A Practical On-Machine Tool Condition Monitoring Approach to Predicting Reamer Tool Life

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Abstract

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Concordia University, 2023

On-machine tool measurement (OMTM) is an emerging technique that can automatically measure cutting tool diameter and length in the machining process with a laser tool setter on the machine table. Tool condition monitoring (TCM) is to measure the width of the flank wear land as tool wear and detect tool failure during machining. Unfortunately, no TCM technique has been developed, tool wear cannot be detected, and tool failure cannot be predicted in machining. It is in high demand that tool wear is measured and compensated, and tools are replaced right before they fail. However, different types of tools wear in different pattern; measuring the tool diameter at a height with OMM cannot well represent tool wear, not even to predict tool failure. To realize TCM with the OMM technique, this research proposes a new approach to predicting a reamer's life so that the reamer can be changed before it fails. It he relationship between tool wear and tool failure has not been thoroughly investigated, especially since there are various cutting tool types, each with its unique failure mode, which means different tool types require specific methods for evaluating tool failure based on wear detection through TCM. This research propose an approach to predicting the tool life of reamer, a type of metal cutting tool, in hole machining. The study begins by examining the geometry of reamers and the cutting principles underlying the reaming process. This analysis aids in investigating the relationship between the geometric changes in reamers resulting from wear and the occurrence of reamer failure.

Additionally, the research extensively explores the main forms of reamer wear and carefully examines their impact on the quality of hole reaming. A comprehensive understanding of these wear forms is crucial for accurately predicting tool life. Moreover, a selection of reamer geometries has been identified, directly influencing the quality of reaming operations. The corresponding effective dimensional tolerances for these geometries are also determined.

This research successfully develops the fusion technology of On-Machine Monitoring (OMM) and Tool Condition Monitoring (TCM), which enables real-time tool wear assessment and facilitates timely maintenance interventions. The proposed approach has notable benefits for the manufacturing industry, including enhanced production efficiency, reduced downtime, and improved machining quality. The findings of this research contribute to advancing reamer tool life prediction methodologies and hold practical implications for optimizing manufacturing processes. The advanced OMM-TCM fusion technology is a valuable tool for ensuring efficient and reliable hole-reaming operations, benefiting the whole manufacturing industry.

Keywords: On-machine measurement; Tool condition monitoring; Reamer; Hole reaming; Tool life; Tool wear; Laser tool setter

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In addition, I would like to extend my gratitude to my fellows in our research lab. Their camaraderie and willingness to share their knowledge and experiences have created a stimulating and collaborative learning environment. Their support and willingness to lend a helping hand were invaluable whenever I encountered challenges during my research. Their diverse perspectives and collective wisdom have undoubtedly enriched my academic journey.

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Chapter 1 Introduction

1.1 Background

CNC machining has become a vital part of modern manufacturing, known for its high accuracy and significant productivity. The integration of machining and measurement has become mainstream, ensuring the precision of machined parts and resulting in numerous advanced measurement techniques. One such technique is the On-Machine Measurement (OMM) of cutting tools, commonly applied in the industry with tool setters to measure the radius and length of the tool during machining. Figure 1.1 shows a laser tool setter widely applied in the on-machine measurement system. It can successfully perform tool measurements without unloading the tool and update the tool size data in the CNC controller before it continues cutting the workpiece [1-2].

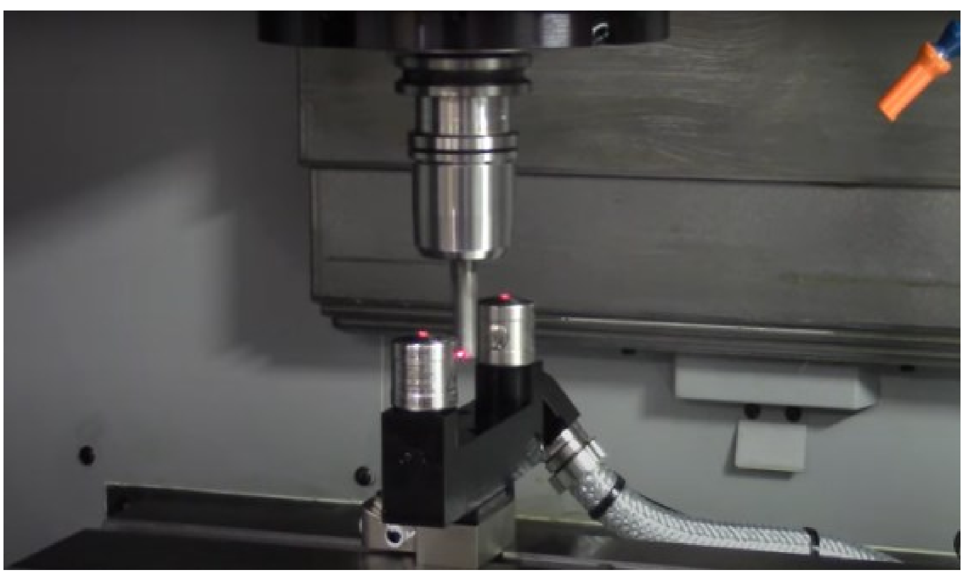


Figure 0.1 The length of a tool is measured with a laser tool setter.

The wear of cutting tools during machining has always been a prominent issue affecting the entire machining process. Figure 1.2 [3] shows the different wear patterns of cutting tools. Tool wear directly affects the dimensional accuracy and surface quality of the machined parts and can also cause cutting vibration due to changes in cutting forces, and even result in scrapped workpieces, tool damage, machine damage, and other serious consequences. Therefore, it is essential to monitor the impact of wear on machining. The significance of wear monitoring is that we can control tool wear within a reasonable range, neither wasting the use of cutting tools nor missing the opportunity to replace the worn-out tool or cutting edge before catastrophic wear occurs. In this way, the efficiency and precision of metal processing can be significantly improved.

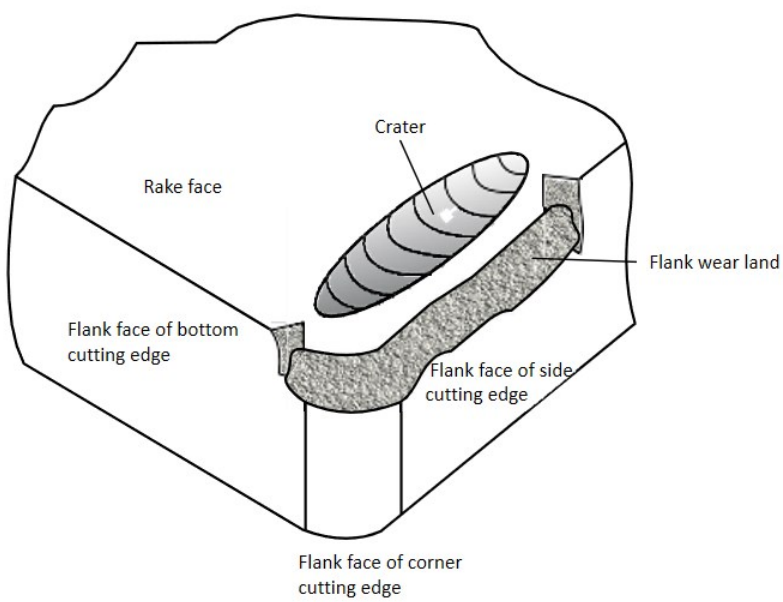


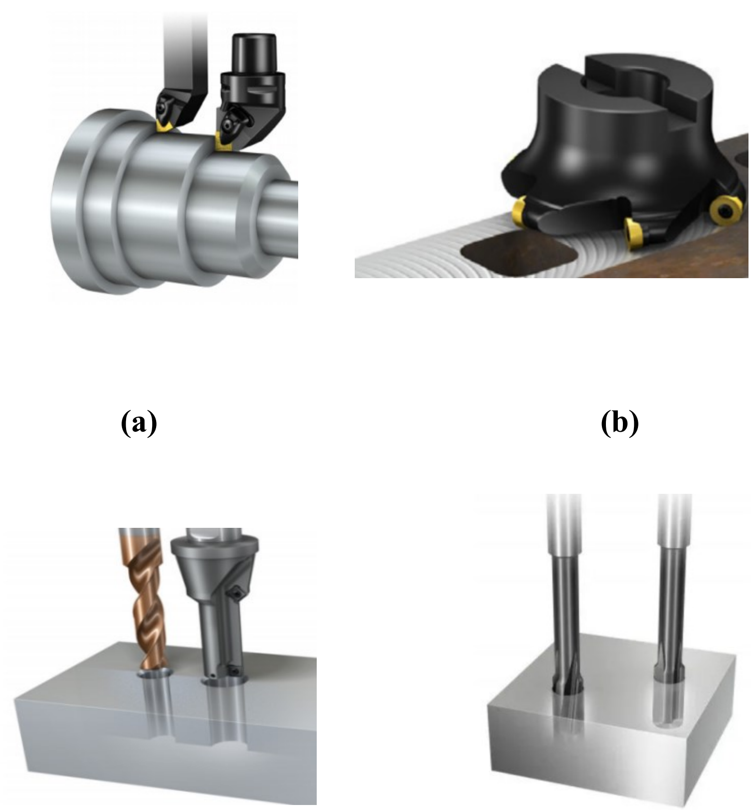
Figure 0.2 Wear occurs on cutting tools.

On-machine measurement offers numerous advantages, including reduced manual intervention, enhanced security, and increased convenience. However, tool wear is an inherent aspect of the cutting process that significantly impacts tool life. Therefore, it becomes crucial to monitor tool wear accurately and predict tool life with greater precision. As a tool becomes worn, the friction between the tool and the workpiece intensifies, leading to a decline in machining quality. Tool Condition Monitoring (TCM) plays a vital role in improving machining quality by automatically predicting tool wear and detecting tool failure during the machining process.

In the context of on-machine measurement of cutting tools, one of the key areas requiring investigation is how to effectively monitor changes in tool diameter and length to determine whether the cutting tool has reached a worn-out state. This is a complex challenge that demands advanced monitoring techniques. By continuously monitoring the changes in tool dimensions, such as diameter and length, it becomes possible to identify signs of wear and estimate the remaining useful life of the tool more accurately. This information empowers operators to take timely actions, such as tool replacement or adjustment, to maintain machining quality and avoid costly consequences, such as workpiece damage or tool breakage.

