moderate effect sizes (Cohen's $d = 0.28\text{--}0.71$), supporting practical equivalence between these compositions. By contrast, AlSi-hBN-Poly exhibited substantially larger reaction forces: the RT normal-force difference is statistically significant ($p = 0.049$) with a very large effect ($d = 2.95$), while comparisons at 300 °C and for tangential forces show large effect sizes ($d = 2.72$) despite $p > 0.05$. Collectively, these outcomes indicate that minor MoCr additions preserve baseline abradability,

whereas the coating with hBN produces a marked and practically meaningful change, most clearly manifested in normal loading at RT.

Table 6.3. Statistical comparison of abrasability reaction forces between each coating and the baseline (AlSi-Poly) under both temperature conditions, showing p-values, effect sizes (Cohen's d), and significance interpretation.

Material Comparison	Force Type	Temp.	p-value	Cohen's d	Statistical Interpretation Regarding Reaction Forces
AlSi-MoCr vs AlSi-Poly	Normal	RT	0.749	0.28	No statistically significant difference; small effect size, suggesting potential practical equivalence [5].
		300 °C	0.668	0.71	Not statistically significant; moderate effect size, suggesting potential practical equivalence.
	Tangential	RT	0.583	0.49	No statistical difference; small-to-moderate effect, suggesting potential practical equivalence [5].
		300 °C	0.582	0.65	Not statistically significant; moderate effect size, suggesting potential practical equivalence.
AlSi-hBN-Poly vs AlSi-Poly	Normal	RT	0.049	2.95	Statistically significant difference ($p < 0.05$); very large effect size, indicating substantially higher reaction forces.
		300 °C	0.113	2.72	Not statistically significant ($p > 0.05$) but very large effect size, suggesting a pronounced practical difference.
	Tangential	RT	0.192	1.54	Not statistically significant; large effect size, suggesting potential practical difference.
		300 °C	0.272	1.50	Not statistically significant; large effect size, suggesting potential practical difference.

Temperature comparisons (Table 6.4) further contextualize these findings. Although none of the RT vs. 300 °C tests presented formal statistical significance (all $p > 0.05$), the effect sizes for normal forces are large to very large across coatings ($d \approx 1.70$ – 2.68), consistent with the observed ~50–70% reductions in normal force at elevated temperature. Tangential-force effect sizes are moderate-to-large ($d \approx 0.77$ – 1.43), indicating a meaningful but smaller temperature dependence. In short, limited sample sizes reduce statistical power, yet the concurrence of non-significant p-values and large effect sizes points to a clear, practically relevant thermal softening effect, particularly for normal forces.

Table 6.4. Statistical comparison of abrasability reaction forces between room temperature (RT) and 300 °C for each abrasable coating, showing p-values, effect sizes (Cohen's d), and significance interpretation.

Temperature Comparison	Material	Force Type	p-value	Cohen's d	Statistical Interpretation Regarding Reaction Forces
RT vs 300 °C	AlSi-Poly	Normal	0.118	1.98	Not statistically significant; very large effect size, suggesting a pronounced practical difference.
		Tangential	0.462	0.77	Not statistically significant; moderate-to-large effect size, suggesting potential practical difference.
	AlSi-MoCr	Normal	0.160	1.70	Not statistically significant; very large effect size, suggesting a pronounced practical difference.
		Tangential	0.317	1.09	Not statistically significant; large effect size, suggesting potential practical difference.
	AlSi-hBN-Poly	Normal	0.115	2.68	Not statistically significant; very large effect size, suggesting a pronounced practical difference.
		Tangential	0.320	1.43	Not statistically significant; large effect size, suggesting potential practical difference.

In terms of rubbing temperature, the surface of each coating was continuously monitored throughout the abrasability tests, as presented in Figure 6.11 and schematically represented in Figure 6.11c. For room temperature tests, Figure 6.11a illustrates the evolution of surface rubbing temperature as a function of incursion depth (data adapted from [4,5] for comparative analysis). Results show that all three coatings exhibited a rapid temperature rise at the beginning of the rubbing test, reaching approximately 45°C within the first 0.25 mm of incursion. As the incursion progressed, the temperature continued to increase with some fluctuations, reaching its highest point at the end of the 2 mm depth. AlSi-hBN-Poly showed the highest rubbing temperature (61.2°C), followed by AlSi-MoCr (56°C) and AlSi-Poly (53.7°C), which aligns with the observed reaction forces at RT. Additionally, the temperature drop observed at the end of the test corresponds to the cessation of frictional heating upon completion of the blade-abrasable interaction at 2 mm incursion depth.

Figure 6.11b illustrates the variation in surface rubbing temperature at tests at an initial $300^{\circ}\text{C} \pm 25^{\circ}\text{C}$ as a function of incursion depth, starting from the non-contact position (-2 mm) up to the maximum incursion depth of 2 mm, as schematically represented in Figure 6.11d. The temperature monitoring revealed that all coatings initially started within the range of $300 \pm 25^{\circ}\text{C}$. As the blade began rotating, the surface temperature of the coatings decreased due to enhanced convective heat transfer caused by the blade's motion, with no rubbing interaction occurring yet.

This cooling effect is expected, as the rotating blade increases airflow and heat dissipation from the coating surface.

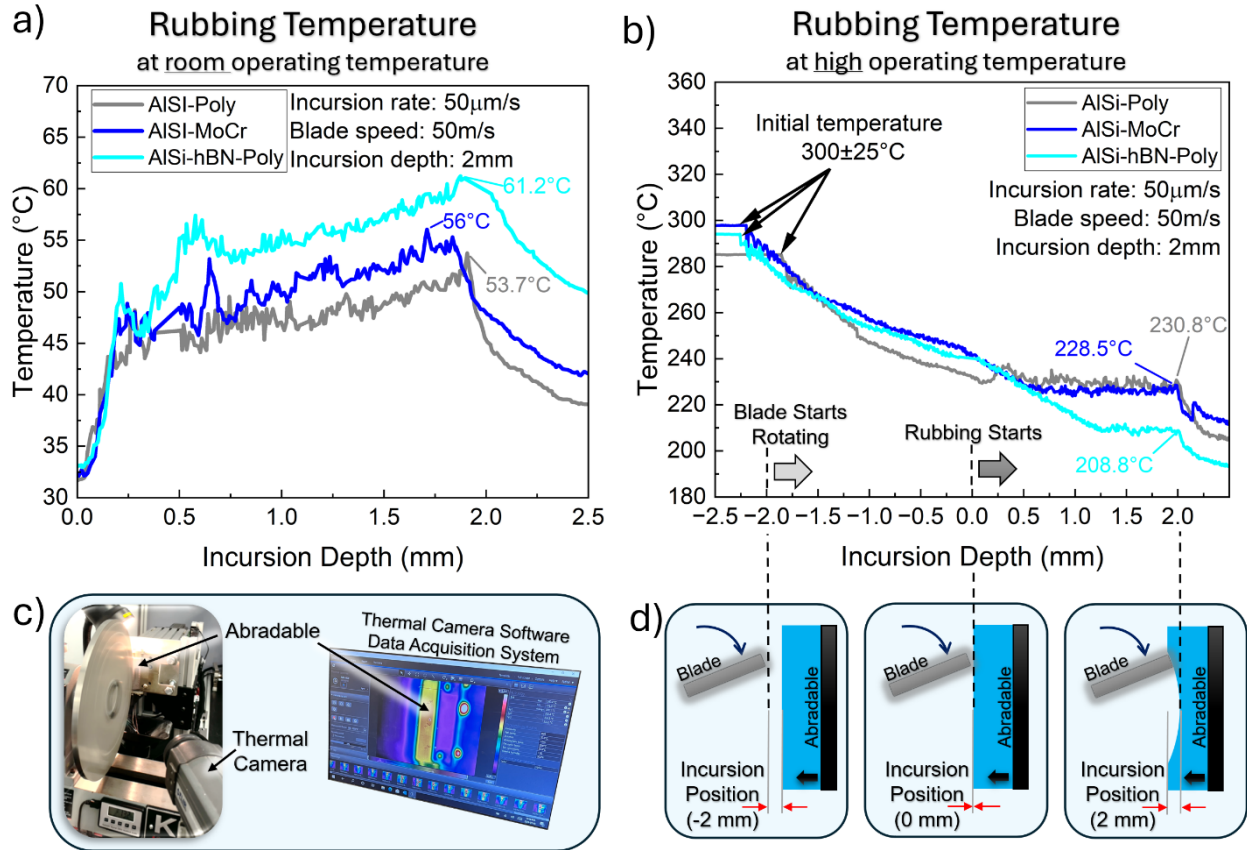


Figure 6.11. Surface rubbing temperature of the coatings under different operating conditions; a) Room temperature test; b) High temperature test; c) Schematic representation of the rubbing temperature measurement; d) Schematic representation of the incursion position of the blade-abradable interaction.

The temperature profiles of AISi-Poly and AISi-MoCr stabilized around 230°C once the incursion unit initiated movement and the rubbing began (at the 0 mm incursion position). At this stage, some fluctuations in the temperature were observed until the end of the 2 mm incursion depth. Although no significant increase in absolute temperature was noted, the frictional heating generated during the blade-abradable interaction compensated the cooling effect of the rotating disk, maintaining a relatively stable temperature range. This balance between frictional heating and convective cooling highlights the thermal dynamics complexity of the system. Moreover, AISi-hBN-Poly exhibited a distinct temperature behavior. After rubbing was initiated, its temperature continued to decrease until approximately 1.25 mm of incursion depth, after which it stabilized around 208°C, with some fluctuations until the test concluded at 2 mm. This behavior may be attributed to the thermal stability and lubricating properties of hBN at higher temperature regimes [215,216].