Research in this area focuses on developing innovative methodologies and technologies for on-machine measurement of cutting tools, including integrating sensors, data acquisition systems, and advanced algorithms. These advancements aim to enable real-time tool wear monitoring, allowing operators to make data-driven decisions and optimize machining processes. By effectively monitoring tool diameter and length changes, the potential for improving tool life prediction and enhancing overall machining quality became feasible, leading to increased productivity and reduced production costs in various manufacturing industries.

In CNC machining, specific cutting tools are dictated by the different cutting methods employed in metal cutting. Figure 1.3 illustrates several commonly used cutting processes, turning, face milling, drilling, and reaming. Each of these machining processes exhibits a distinctive failure mode, necessitating the application of different evaluation methods for assessing tool failure through wear detection using Tool Condition Monitoring (TCM). This research specifically emphasizes investigating the tool life of reamers applied in hole reaming operations, making reamers the primary focus of the study.



(a) **(b)**

(c) **(d)**

Figure 0.3 (a) Turning (b) Milling (c) Drilling (d) Reaming .

1.2 Literature review

1.2.1 On-machine measurement with a laser tool setter

On-machine measurement techniques is highly regarded for its precision and seamless integration into manufacturing processes, and it has been hailed as the "future of manufacturing metrology" [4]. On-machine measurement techniques have become increasingly prevalent in modern manufacturing, particularly in measuring cutting tools. These techniques can be classified into two major categories: measuring parts with touch probes and measuring cutters with tool setters. In this context, an advanced on-machine tool measurement system utilizing a laser tool setter has been developed, which consists of three key components: a laser tool setter device, an interface unit, and a CNC control.

The laser tool setter device [5] is equipped with a laser transmitter and an optical receiver (Figure 1.4), which transforms physical movement into digital. The interface unit is responsible for processing these signals and communicating them to the CNC machine controller (Figure 1.5). The CNC machine (Figure 1.6) serves as the receiver of the signals and provides a programming environment for the tool setting software used to measure cutting tools. The measurement procedure involves the operator setting measurement tasks and programming the machine tool to perform measurements and activate the tool setter. During the interaction between the cutting tool and the tool setter, the interface unit processes the triggered signal, and a solid-state relay signal is output to the machine tool. The tool setting software then calculates the tool radius and length, updating the tool offsets and compensating for the new tool offsets in the following machining operations. This advanced on-machine tool measurement system utilizing a laser tool setter offers a highly accurate and efficient means of measuring cutting tools. It provides real-time feedback on tool dimensions, allowing for more precise and consistent machining operations and improving overall product quality and efficiency.

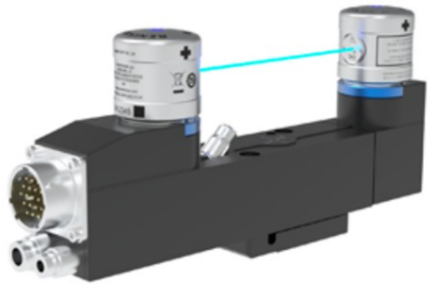


Figure 1.4 The laser tool setter processes triggered signals.

Figure 1.5 The interface unit converts signals.

Figure 1.6 The CNC machine is the receiver of signals.

Applying on-machine tool measurement with a laser tool setter improves machining accuracy by reducing human error compared to manual offsets and offers advantages over offline tool settings. This approach measures the cutting tool while rotating, thus eliminating errors caused by spindle run-out, tool holder, and the cutting tool itself, ensuring consistent and reliable measurements. Additionally, it simplifies the measuring process, enhancing convenience and operator safety by eliminating the need for manual touch-off.

Over the past decade, numerous research articles have been published on indirect Tool Condition Monitoring (TCM) methods in the field of machining. These articles discuss various techniques for collecting process signals, analyzing wear-sensitive features, and extracting valuable information. For instance, Kwon and Fischer [6] introduced the Tool Wear Index (TWI) and a tool life model based on micro-optics, image processing, and analysis algorithms. Their approach focused on understanding wear surface areas and tool material loss, with the TWI serving as a measure of minimum risk for in-process tool failure. The TWI was integrated into an optimal control strategy to improve productivity and reduce manufacturing costs.

Ozel et al. [7] investigated the influence of cutting parameters on tool flank wear and surface roughness in the finish turning of hard steel. They used scanning electron microscopy (SEM) to observe crater and flank wear of ceramic tools, and developed linear regression and neural network models to predict tool flank wear and surface roughness.

Similarly, Lajis et al. [8] employed similar modeling techniques and measuring methods in end milling of hardened steel. They identified flank wear as the major failure mode affecting tool life. Wang et al. [9] proposed a Gaussian mixture regression model (GMR) for robust tool wear prediction. Their model established the relationship between tool wear value and features, resulting in accurate predictions.

In the realm of hard milling, Iqbal et al. [10] utilized fuzzy-rules-based strategies for flank wear estimation. They conducted experiments to develop fuzzy expert systems, and the online system exhibited 67.9% higher accuracy in predicting flank wear compared to the offline system. Lu et al. [11] proposed a flank wear prediction model in milling Inconel 718, based on 3D finite element simulation, which was cost-effective and easy to operate.

Roney et al. [12] focused on tool flank wear and tool failure prediction in face milling, studying the wear of reamers. Flank wear and corner wear are typical wear types observed during the reaming process. Liang and Liu [13] conducted dry-turning experiments and found that tool flank wear affects the depth of plastic deformation, especially when the depth of cut is lower than the minimum thickness of the cut. Corner wear strongly characterizes drill life [14], and earlier researcher, Stefano [15] attributed crater wear to material properties like hardness and thermal conductivity. However, slipping of the Built-Up Edge (BUE) particles through the tool-chip interface has also been considered a cause of tool wear [16-17]. Tool wear and surface roughness are commonly evaluated parameters in machining studies [18-19], influenced by various factors such as machining parameters, cutting fluid, workpiece material properties, tool material, and machine tool stability [20-25].

1.2.2 Reaming process and reamers

Reaming plays a crucial role in CNC machining as a vital metal-cutting process. As shown in Figure 1.7, the primary objective of reaming lies in the enlargement, refinement, and enhancement of pre-existing holes within a workpiece, leading to improved accuracy, enhanced surface finish, and tighter tolerances. This process involves the application of cutting tools known as reamers. During the reaming process, the reamer is guided into the pre-drilled hole, removing small increments of material from the interior surface. This controlled material removal ensures that the hole achieves the desired dimensions and geometry, contributing to the overall precision and quality of the machining operation. As the reamer progressively advances, it effectively smooths out any irregularities or imperfections that prior machining operations may have left behind. This smoothing action results in a superior surface finish, eliminating rough edges and producing a more refined appearance.

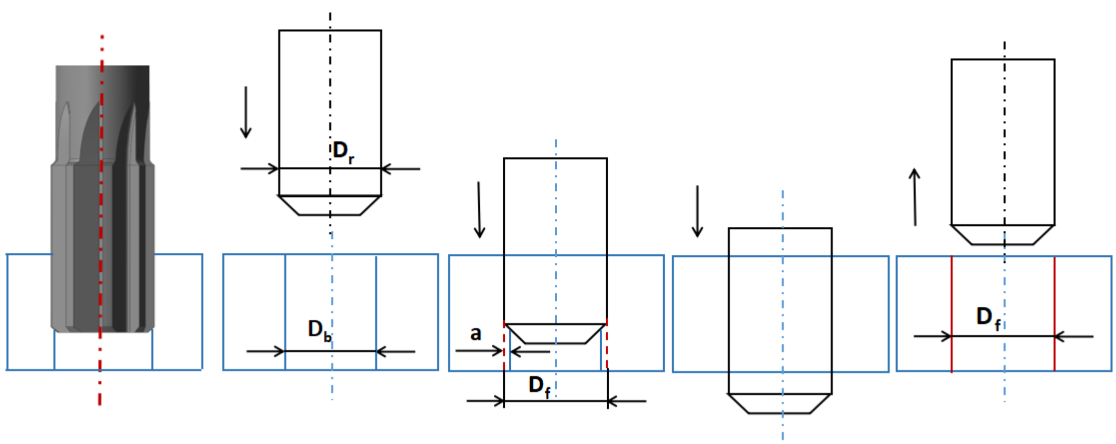


Figure 1.7 Machining process of reaming hole.

Moreover, reaming plays a significant role in enhancing the tolerance of the hole. By removing any excess material, the reaming process allows for a tighter fit with mating parts or reduces the potential for interference. This optimization of tolerance contributes to the overall functionality and reliability of the workpiece. Reaming is particularly invaluable in applications with high accuracy and precision levels.

The reaming process finds extensive application in various industries, particularly where a finished hole with specific dimensions and a smooth surface is of utmost importance. By incorporating reaming into CNC machining, manufacturers can attain exceptional hole quality, ensuring proper functionality and facilitating the seamless assembly of components with minimal clearance or interference. The precision and control offered by reaming are integral to the overall success and efficiency of metalworking operations.

Reamers, as shown in Figure 1.8, are essential cutting tools employed in CNC metal machining processes to effectively eliminate excess material from the surface of a hole. They are designed with multiple cutting edges, which enable efficient and precise material removal. Reamers are commonly crafted from high-speed steel, carbide, or diamond-coated materials, providing durability and longevity during demanding machining operations. These tools are available in various sizes and shapes and cater to diverse hole diameters and geometries encountered in metalworking applications. Manufacturers offer a variety of reamers with different dimensions to achieve specific hole diameters accurately. The precision required is a critical consideration, as some applications demand exceptionally tight tolerances that require specialized reamers capable of achieving high accuracy. The specific application at hand influences the choice of reaming tool. For instance, reamers designed for general-purpose use may suffice for routine tasks, while specialized reamers cater to unique requirements like chamfering, deburring, or countersinking.