6.4. Discussion

6.4.1. High-Temperature Module Performance

The high-temperature module developed for this study proved to be a valuable tool for evaluating abradable coatings under extreme operating conditions, effectively replicating realistic gas turbine environments and advancing the TRL development of abradable materials. The integration of heating elements and insulation ensured successful heat transfer to the abradable sample, while precise temperature regulation enabled consistent heating, as presented in Figure 6.3 and Figure 6.11. Additionally, the system's ability to maintain force measurement stability ensured reliable tribological assessments at elevated temperatures (Figure 6.9 and Figure 6.10). However, an operational challenge identified was the cooling effect, which was caused by the airflow generated by the rotating disk during rig operation, potentially influencing thermal conditions at the contact interface. This factor was carefully considered when analyzing rubbing tests and frictional heating (Figure 6.11b). Overall, the high-temperature module significantly improved the assessment of abradability performance in demanding environments, supporting future investigations into high-temperature wear mechanisms and abradability behavior.

6.4.2. Coating Investigation

In terms of wear track roughness evaluation, the results from abradability tests demonstrated that AlSi-hBN-Poly exhibited, on both operating temperature conditions (RT and 300 °C), overall higher roughness values (Ra and Rz) compared to AlSi-Poly and AlSi-MoCr, leading to more pronounced abrasive grooving (Figure 6.5 and Figure 6.6). This can be attributed to the lower polyester content and the higher rubbing reaction forces associated with the AlSi-hBN-Poly coating. Previous studies [17,146] have also reported a direct correlation between increased wear track roughness and higher rubbing forces during blade-abradable interactions.

At 300 °C, the results of both AlSi-Poly and AlSi-MoCr coatings exhibited an increase in roughness, as indicated by the Ra and Rz measurements (Figure 6.6). These results suggest that elevated temperatures enhance thermal softening, which in turn promotes more adhesive transfer from the aluminum-based coating to the titanium blade during the blade-abradable interaction. As a result, leading to an increase in surface irregularities on the coating wear track (Figure 6.5). This behavior aligns with findings from Martinet et al [105], who reported that at high temperatures, the softening of polymeric binders in the aluminum-polyester alloy alters wear mechanisms, increasing plastic deformation and adhesive interactions, which in turn generate rougher and more irregular wear scars. Furthermore, on a Cobalt-Nickel-based alloy, Dadouche et al [17] observed that tests at higher temperatures produced wear scars that were significantly rougher and more

irregular due to tearing and spalling. Reinforcing the significant role of temperature in modifying wear track morphology even at different chemical compositions.

Interestingly, the AlSi-hBN-Poly coating exhibited minimal changes in roughness under tests at 300 °C (Figure 6.5 and Figure 6.6), suggesting two key factors. First, the presence of hBN enhances the coating's ability to maintain surface morphology at elevated temperatures due to its high thermal stability and self-lubricating properties. Second, the lower polyester content in AlSi-hBN-Poly reduces the influence of polymeric softening, leading to less pronounced changes in wear track morphology at higher temperatures compared to AlSi-Poly and AlSi-MoCr. Similar behavior has been reported in the literature, such as in the study by Sun et al [100], which discusses that hBN-containing coating forms a self-lubricating protective film at high temperatures. This film reduces the friction coefficient, improving wear resistance and making hBN-based coatings effective as sealing materials in high-temperature applications.

These findings on wear track roughness underscore the importance of service temperature in influencing abrasability performance. While AlSi-Poly and AlSi-MoCr showed superior smoothness at RT, their performance degraded at elevated temperature, whereas AlSi-hBN-Poly maintained consistent roughness levels across temperatures. This indicates that AlSi-hBN-Poly may be more suitable for applications involving significant thermal fluctuations, despite its inherently higher roughness compared to the other coatings.

Additionally, the negligible blade wear across all tested conditions highlights the mechanical robustness and thermal stability of the Ti6Al4V blade under typical LPC conditions. Furthermore, the results affirm the suitability of all tested coatings in providing a sacrificial function without compromising blade integrity, which is essential for reliable engine operation. This outcome is especially relevant for AlSi-hBN-Poly, which, despite showing higher roughness and force fluctuations, did not result in increased blade wear.

6.4.3. Blade-Abradable Interaction

With regard to force measurements, the findings suggest that elevated operating temperatures reduce reaction forces, potentially due to thermal softening of the coatings and enhanced lubricity. Liu et al [25] also observed a similar behavior, where increasing operating temperature led to lower reaction forces, and consequently improved abrasability performance in Al-based coatings.

At RT, limited thermal softening resulted in a predominantly abrasive wear mechanism, with higher reaction forces contributing to rougher wear track surfaces [4,5]. In contrast, at 300 °C, the surface roughness (Figure 6.6) increased while reaction forces (Figure 6.9 and Figure 6.10) decreased, indicating enhanced material plasticity. The elevated operating temperature reduced the coating's yield strength, allowing asperities to deform more easily under the applied load. This led

to a decrease in both the maximum tangential (F_t) and normal (F_n) reaction forces (Figure 6.9 and Figure 6.10), as the softened material offered reduced mechanical resistance. These findings align with previous studies [105,214], such as Dadouche et al [17] who also observed that roughness and rub forces are significantly influenced by operating temperature, further validating the observed temperature-dependent wear behavior.

In terms of coating evaluation, particularly for AlSi-Poly and AlSi-MoCr, which contain higher polyester content (Table 6.1), a significant thermal softening effect of the polymeric phase was expected at 300 °C, as observed by [104,130] on similar alloys. This softening likely reduced the overall friction, resulting in lower tangential forces, which overcame the expected increase in tangential force due to the higher adhesive wear of aluminum, typically more pronounced at elevated temperatures. The adhesion behavior of aluminum over titanium, a key factor in this process (Figure 6.8), has been extensively discussed by Wu et al [162] in a comparable friction study, providing an understanding of the mechanisms driving the friction behavior.

On the other hand, despite the higher absolute reaction forces observed for AlSi-hBN-Poly compared to AlSi-Poly and AlSi-MoCr, AlSi-hBN-Poly exhibited the greatest reduction in forces between 300 °C and RT tests, with a normal force reduction of about 70% and a tangential force reduction of approximately 60%. This significant decrease can be attributed to the thermal stability of hBN's lubricating properties, which become more effective at elevated temperatures, as previously reported in the literature [45,217]. However, AlSi-hBN-Poly also showed greater fluctuations in force measurements (Figure 6.9b and Figure 6.10b), which was expected due to the high heterogeneity of the composite coating, especially considering the presence of metallic (AlSi), polymeric (polyester) and ceramic (hBN) phases in its microstructure, and consequently leading to localized variations during wear [4,117]. Furthermore, the intensity and variation of these impulses are often associated with coating hardness [31], which was found to be higher for AlSi-hBN-Poly coating (Table 6.1).

Interestingly, the dynamic interaction coefficient (F_t/F_n), representing the ratio of maximum tangential forces (Figure 6.10) to maximum normal forces (Figure 6.9) during blade-abradable interactions, provides critical insights into the temperature-dependent frictional behavior of the coatings. As shown in Figure 6.12, all coatings demonstrated increased F_t/F_n values when transitioning from RT to 300°C, indicating the critical role of operating temperature in dictating abrasability performance and material dynamics.

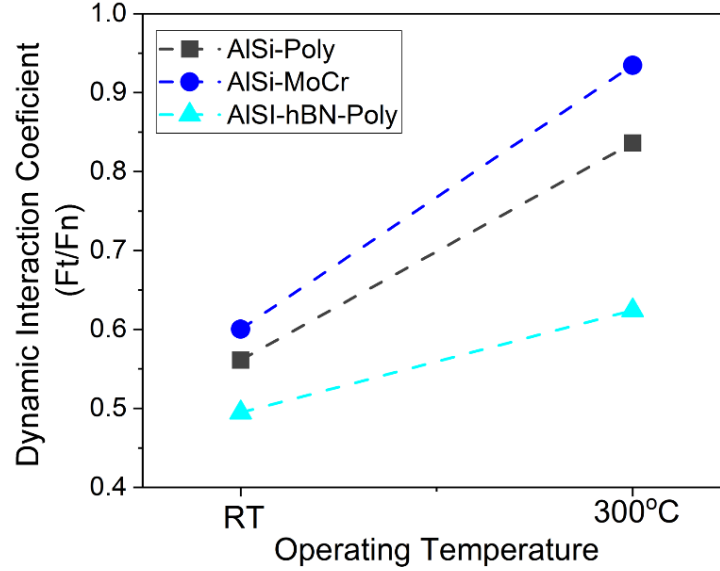


Figure 6.12. Dynamic interaction coefficient (F_t/F_n) of the AlSi-based abrasible coatings under different operating temperatures.