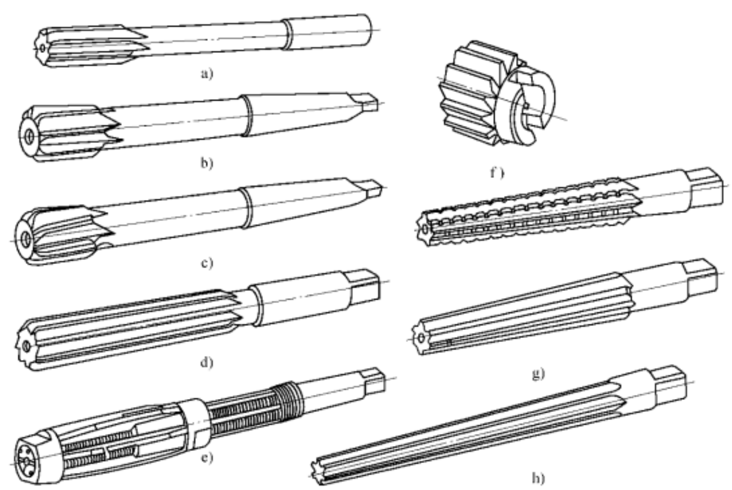


Figure1.8 (a) Straight Shank Machine Reamer (b) Taper Shank Machine Reamer (c) Carbide Taper Shank Machine Reamer (d) Hand Reamer(e) AdjusTable Hand Reamer (f) Shell-Type Machine Reamer(g) Straight Shank Morse Taper Reamer(h) Hand Reamer with 1:50 Tapered Pilot.

In CNC machining, machine reamers (Figure 1.9) are the primary reaming tools used. It is typically used in a milling machine or drilling machine. Machine reamers are typically made from high-speed steel (HSS), carbide, or other hardened materials that offer durability and wear resistance, often in the form of straight flutes or helical flutes. Machine reamers are widely used in metalworking operations to improve the accuracy, surface finish, and dimensional precision of pre-drilled holes. This research figures out an on-machine tool condition monitoring approach to predicting the tool life of reamers, referring to machine tool reamers specifically, not other types of reamers.

Figure 1.9 Machine Reamers

Several studies have examined the factors affecting dimensional accuracy and surface quality in reamed holes, including reamer geometry, edge treatment, cutting parameters, and vibration. Tool dynamics and vibration have been extensively researched [26–32], and micro-geometry optimization of cutting edges has been explored to enhance stability and stiffness [33].

The relationship between tool wear and edge geometry has also been investigated. Ramirez [34] evaluated tool wear and surface integrity in hole drilling, studying how tool wear affects the cutting edge profile. Montoya [35] conducted a comprehensive research on the wear mechanisms of coated and uncoated tungsten carbide drills when drilling aluminum alloy, measuring wear progression of the cutting edges. Konstantin [36] characterized the relationship between tool geometry, process forces, and tool wear through reaming tests, considering diverse carbide tools with different rake and clearance angles.

In addition to reaming, mechanical micro-milling has emerged as a promising micro-manufacturing process for accurate complex-feature generation. Balázs [37] reviewed recent results and developments in micro-milling, covering topics such as microchip removal, micro-burr formation mechanisms, cutting forces, cutting temperature, vibrations, surface roughness, cutting fluids, workpiece materials, process monitoring, micro-tools and coating, and process modeling.

1.2.3 Reamer tool life prediction

In mass production scenarios, where multiple holes need to be machined in a single workpiece, the reamer tool may become worn and damaged, even though there are still un-machined holes. Figure 1.10 shows that a large number of holes are being machined in a workpiece. The traditional method to solve this problem is to interrupt machining after a certain number of holes have been processed and workers manually unload tools from the spindle, measure their lengths and diameters on tool pre-setter to determine tool failure. If the the reamer is already worn out, and a new reamer should be replaced.

Figure 1.10 Reaming holes in a workpiece.

Current research [6-10] on the prediction of tool life often relies on indirect methods such as measuring cutting force, vibrations and temperatures to estimate tool longevity. A more direct and precise approach to predicting tool life involves measuring the dimensional changes in the tool caused by wear. However, the current in-machine measurement applications for tool detection can only measure the diameter and length of the tool, and they cannot directly forecast the reamer tool's lifespan. Moreover, there are numerous types of cutting tools, each exhibiting different forms of wear and failure, leading to varying tool life prediction models. This complexity further exacerbates the challenge of predicting tool life.

My research aims to address this issue by exploring the wear and failure patterns of reamer tools and establishing the relationship between reamer wear and dimensional changes. By considering the cutting principles involved in reaming, I have identified critical dimensional values that can be used to determine reamer tool failure. Building upon in-machine measurement techniques, I propose a method for in-machine measurement of reamer tools to predict their lifespan. This method may also serve as inspiration for the design of lifespan detection methods for other types of tools.

1.3 Research objectives

The impact of wear on the geometry of the reamer and the specific geometry changes that affect the machining quality of holes have not been thoroughly investigated. However, by researching these two aspects, it is possible to quickly determine the effectiveness of a reamer by measuring specific geometries based on On-machine measurement. This method can enhance both the machining efficiency and quality of reamed holes. In the context of academic research objectives, it is crucial to investigate the influence of reamer wear on geometries and identify the geometry variations that directly affect the machining quality of holes. By understanding these factors, a reliable and efficient method can be developed using OMM to assess the viability of reamers. Such an approach has the potential to improve the efficiency and quality of hole machining processes significantly.

This thesis proposes a practical approach for OMM-TCM fusion based on the laser tool setter. The main objective is to measure reamer geometry to predict the reamer tool life. It can be concluded in the following aspects:

- Establishing new models of reamer diameter reduction and reamer back-taper change.
- Proposing a new approach to determining the critical values of reamer diameter reduction and back-taper changes.
- Proposing a new procedure of on-machine reamer measurement for tool life.

1.4 Outline

The thesis is organized as follows. In Chapter 2, the geometries of reamer tools and the principle of reaming operation are researched in detail. Chapter 3 introduces reamer wear forms and their effects on reamer geometry and hole machining quality. Chapter 4 establishes an on-machine measurement approach to predict the reamer tool. Chapter 5 sets up a reamer-cutting experiment to verify the validity of the reamer on-machine measurement method. At last, Chapter 6 gives the conclusions.

Chapter 2 Geometries of reamer tools and the principle of reaming operation

2.1 The geometry of reamer and the material removal process during reaming

As shown in Figure 2.1, a reamer is a tool comprising three integral components, the working part, the recess part, and the shank part. The working part can be subdivided into two segments, the cutting section and the cylindrical section. The cutting section of the working part executes the critical function of removing material from the workpiece, while the cylindrical section serves as a guide to ensure that the reamer remains on course during operation, minimize undesirable vibrations, provide for improved surface finish, and maintains proper alignment. The dimensional accuracy and geometric precision of the reamed hole are inextricably linked to the precision of the reamer.

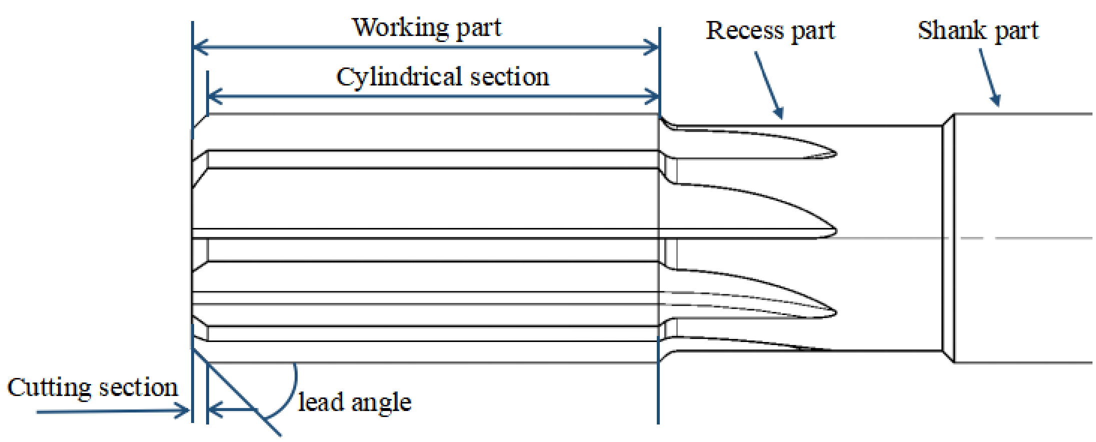


Figure 2.1 The construction of reamer.

The cutting section of a mechanical reamer assumes a critical role in the material removal process during reaming operations. This specific section is designed with an angle relative to the axis of rotation, known as the lead angle (Figure 2.2). The primary focus of material removal revolves around this cutting section, as it is chiefly responsible for shaping and enlarging the hole to meet the desired specifications. As the reamer rotates within the workpiece, its strategically positioned cutting edges effectively engage with the material. The lead angle facilitates a gradual removal of material from the interior surface of the hole. This deliberate approach ensures meticulous precision in enlarging and refining the dimensions of the hole. The cutting edges of the reamer by delicately scraping away small increments of material as they progress along the hole's length. This scraping action allows for controlled material removal, ensuring an accurate and smooth enlargement of the hole. By eliminating excess material, the cutting edges meticulously shape the hole, resulting in the desired dimensions and surface finish.

Conversely, the cylindrical section of the reamer does not actively participate in the material removal process. Rather, it assumes the role of a guide, imparting proper alignment and stability to the reaming operation. By maintaining the correct positioning and orientation of the cutting section, the cylindrical section guarantees precise hole enlargement while minimizing the risk of deviations or inaccuracies.

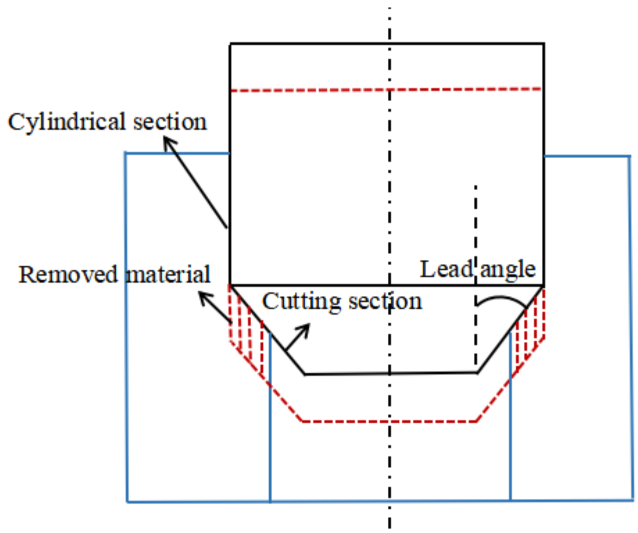


Figure 2.2 The process of reaming.