Among the coatings tested, AlSi-Poly and AlSi-MoCr exhibited the most pronounced increase in F_t/F_n , with values rising from approximately 0.6 to 0.9. This behavior can be attributed to the thermal softening of their higher polyester content (40 wt%) compared to AlSi-hBN-Poly. Conversely, AlSi-hBN-Poly exhibited a more moderate increase (from about 0.5 to 0.6), reflecting the combined effects of its lower polyester content (20 wt%) and the lubricating properties of hBN, despite the coating's inherently higher surface roughness, as observed in Figure 6.5.

The observed trend in the F_t/F_n aligns with established findings in the literature [105], where elevated temperatures produced higher F_t/F_n ratios. According to Martinet et al [105], this phenomenon reflects a transition in wear mechanisms, as temperatures increase, the dominant material response shifts from brittle cutting to ductile deformation. Specifically, for coatings containing polyester (PE), when temperatures exceed 125 °C, the thermal softening and enhanced adhesion of PE significantly increase the energy required for plastic deformation, promoting adiabatic shearing. This mechanism explains the pronounced F_t/F_n increase observed in this study for AlSi-Poly and AlSi-MoCr, and the greater accumulation of carbon traces observed in the chemical mapping analysis of blade top surfaces under 300 °C (Figure 6.8).

Additionally, the rubbing temperature measurements from tests at 300°C revealed distinct thermal behaviors among the coatings (Figure 6.11), highlighting the complex interplay between material composition and abrasability performance. AlSi-hBN-Poly exhibited less sensitivity to frictional heating during the rubbing interaction at 300 °C compared to AlSi-Poly and AlSi-MoCr. The temperature profile (Figure 6.11b) of AlSi-hBN-Poly suggests its superior thermal management capabilities under high-temperature conditions, likely due to the combined effects of hBN's lubricity, the thermal stability of ceramic phase (6% hBN), and the reduced content of polymeric phase in the coating microstructure. Emphasizing how strategic material design can also enhance the performance of abrasible coatings in high-temperature applications.

6.5. Conclusions

This study successfully demonstrated the development and application of a high-temperature abrasion test rig capable of simulating extreme aeroengine conditions at 300 °C. The integration of the HT module enabled a more realistic and cost-effective tribological approach to assess the blade-abrasion interaction. It may support the development of green-engineered abrasives for efficient and sustainable propulsion, including gas turbine and hydrogen-compatible turbines.

The evaluation of three AlSi-based thermally sprayed coatings (AlSi-Poly, AlSi-MoCr, and AlSi-hBN-Poly) under both RT and 300 °C revealed distinct temperature-dependent performance characteristics. Overall, an increase in test temperature to 300 °C led to a substantial reduction in both reaction forces (F_t and F_n) for all coatings, attributed primarily to the thermal softening of the polymeric phase. Such force reductions may translate to improved efficiency and reduced mechanical wear in operational engines. Additionally, negligible blade wear was observed under all tested conditions.

Material composition played a decisive role in tribological performance at elevated temperature. AlSi-Poly and AlSi-MoCr showed greater increases in surface roughness and F_t/F_n ratios, due to significant softening of their higher polyester content and adhesive behavior. On the other hand, in the AlSi-hBN-Poly coating, the inclusion of hBN and its self-lubricating and thermally stable characteristics reflected in more consistent wear track roughness values and reduced sensitivity to frictional heating. Despite slightly higher absolute forces, AlSi-hBN-Poly demonstrated the greatest percentage reduction in force levels along with the smallest increase in the F_t/F_n ratio.

Overall, the current rig proved effective in bridging laboratory-scale tests and operational aeroengine environments. Among the coatings, AlSi-hBN-Poly is highlighted by its thermal stability. Meanwhile, AlSi-MoCr performed comparably to the baseline AlSi-Poly, confirming its potential as a reliable alternative across both room and elevated temperature conditions.

While the present study focused on wear and thermal interactions, additional performance factors should be explored in future studies to advance OEMs (Original Equipment Manufacturers) and industrial integration and certification processes under aerospace standards. In particular, future research should assess the corrosion and erosion resistance, as well as the corrosion–erosion interplay of these AlSi-based coatings at elevated temperatures. These properties are critical for long-term coating reliability and are essential for qualification in operational turbine environments. Additionally, as an emerging trend in the field of abrasion and composite materials, there is a need to explore hybrid strategies combining thermal spraying and additive manufacturing (3D printing), as well as incorporating numerical modeling, particularly simulations of thermal gradients and mechanical stress, aiming to enhance performance, repairability, and sustainability in next-generation aviation systems.

Conclusions and Recommendations

7.1. Summary and Conclusions

This PhD thesis advances the science and engineering of abradable coatings through two complementary contributions: (1) the development and validation of an innovative testing methodology for abrasability assessment, and (2) a systematic, multi-TRL evaluation of three AlSi-based coatings under simulated aerospace-relevant conditions.

The first major achievement was the design and fabrication of a cost-effective abradable test rig capable of closely replicating LPC rubbing conditions. During the research, the rig was upgraded with a high-temperature module, enabling performance evaluation across the LPC service temperature range. The system combines operational flexibility, allowing cost-effective and rapid adaptation to different coating types, with the capability to generate high-quality direct outputs (normal and tangential reaction forces, interfacial rubbing temperature) and indirect diagnostic data when paired with post-test characterization (wear-track morphology, debris characteristics, adhesive transfer, blade wear). These results can be quantitatively correlated with standard tribological tests and benchmarked against data from large, custom-built reference rigs. The developed rig therefore provides a rapid, lower-cost pre-screening platform to accelerate TRL progression and improve the efficiency of abradable material qualification.

The second key contribution relates to in-depth material evaluation. Three thermally sprayed AlSi-based coatings were produced and assessed across multiple TRL stages. Starting with microstructural characterization and property measurements (TRL 2), progressing to proof-of-concept validation through standard tribological tests such as ball-on-flat and ball-on-disk (TRL 3), and culminating in subscale, component-relevant testing at RT and 300 °C using the developed abradable rig (TRL 4). The main findings are as follows:

- AlSi-Poly (baseline) – AlSi + 40 wt% polyester. Exhibited uniform filler distribution, balanced performance (CoF ~0.3, smooth cutting, negligible blade damage), and normal reaction forces around 120 N. At elevated temperature (300 °C), polyester softening reduced normal forces by ~50% but increased wear-track Ra roughness by ~33% and the F_t/F_n ratio from 0.6 to 0.9, indicating temperature sensitivity of polyester-rich systems. These results suggest that elevated temperatures reduce the coating's yield strength and promote thermal softening, allowing asperities to deform more easily under load and increasing adhesive transfer from the aluminum-based coating to the titanium blade during interaction.

- **AlSi-MoCr** – AlSi with minor MoCr additions. Displayed microstructural characteristics, hardness, and as-sprayed roughness comparable to the baseline. Tribological and abrasability metrics were also similar, with only minor increases in aluminum transfer to titanium blades and negligible blade damage. Like the baseline, 300 °C abrasability tests showed higher Ft/Fn ratios and surface roughness, mainly due to polyester softening and adhesive effects. These results indicate that small MoCr additions may enhance corrosion and oxidation resistance without compromising abrasability.
- **AlSi-hBN-Poly** – AlSi + 6 wt% hBN + reduced polyester. Contained uniformly distributed hBN, lower total filler content, and higher HR15Y hardness than the baseline. At TRL 3, it exhibited higher sliding wear due to hBN-induced debris generation, along with higher reaction forces and frictional heating at TRL 4 under room-temperature testing. However, at 300 °C, it outperformed all other systems in relative normal force reduction (~70%) and exhibited the smallest roughness variation (~5%), highlighting hBN’s solid-lubricating properties and thermal stability. These results reveal a trade-off: hBN addition and polyester reduction increase room-temperature wear and abrasability reaction forces, but enhance high-temperature stability.

A synthesized performance comparison of the three coatings against baseline LPC requirements is presented in Figure 7.1, offering a concise visual benchmark of their relative strengths and limitations.

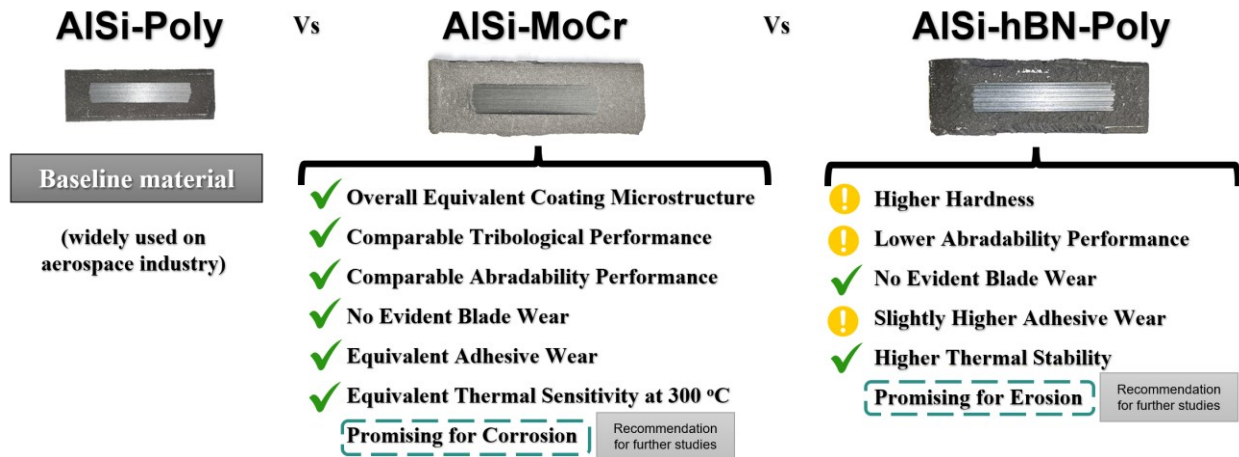


Figure 7.1. Abradable coating performance summary.