The geometry of the reamer determines the cutting performance; it is important to understand the following terms related to its different faces and edge. As shown in Figure 2.3, the rake face is the surface of the reamer that extends from the cutting edge up to the flute. The face comes into contact with the workpiece material during the cutting process. The rake angle (Figure 2.4a) is the angle between the rake face and a line perpendicular to the reamer's axis. The rake face angle determines the direction and amount of chip flow and the cutting forces acting on the reamer. The flank face is the surface of the reamer that extends from the cutting edge to the margin. The face supports the cutting edge and provides stability during the cutting operation. The flank angle (Figure 2.4a), also known as the clearance angle, is the angle between the flank face and a line perpendicular to the reamer's axis. The flank angle ensures proper chip evacuation, reduces friction and prevents rubbing between the reamer and the workpiece. The cutting edge is the sharp edge formed at the intersection of the rake face and the flank face. It is the primary surface that removes material from the workpiece, creating or enlarging the hole.

Depending on their design, reamers can have multiple cutting edges, typically two, three, or four. The cutting edges must be sharp, properly aligned, and have the correct geometry to ensure efficient cutting action and a smooth surface finish. The margin (Figure 2.4b) is the land area on the reamer located between the cutting edge and the shank. It provides stability and support to the cutting edges, minimizing vibrations and chatter during the machining process. The margin width can vary depending on the specific reamer design and its intended application. A wider margin helps increase stability, while a narrower margin allows for better chip evacuation. It's worth noting that the rake face, flank face, cutting edge, and margin are crucial features that impact the cutting performance, tool life, and quality of the machined hole. The design and dimensions of these features are carefully selected based on the machined material, cutting conditions, and desired hole specifications.

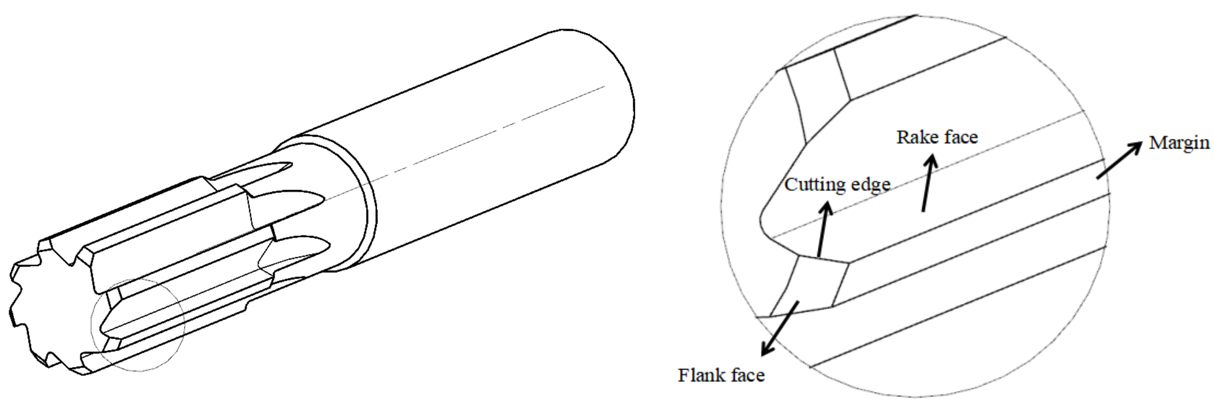
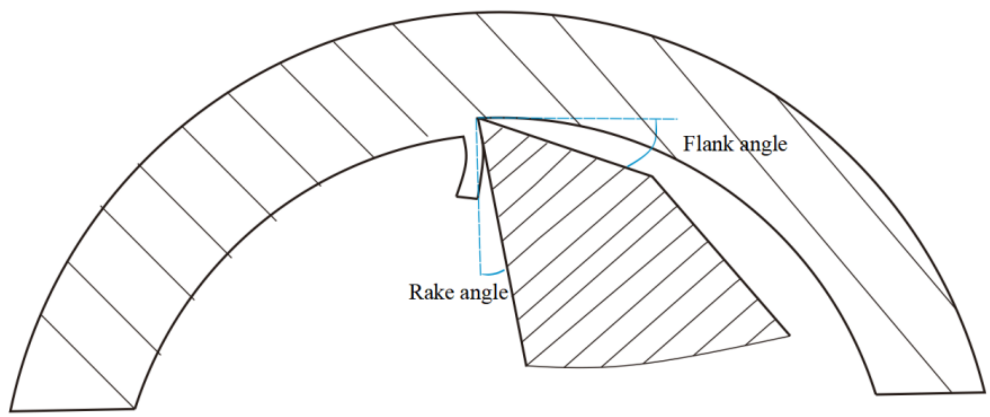


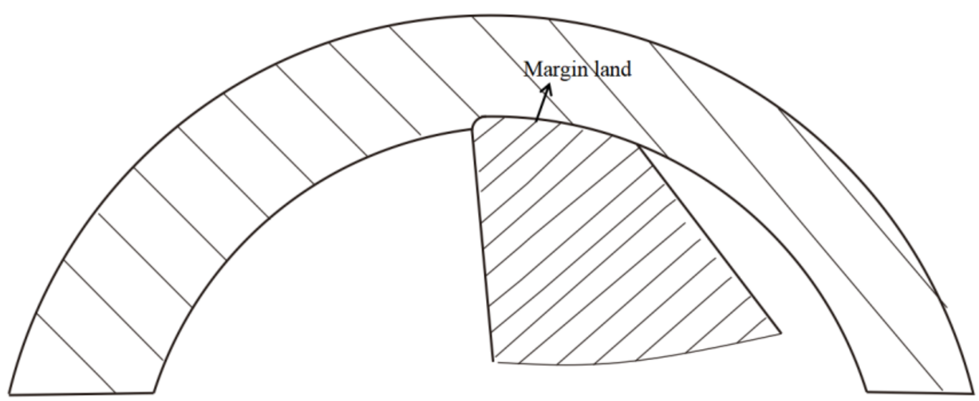
Figure 2.3 The geometry of reamer

Reaming is a precision machining process to enhance the dimensional accuracy and surface quality of a previously drilled hole. A machine reamer facilitates this process with cutting edges in the cutting section and a wider land in the cylindrical section. In Figure 2.4(a), the cutting edges lack an edge land, ensuring direct material contact for efficient chip removal. The small edge radius concentrates cutting action, promoting smooth material removal and chip generation while minimizing the risk of tool chatter or vibrations. Figure 2.4(b) showcases the wider land on the cylindrical section. This design increases contact with the hole wall, enhancing stability during reaming. The wider land acts as a guide, aligning the reamer within the hole and preventing any deviation from the intended path. This guidance is particularly critical when dealing with holes that may have slight inaccuracies from drilling. The benefits of the wider land extend beyond stability. Providing more support to the reamer, it aids in maintaining calibration bore diameter accuracy, meeting precise tolerances required for certain applications. Moreover, the increased stability and reduced vibrations contribute to superior surface quality in the reamed hole, yielding a smoother finish.

In summary, the reaming process with a machine reamer involves well-designed cutting edges and a wider land to achieve precise and high-quality machined holes. The absence of an edge land in the cutting section ensures efficient material removal. In contrast, the guiding function of the wider land improves stability, calibration accuracy, and surface finish, making it an essential step in achieving accurate and smooth holes.



(a)



(b)

Figure 2.4 (a) Cutting edge remove material (b) hole wall being squeezed by the margin land.

2.2 Back taper on cylindrical section of reamer

The cylindrical section of a reamer is designed with a small back taper angle (Figure 2.5) to achieve optimal performance, which is designed to prevent the reamer from rubbing against the newly cut surface of the hole and causing damage or excessive wear. If the entire cylindrical section is completely straight without any back taper angle, it will result in a larger contact area with the hole wall, providing better guidance. However, this increased contact area also leads to greater friction with the hole wall, which adversely affects the surface quality of the hole wall. Furthermore, the increased friction generates additional heat that contributes to an increase in the diameter of the hole. To mitigate these issues, the back taper design can reduce the contact between the reamer and the hole wall while still providing effective guidance. This design reduces the friction between the reamer and the hole wall, improving surface quality while minimizing heat generation and maintaining a consistent hole diameter.

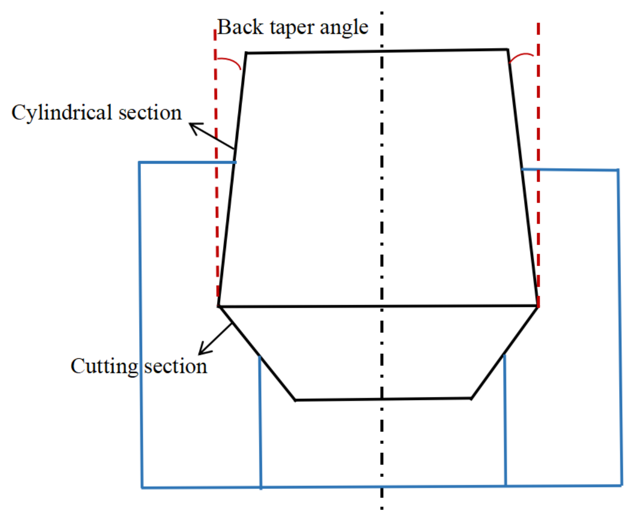


Figure 2.5 Back taper angle on cylindrical section.

When the cylindrical section of a reamer is completely straight or has a smaller back taper angle, the resulting friction between the reamer and the hole wall increases, this increased friction reduces the surface quality of the hole wall and generates more cutting force. Conversely, if the back taper angle of the cylindrical section is too large, the contact between the reamer and the hole wall is reduced, which results in the cylindrical section being unable to effectively guide the reamer. This reduction in guidance may lead to increased vibration, poor cylindricity, and lower surface quality. Therefore, the selection of an appropriate back taper angle for the cylindrical section of a reamer is critical for achieving the desired surface quality and minimizing cutting force during the reaming process. This back taper structure has important implications for the optimization of reaming processes and the improvement of hole quality in a variety of industrial applications.

Chapter 3 Reamer wear forms and their effects on reamer geometry and hole machining quality

3.1 The main forms of reamer wear and the effect on the reamer geometry

Reaming is a precise machining method for holes, and the diameter accuracy of the hole and the surface quality of the hole wall are the main criteria for determining the effectiveness of the reamer. Axinte and Andrews [38] introduced that reamer wear significantly impacts hole diameter and surface quality in machining processes. As reamers wear down, they can cause several issues. Hole diameter problems include oversized holes due to dull cutting edges, resulting in imprecise dimensions and inconsistent diameters due to uneven wear. This reduced size control can be especially problematic in critical applications.

Surface quality is also affected as reamers wear. Dull edges lead to increased chatter and vibrations during machining, causing rougher surface finishes. Additionally, worn reamers can leave tool marks or imperfections on the hole's surface, diminishing overall part quality. Moreover, increased friction between the worn reamer and workpiece material may lead to heat buildup and poor chip evacuation, potentially damaging the workpiece and further degrading surface quality.

In machining a workpiece on a CNC machine, the reamer wear shown in different forms. Reamer tool wear can be classified into six forms (Figure 3.1): flank face wear, rake face wear, notch wear, breakage, hairline cracks, and built-up edge.

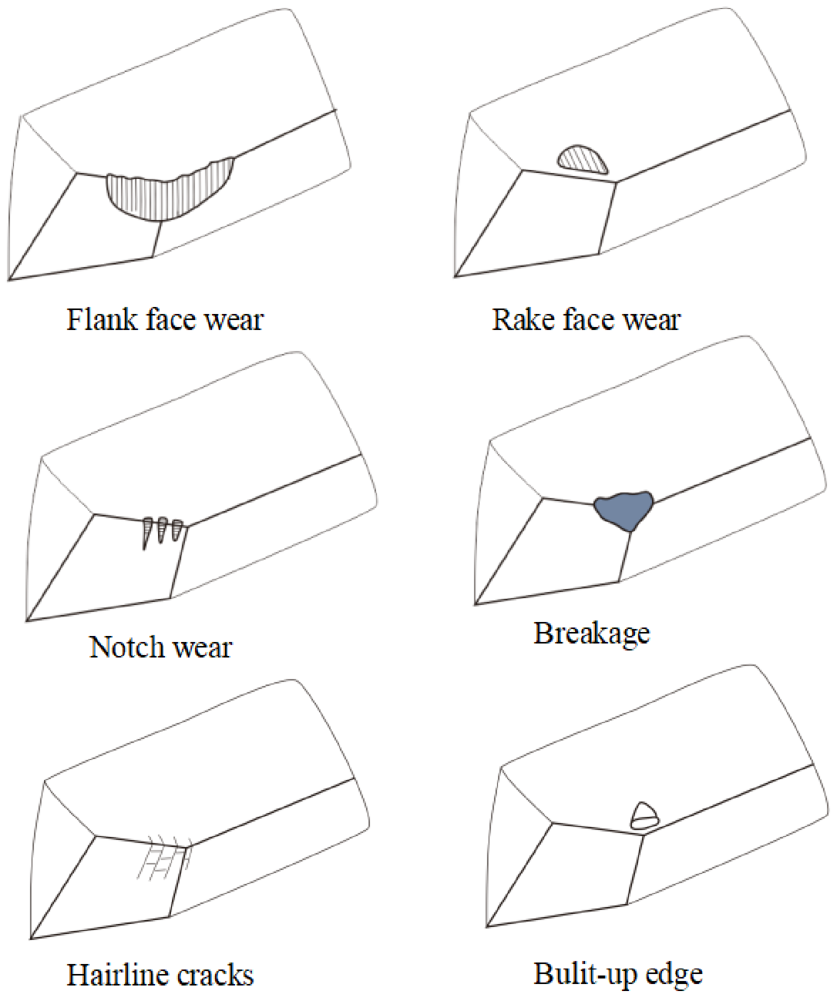
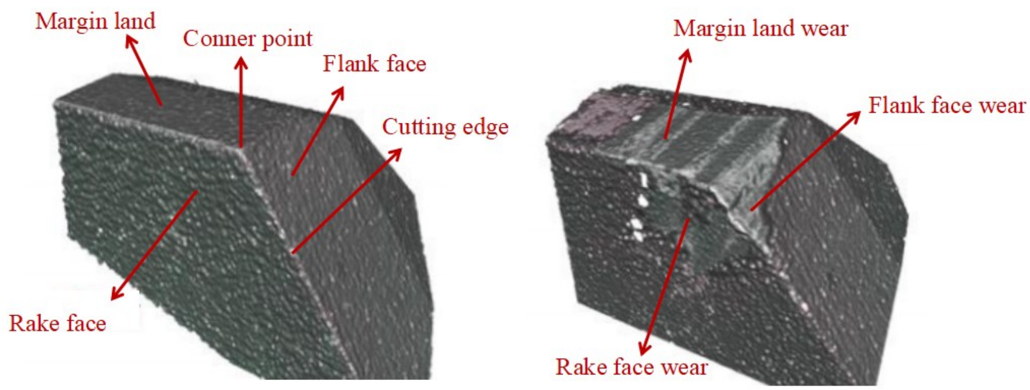


Figure 3.1 Different forms of reamer wear.

Flank face wear refers to the wear occurring on the reamer's side or flank faces adjacent to the cutting edges. This type of wear is characterized by the gradual rounding or dulling of the flank faces. Rake face wear refers to the wear on the top surface of the reamer's cutting edges, also known as the rake face. This wear can manifest as gradually losing the sharp cutting edge or developing wear patterns. Notch wear refers to the wear at the corners or notches of the reamer's cutting edges. It is characterized by the rounding or chipping of the sharp edges. Breakage refers to the fracture or complete failure of the reamer during machining. Hairline cracks are small, fine cracks that develop on the surface of the reamer. They are usually not immediately visible but can propagate and worsen over time. Built-up edge has been described earlier as the formation of a layer of workpiece material on the cutting edge. It can adversely affect cutting performance and dimensional accuracy.

Reaming is precision machining with a small amount of material removed. When selecting suitable materials for a reamer and using proper cutting parameters during machining, flank face wear is the primary type of wear that occurs on the reamer. Flank face wear is primarily caused by abrasive wear and material transfer resulting from the interaction between the workpiece material and the reamer's flank faces during machining. Abrasion occurs when the workpiece material rubs against the flank face, gradually wearing them down. Additionally, the high temperatures generated during machining can lead to the formation of a layer of workpiece material that adheres to the flank faces due to frictional forces. This material transfer further contributes to flank face wear. Moreover, when reaming hard materials, the increased contact pressures and the inherent abrasiveness of such materials accelerate the wear process on the flank faces.

Jaroslava[39] studied the wear of carbide reamers. As shown in Figure 3.2, the wear on the flank face of the cutting section is very obvious, which is typical of flank face wear, and the flank face wear also appears on the margin land of the cylindrical section, which can also know as margin land wear. Flank wear gradually dulls the edges and reduces their cutting ability. Although rake face wear is also evident, it is not the primary factor affecting tool life.



(a) (b)

Figure 3.2 (a) Electron microscope photo of the reamer before machining. (b) Electron microscope photo of the reamer after machining.

Voina[40] studied the wear resistance during the reaming tests. Reamers were analyzed at predefined intervals of 3, 15, 30, 45, and 60m to explore the cutting edge wear and deterioration. At these intervals, the wear of the cutting edge was scanned using an electron microscope to observe the evolution of the wear, material adhesion, and coating deterioration. Based on the images of the wear evolution from Figure 3.3 [40], it can be observed that the abrasion tendencies of the flank face and margin land.

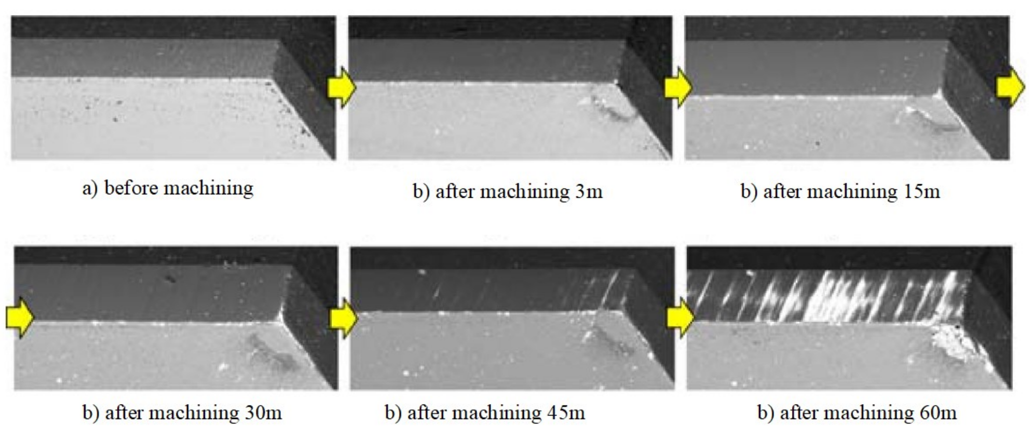


Figure 3.3 Wear evolution during the durability tests.

The wear of reamers directly impacts geometries, which in turn affects the size, accuracy, and surface quality of the hole being machined. Figure 3.4 shows those important profile geometries of reamers, which list as below:

P_1-intersection point between cylindrical section and cutting section,

D_1-diameter of reamer measured on the connection point P_1,

k_t- back taper angle of cylindrical section,

k_l- lead angle of cutting section.

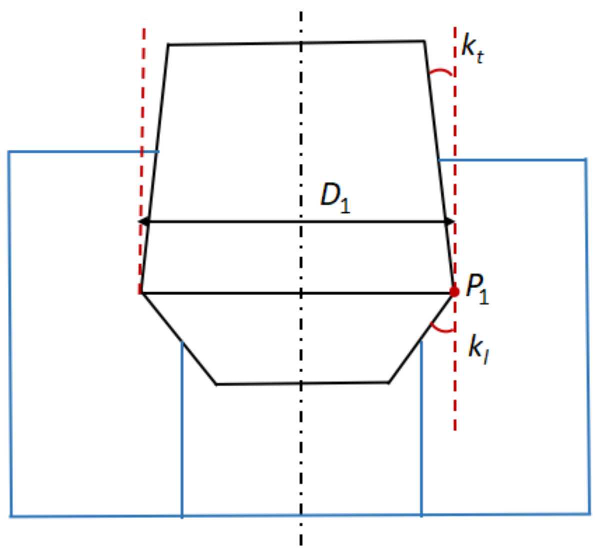


Figure 3.4 Important profile geometries of reamers.