Additionally, a detailed cross-comparison of the tribological, abrasability, and thermal performance of the three AlSi-based abradable coatings is tabulated and summarized in Table 7.1, providing a clear benchmark of their behavior across different TRLs. The table consolidates critical results on wear behavior, reaction forces, surface finish evolution, and thermal sensitivity, enabling direct evaluation of performance trade-offs. This comparative matrix highlights not only the relative advantages of each coating but also key wear mechanisms and material responses that enhance abradable coating understanding.

Table 7.1. Performance matrix of AlSi-based abradable coatings across different TRLs and thermal response.

Coating	Tribological Performance (TRL 3)	Abradability Performance (TRL 4)	Thermal Response (TRL 4 at 300°C)
AlSi-Poly	- Max. wear depth: 28-60 μm - CoF: 0.29-0.32 - Wear mechanism: Cracks, abrasive marks, loose debris, and tribofilms formation - Counterface: Negligible wear and minor Al transfer	- Normal force: $119.6 \pm 35.7 \text{ N}$ - Tang. force: $67.1 \pm 24.2 \text{ N}$ - Ft/Fn ratio: ~ 0.6 - Surface finish: Smooth cutting (Ra: $29.1 \pm 0.6 \mu\text{m}$) - Wear mechanism: Abrasive marks and smeared surface - Blade: Negligible wear and minor Al transfer	- Normal force reduction compared to RT: $\sim 50\%$ - Ft/Fn ratio: ~ 0.9 - Surface finish Ra: $38.8 \pm 0.9 \mu\text{m}$ ($\sim 33\%$ increase compared to RT) - Wear mechanism: Equivalent to RT - Key thermal response: Polyester softening-induced plasticity
AlSi-MoCr	- Max. wear depth: 28-60 μm ($\approx$baseline) - CoF: 0.25–0.29 - Wear mechanism: Cracks, abrasive marks, loose debris, tribofilm formation, smeared layer, and microcracks - Counterface: Negligible wear	- Normal force: $132.1 \pm 51.9 \text{ N}$ ($\approx$baseline) - Tang. force: $79.3 \pm 25.9 \text{ N}$ ($\approx$baseline) - Ft/Fn ratio: ~ 0.6 ($\approx$baseline) - Surface finish: Smooth cutting (Ra: $28.3 \pm 1.0 \mu\text{m}$) ($\approx$baseline) - Wear mechanism: Abrasive marks and smeared surface ($\approx$baseline) - Blade: Negligible wear and minor Al transfer ($\approx$baseline)	- Normal force reduction compared to RT: $\sim 50\%$ ($\approx$baseline) - Surface finish Ra: $35.4 \pm 1.0 \mu\text{m}$ ($\sim 25\%$ increase compared to RT) - Wear mechanism: Equivalent to RT - Key thermal response: Equivalent thermal sensitivity to baseline
AlSi-hBN-Poly	- Max. wear depth: 158-227 μm (~ 380-560% of the baseline) - CoF: 0.31–0.32 - Wear mechanism: Abrasive marks and loose debris - Counterface: Moderate to high Al transfer	- Normal force: $355.3 \pm 129.6 \text{ N}$ (200% increase compared to baseline) - Tang. force: $175.7 \pm 117.8 \text{ N}$ ($\sim 160\%$ increase compared to baseline) - Surface finish: Rough grooving (Ra: $52.5 \pm 0.7 \mu\text{m}$) ($\sim 80\%$ increase compared to baseline) - Wear mechanism: Abrasive marks, smeared surface and evident grooving formation - Blade: Negligible wear and elevated prongs of Al	- Normal force reduction compared to RT: $\sim 70\%$ - Normal force reduction compared to baseline: $\sim 40\%$ - Surface finish Ra: $50.0 \pm 1.1 \mu\text{m}$ ($\sim 5\%$ decrease compared to RT) - Wear mechanism: Equivalent to RT - Key thermal response: Greater thermal stability

From the statistical investigation, the results confirm that AlSi-MoCr is statistically equivalent to the baseline, whereas AlSi-hBN-Poly exhibits a significant increase in normal reaction force at RT and consistently large effect sizes at both temperatures, indicating a pronounced, practically meaningful change in abrasability reaction forces. Temperature induces large reductions in normal force for all coatings, consistent with thermal softening; tangential effects are smaller but still notable. Despite limited sample sizes, the joint consideration of p-values, effect sizes, and the scalable TRL testing framework provides robust, data-driven guidance for material selection and advancing the readiness of next-generation abrasable coatings for aero-engine applications.