As shown in Figure 3.5, flank face wear and margin land wear have a significant effect on the profile geometries of the reamer, which lead to the decrease in the diameter at the point P_1. The wear also affects the back taper angle of the cylindrical section and the lead angle of the cutting section. It is essential to research how these geometry changes affect the quality of hole being machined to monitor the validity of reamer.

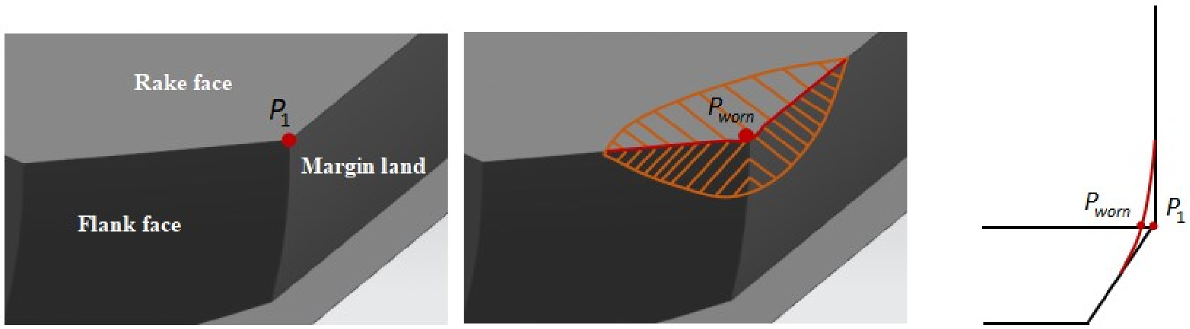


Figure 3.5 Several geometries affected by flank wear on reamer.

3.2 The effect of reamer diameter on the quality of the hole being machined

The effective diameter of a machine reamer is measured at a specific point P_1(Figure 3.6), the intersection point between the cylindrical section and the cutting section, called the "major diameter." The major diameter is the largest diameter of the reamer, which is critical because it determines the final size and surface quality of the hole.

In the hole reaming process, material removal and chip generation mainly occur on the cutting section during the reaming process. As shown in Figure 3.6, the diameter of the reamer plays a crucial role in determining the magnitude of the cutting allowance. The cutting allowance refers to the difference between the diameter of the reamer and the target diameter of the finished hole and can be calculated as below:

$$A = D_r - D_h \,. \tag{1.1}$$

The cutting allowance plays a significant role in achieving the desired dimensional accuracy of the reamed hole. The cutting allowance determines the amount of material that needs to be removed during reaming. A smaller cutting allowance requires less material removal, leading to a more accurate and controlled diameter for the reamed hole. Tighter tolerances can be achieved with a smaller cutting allowance, resulting in improved dimensional accuracy. The cutting allowance also influences the surface finish of the reamed hole. A larger cutting allowance can result in a rougher surface finish due to increased material removal and higher cutting forces.

Conversely, a smaller cutting allowance leads to less material removal, reducing the chances of surface imperfections and achieving a smoother finish. Adequate chip evacuation is crucial for maintaining cutting performance and preventing damage to the reamer and workpiece. With a larger cutting allowance, there is more space for chip evacuation, reducing the risk of chip clogging and tool damage. However, a smaller cutting allowance may restrict chip evacuation, requiring proper chip management techniques to ensure efficient removal.

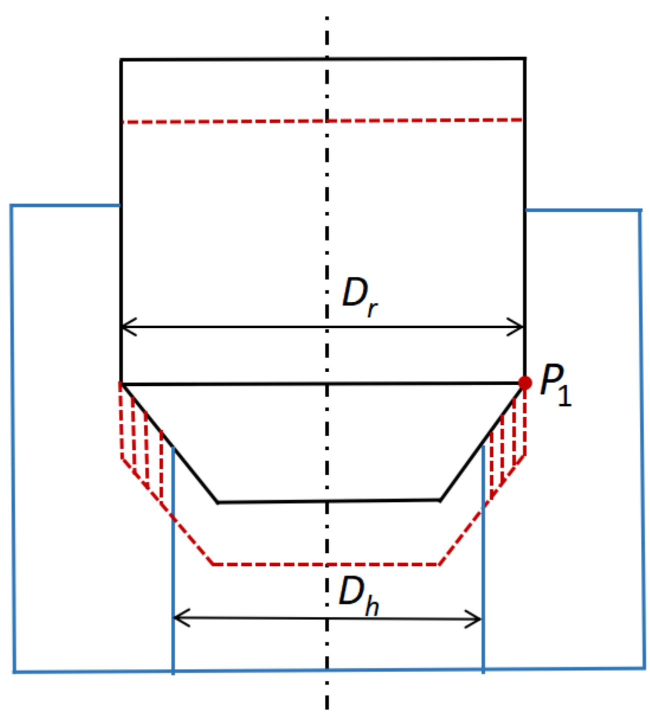


Figure 3.6 Material removal process for reaming.

The diameter of the reamer directly affects the cutting allowance of reaming, which serves as a crucial criterion for evaluating the effectiveness of the reamer. The diameter tolerance of a reamer plays a vital role in determining the dimensional accuracy of the machined hole as well as the service life of the reamer. Several factors influence the diameter relationship between the reamer and the hole during reaming. Uneven allowance of the reamed hole and radial runout of the reamer teeth contribute to the occurrence of an unbalanced force acting on the reamer. This can lead to variations in the diameter of the reamed hole.

Although the cylindrical section of the reamer provides some correction to the final machined diameter of the hole, the reduction in the effective diameter of the reamer due to tool wear affects the removal of material, and the elastic recovery effect further amplifies the negative impact of the reduction in diameter. It is, therefore, important to discuss how reamer diameter reduction affects material removal during reaming.

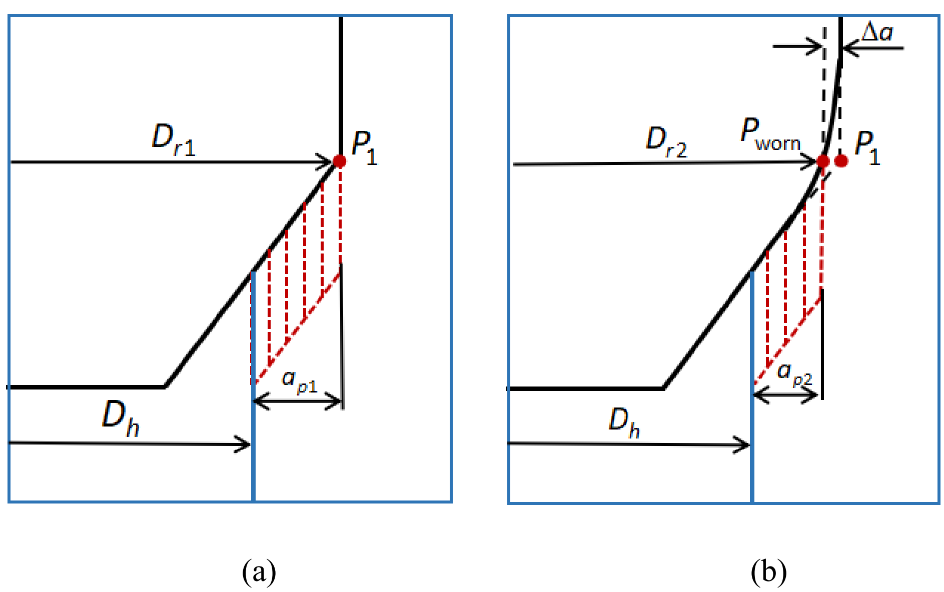


Figure 3.7 (a)Material removal process of the hole wall when the cutting edge is new, (b)Material removal process of the hole wall when the cutting edge worn out.

Reamer wear occurs mainly near the intersection point where the cutting section and the cylindrical section meet, which is point P_1 shown in Figure 3.7(a). As edge wear increases, the sharp contour of the intersection point P1 is gradually worn down to a rounded contour, and point P_{worn}, shown in Figure 3.7(b), becomes the new intersection point connected with the cutting section and the cylindrical section. The cutting depth of the new reamer is

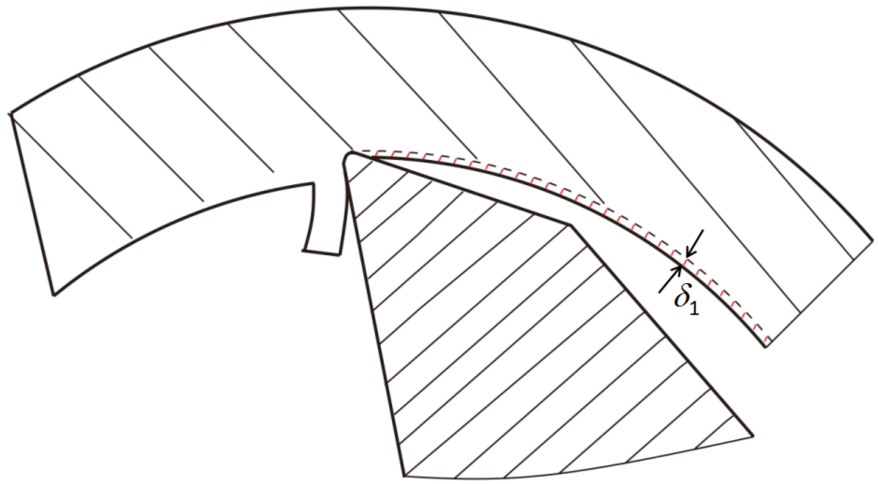
$$a_{p1} = D_{r1} - D_h . \tag{1.2}$$

The cutting depth of the worn reamer is

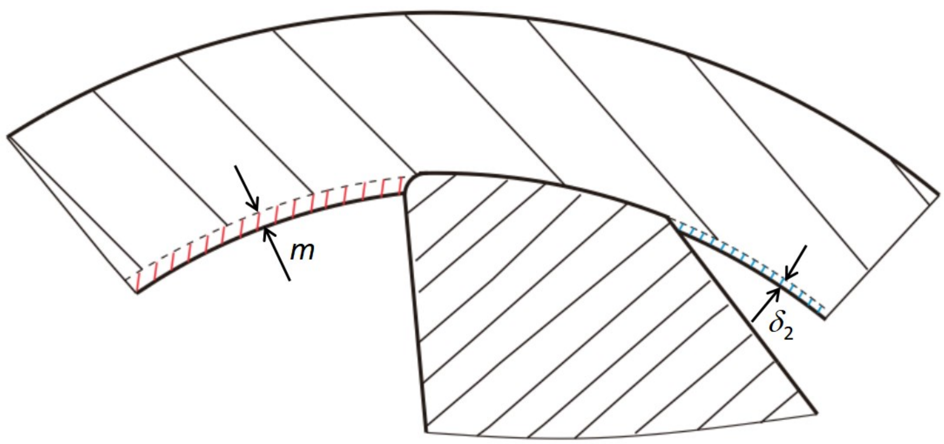
$$a_{p2} = D_{r2} - D_h . \tag{1.3}$$

Reamer wear reduces reamer diameter, so the value of D_{r2} is smaller than D_{r1}. The material that should have been removed by the cutting edge was not removed, and the width of this remaining material is

$$\Delta a = a_{p1} - a_{p2} . \tag{1.4}$$



(a)



(b)

Figure 3.8 (a) Cutting edge of cutting section removes material and forms chip (b) Margin land of cylindrical section squeeze the hole wall.

During the machining process, the material removal of the hole wall mainly occurs at the cutting section. As shown in Figure 3.8(a), after hole machining, with the completion of the cutting edge's cutting, the already machined hole wall will exhibit a rebound phenomenon, namely " elastic recovery". During the reaming process, the cutting edge of the reamer applies cutting forces to the workpiece material. These forces cause deformation in the material around the hole, resulting in the elastic deformation of the surrounding metal. Elastic deformation refers to the temporary distortion of a material by applying external forces. In the case of hole reaming, the material surrounding the hole undergoes elastic deformation due to the compressive forces exerted by the reamer. This deformation causes the metal to temporarily change its shape. However, once the reamer is removed from the hole, the elastic forces are released, and the material attempts to return to its original shape. Elastic recovery causes the metal surrounding the reamed hole to spring back slightly, reducing the diameter of the hole.

As shown in Figure 3.8(b), the cylindrical section of the reamer has a wide margin land, which can squeeze the machined hole wall and compress material inside the wall; the margin land of the reamer also applies cutting forces to the workpiece material, reducing the amount of elastic recovery amount which generated by cutting edge processed and improving the machining quality. The thickness of the material being squeezed on the cylindrical section is

$$m = \delta_1 + \Delta a . \tag{1.5}$$

The reduction in diameter due to the wear of a reamer leads to the retention of undesired hole wall material that should have been removed during the cutting process. The thickness of the material not removed is Δa, which is left on the cylindrical section to be processed. However, the cylindrical section of the reamer has margin lands instead of cutting edges, which means that material can not be removed through chip formation on the cylindrical section. As a consequence, the squeezed material thickness m on the cylindrical section increases, leading to an augmented spring back in the hole wall, which will directly result in the diameter of the machined hole exceeding the lower tolerance limit. Furthermore, the elevated extrusion force will affect the surface quality of the hole wall.

In conclusion, the reamer diameter is based on measuring the diameter at the intersection of the cutting section and the cylindrical section. The diameter of the reamer tool plays a crucial role in the reaming process due to its significance in achieving the desired hole size and quality. The diameter of the reamer determines the final size of the hole being reamed. Therefore, determining whether the diameter of the reamer exceeds the tolerance is a crucial criterion for evaluating the effectiveness of the reamer.

3.3 The effect of back taper on the quality of the hole being machined

Reamers have a certain amount of back taper setting, which refers to the gradual reduction in diameter towards the end of the reamer. The absence of a back taper in a reamer can significantly impact the quality of hole machining, as it increases cutting forces, diminishes surface finish, and accelerates tool wear. When a reamer lacks a back taper, it gives rise to several issues that affect hole quality.

The absence of a back taper in a reamer leads to increased cutting forces exerted on the hole walls. As illustrated in Figure 3.9, the cutting forces can be categorized into three primary components: axial force, radial force, and tangential force. The axial force acts parallel to the hole's axis and determines the depth of cut by pushing the reamer into the workpiece. The radial force acts perpendicular to the hole's axis, pressing the reamer against the hole wall. In the absence of a back taper, the contact area between the margin land and the hole wall increases, resulting in higher radial forces. The force operates tangentially to the reamer's cutting edge, facilitating its rotation and engagement with the workpiece material. The magnitude of the tangential force depends on factors such as cutting speed, reamer geometry, and friction between the reamer and the workpiece. Without a back taper, the enlarged contact area between the margin land and the hole wall increases friction, elevating the tangential forces.

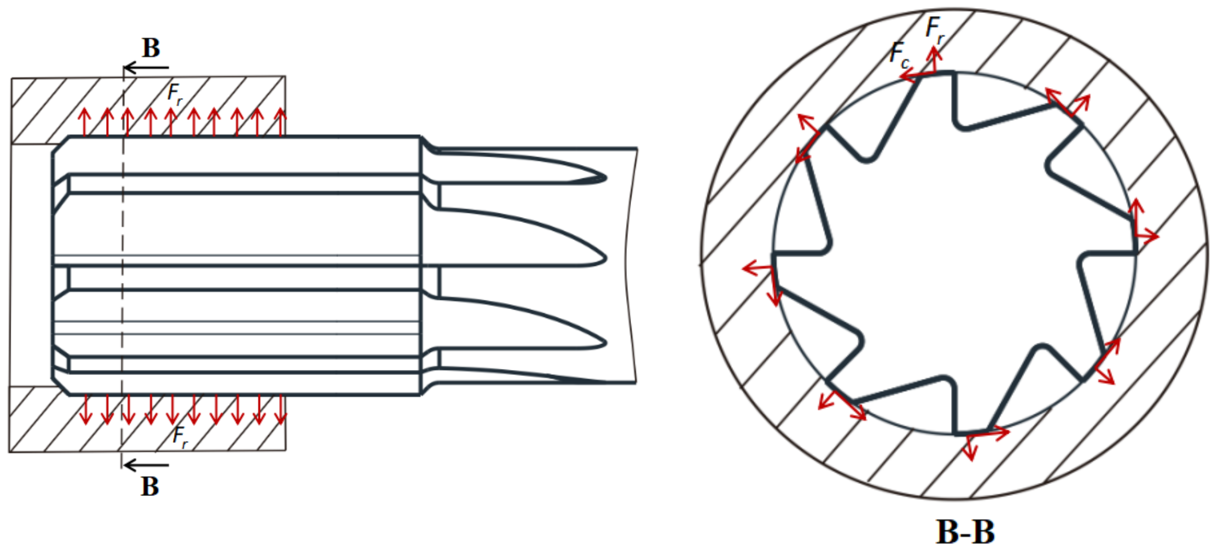


Figure 3.9 Cutting force display on the the wall of hole.

After hole machining, with the completion of the cutting edge's cutting, the already machined hole wall will exhibit a rebound phenomenon, namely "elastic deformation" (see Figure 3.10). Suppose the tool's back angle for hole machining is 0°, which means the back taper value is zero. In that case, the elastic recovery of the hole wall needs to be continued to be processed and compressed by the margin land on the reamer's cylindrical section. However, this will cause the radial and tangential forces to rise sharply during machining. The roughness value will increase due to the margin land of cylindrical bearing the elastic recovery material and compression of the hole wall.

In conclusion, the absence of back taper causes heightened tool deflection, vibrations, and chatter, resulting in compromised dimensional accuracy, surface finish, and the potential for tool breakage. Moreover, the elevated cutting forces strain the machine tool, affecting its stability and overall performance. A reamer with a back taper effectively distributes cutting forces and reduces surface contact between the reamer and the hole walls. Back taper design helps minimize tool marks, scoring, and chatter marks, improving surface finish. Without a back taper, insufficient contact contributes to a rougher surface finish, compromising the quality and appearance of the machined hole. Therefore, the reamer must be set with an appropriate back taper value.

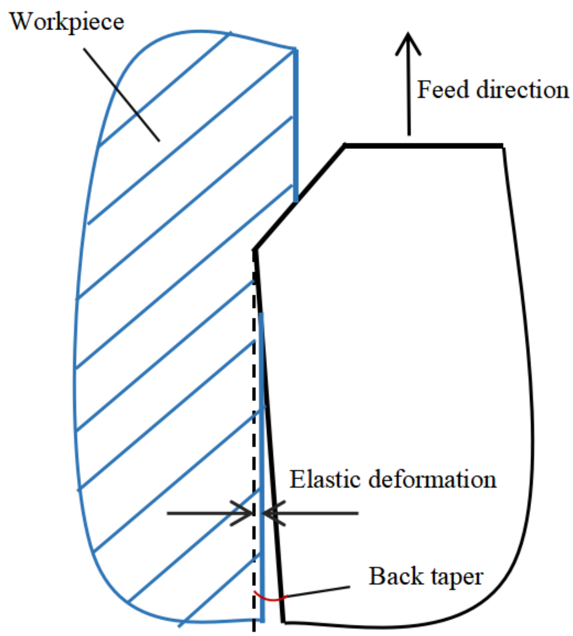


Figure 3.10 Elastic deformation of the machined hole wall

Chapter 4 Establishing an on-machine measurement approach to predict reamer tool life based on the machining requirements of reamed holes

4.1 Calculating the critical value of reamer diameter for determining tool failure

Hole shrinkage, also known as hole contraction or hole size reduction, can occur during the reaming process. It involves a decrease in the final diameter of a hole after reaming. Several factors contribute to hole shrinkage during reaming, including elastic recovery, tool runout, cutting speed and feed rate, and improper tool geometry.