Collectively, the findings establish practical material design guidelines linking chemical composition and filler area fraction to wear performance. The addition of hBN while reducing polyester content effectively enhances thermal stability and high-temperature frictional response, but necessitates strategies to mitigate abrasion reaction forces, debris formation, and adhesive transfer. Introduction of a low fraction of MoCr has minimal impact on abrasability, making it a promising modifier for applications requiring improved resistance to harsh corrosive environments.

In summary, the developed test rig and multi-TRL experimental approach provide a validated, scalable framework for accelerated abrasable materials development. The combined methodological and material insights presented here enable targeted optimization to balance the often-competing requirements of abrasability in aircraft turbine sealing systems.

7.2. Contributions to Original Knowledge

This thesis makes several novel and substantive contributions to the science and engineering of abradable coatings and their evaluation:

1. Design and manufacturing of an innovative custom-made abrasability test rig, delivering reproducible and application-relevant performance assessments under realistically simulated aerospace thermal and mechanical conditions.
2. Establishment of a novel multi-TRL experimental framework linking laboratory-scale tribological testing (TRL 3) to sub-scale component validation (TRL 4) for turbine sealing applications.
3. Evaluation of the dual effect of hBN addition and polyester reduction on AlSi-based coatings regarding abrasability performance, which is currently not yet well explored academically.
4. Pioneering academic investigation of the influence of MoCr addition on AlSi-based coating under thermal and mechanical abrasability conditions.
5. Significant advancement in aerospace abradable material qualification, integrating coating deposition and characterization, along with abrasability performance investigations.

7.3. Limitations

1. Restricted operating speed: The rig accurately reproduced LPC contact mechanisms but was limited in maximum rotational speed, preventing full representation of higher-speed engine conditions.
2. Simplified contact geometry: A flat-tipped blade configuration was used to isolate material behavior, but this simplification does not fully capture the complex three-dimensional blade–casing interactions of real engines.
3. Non-uniform thermal conditions: The thermal field within the setup was spatially non-uniform; unheated blades and localized cooling from disk airflow may have altered actual surface temperatures at the contact zone.
4. Limited correlation to full-scale performance: While suitable for TRL 4-level assessments, direct correlation to engine-scale performance requires validation through high-speed or full-scale OEM testing.
5. Incomplete debris characterization: The morphology and mechanical behavior of wear debris were not systematically analyzed, limiting understanding of third-body effects and potential downstream erosion.
6. Small sample size and lack of statistical treatment: Limited test repetitions were performed due to time and resource constraints, precluding rigorous statistical validation of observed trends.

7.4. Suggestion for Future Work

1. Enhance the developed abrasability rig by integrating higher rubbing speed capability, adjustable blade/coating geometries, and other upgrades to closely replicate LPC operating conditions.
2. Incorporate in-situ monitoring technologies during rig testing to capture real-time wear, blade behavior, and rubbing/cutting initiation for a deeper understanding of the wear.
3. Characterize tribo-debris (particle morphology, composition, hardness) from abrasable rig and tribological tests to quantify downstream erosion potential and particle behavior.
4. Integrate advanced numerical modeling, including coupled thermal–mechanical simulations, to predict gradients, stress fields, and wear mechanisms, supporting design improvements for performance, repairability in next-generation aviation systems.
5. Pursue industrial alignment and certification pathways by collaborating with OEMs to match testing protocols with certification requirements, followed by full-scale validation as a step toward material qualification.
6. Investigate hybrid manufacturing and repair approaches, combining thermal spray, additive manufacturing (3D printing), and localized laser remelting to develop novel abrasable materials with enhanced in-service repairability.
7. Establish comprehensive process–microstructure mapping by systematically varying thermal spray parameters to correlate porosity, filler dispersion, and mechanical properties, defining optimal process windows for balancing abrasability, erosion, and corrosion resistance.
8. Explore novel alloys to optimize abrasable sealing systems, including alternative matrices, fillers, and solid lubricants for aerospace applications.
9. Conduct erosion performance assessments under realistic aerospace engine conditions to evaluate durability against high-velocity particle impact.
10. Perform corrosion resistance testing in relevant aerospace environments, including salt spray, immersion, humidity, and synthetic exhaust conditions.
11. Examine synergistic degradation effects, such as abrasability–erosion, abrasability–corrosion, and corrosion–erosion interactions, to establish holistic performance models for real-world service conditions.
12. Investigate refinements to conventional tribological protocols to better reproduce aerospace-relevant rubbing conditions and systematically validate these modified tests against the custom abrasability rig developed in this thesis.

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