Elastic recovery is a common phenomenon during hole reaming. After the reamer is removed from the hole, the material surrounding the hole undergoes elastic deformation and springs back slightly, reducing the hole diameter. Excessive tool runout, which refers to the deviation of the cutting tool's rotation axis from its ideal centerline, can cause uneven cutting forces and uneven material removal, leading to hole shrinkage. Incorrect cutting speeds or feed rates during reaming can generate excessive heat, temporarily causing the workpiece material to expand and enlarge the hole. However, upon cooling, the material contracts, resulting in hole shrinkage. Improper tool geometry, including inadequate clearance angles, suboptimal flute design, or incorrect cutting edge geometry, can cause excessive friction and heat generation, leading to material contraction.

Designing the diameter tolerance of a reamer involves considering the machining tolerance requirements of the hole being reamed. The goal is to select a reamer size that will produce a hole within the desired dimensional tolerance range. The basic dimension of the reamer diameter is equal to the basic dimension of the hole diameter. The upper and lower deviations of the reamer diameter should be determined based on the tolerance of the machined hole, the contraction that occurs during reaming, and the manufacturing and wear tolerances of the reamer.

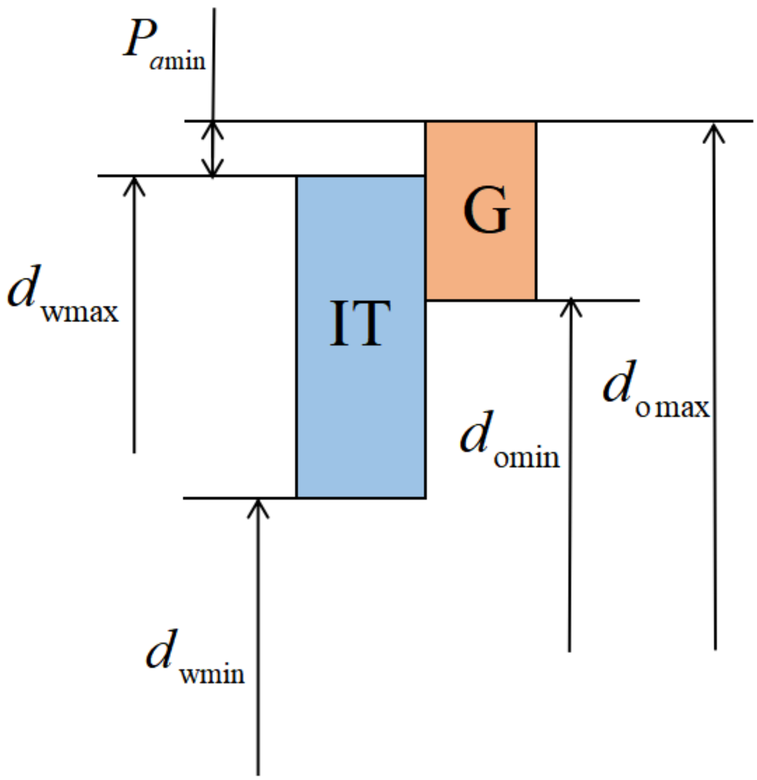


Figure 4.1 Reamer diameter tolerance for hole shrinkage after reaming

The reamer diameter tolerance band is calculated as shown in Figure 4.1. The relevant dimensions are as follows:

IT -Tolerance zone of base hole

G -Reamer diameter manufacturing tolerance

$d_{w\max}$ -The upper limit tolerance of hole

$d_{w\min}$ -The down limit tolerance of hole

$d_{o\max}$ -The upper limit tolerance of reamer

$d_{o\min}$ -The upper limit tolerance of reamer

$P_{a\min}$ -The amount of bore shrinkage in a hole machined with a carbide reamer.

$P_{a\max}$ -The amount of bore expansion in a hole machined with a carbide reamer.

According to national standards, the manufacturing tolerance of the reamer is specified as

$$G = 0.35IT \tag{1.6}$$

When the shrinkage occurs after reaming, according to general empirical data, the maximum expansion of carbide reamers is $P_{a\min}$

$$P_{a\min} = 0.1gIT \tag{1.7}$$

The maximum limit size of the reamer is given by

$$d_{o\max} = d_{w\max} + P_{a\min} \tag{1.8}$$

Therefore, the minimum limit size of the reamer is given by

$$d_{o\min} = d_{o\max} - G \tag{1.9}$$

In order to ensure the accuracy of the hole, the diameter of the reamer is also required to meet the tolerance requirements. The tolerance of the reamer is calculated based on the tolerance of the finished hole; the most common tolerance on reaming the finished hole is H7.

Table 4.1 is the tolerance Table for holes with H7 precision grade. Table 4.2 shows the diameter tolerance requirements for the reamer used when machining holes with different diameters with an accuracy requirement of H7.

Table 4.1 H7 hole tolerance

Hole Tolerance			
Diameter		**Tolerance Limit (mm)**	
Over	**Up to and including**	**High +**	**Low +**
	3	0.010	0
3	6	0.012	0
6	10	0.015	0
10	18	0.018	0
18	30	0.021	0
30	50	0.025	0
50	80	0.030	0

Table 4.2 Reamer diameter tolerance table based on H7 hole machining.

Reamer Tolerance			
Diameter		**Tolerance Limit (mm)**	
Over	**Up to and including**	**High +**	**Low +**
	3	0.008	0.004
3	6	0.010	0.005
6	10	0.012	0.006
10	18	0.015	0.008
18	30	0.017	0.009
30	50	0.021	0.012
50	80	0.025	0.014

4.2 Determining the critical value of reamer back taper for determining tool failure.

The back taper refers to a gradual reduction in the diameter of the reamer tool as it extends away from the end point of the cutting section and decreases slightly towards its cylindrical section. As shown in the Figure 4.2, the back taper value of a reamer is determined by measuring the change in diameter between two points, P_1 and P_2, these two points are 10 mm apart in the axial direction. The diameter near the cutting part should be larger than the diameter far from the cutting part, and the difference between these two diameters is the back taper value. The diameter measured at point P_1 is d_{01}, the diameter measured at point P_2 is d_{02}, then the value of the back taper value of the reamer is

$$\Delta d = d_{01} - d_{02} \tag{2.0}$$

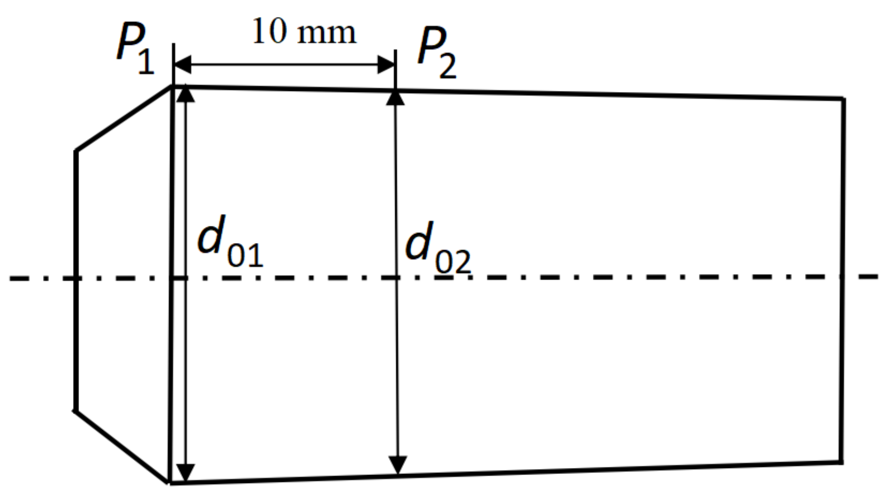


Figure 4.2 Elastic deformation of the machined hole wall.

Leveille [41] investigates the influence of different back taper values of the reamer on the quality of hole processing when reaming holes in stainless steel materials. The back taper value will vary depending on the material being machined. So, it's important to know the type of material you will be machining. Based on the empirical values within the reamer manufacturing industry, the design range of back taper values for reamers can be summarized for commonly used metallic materials. Table 4.3 lists the reamer back taper settings for machining common metals.

Table 4.3 Back taper value of the general metal

Material	Difference in diameter between axial lengths of 10mm
Bronze, brass, aluminum alloy, and other light alloys	0.001—0.005(mm)
Soft steel and medium hardness steel	0.003—0.007(mm)
Alloy steel and stainless steel	0.004—0.009(mm)
Heat-resistant steel and high-chromium stainless steel	0.006—0.012(mm)

The back taper value of a reamer is relatively small, but even slight variations in its value can significantly affect the surface quality of the machined hole. As shown in Figure 4.3, tool wear can easily cause changes in the back taper value, making it a useful criterion for determining tool failure. The following situations in the back taper value of a reamer can indicate tool failure: (1) the back taper value exceeds a predefined threshold, and (2) zero or positive taper angles are observed.

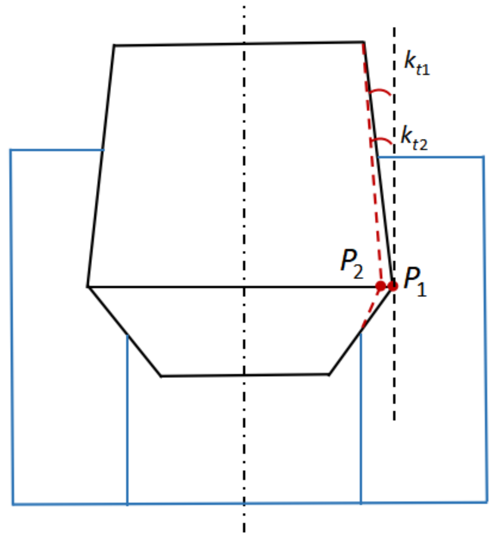


Figure 4.3 Flank face wear affects back taper value.

4.3 The tool life prediction process of reamer based on On Machine Measurement

Figure 4.4 shows a schematic of the reamers condition monitoring system. First, the diameter of the reamer is measured, which should be measured at the intersection point between the cylindrical section and the cutting section. If the radius exceeds the threshold value, the reamer is determined to be invalid, which means the failed reamer should be exchanged with a new one. Second, the back-off angle of the cylindrical should be measured after the radius is determined to be valid. The reamer is determined to be invalid when the back-off angle exceeds the threshold value. At last, if the radius and back-off angle are both measured to be valid, the reamer condition monitoring comes to an end.

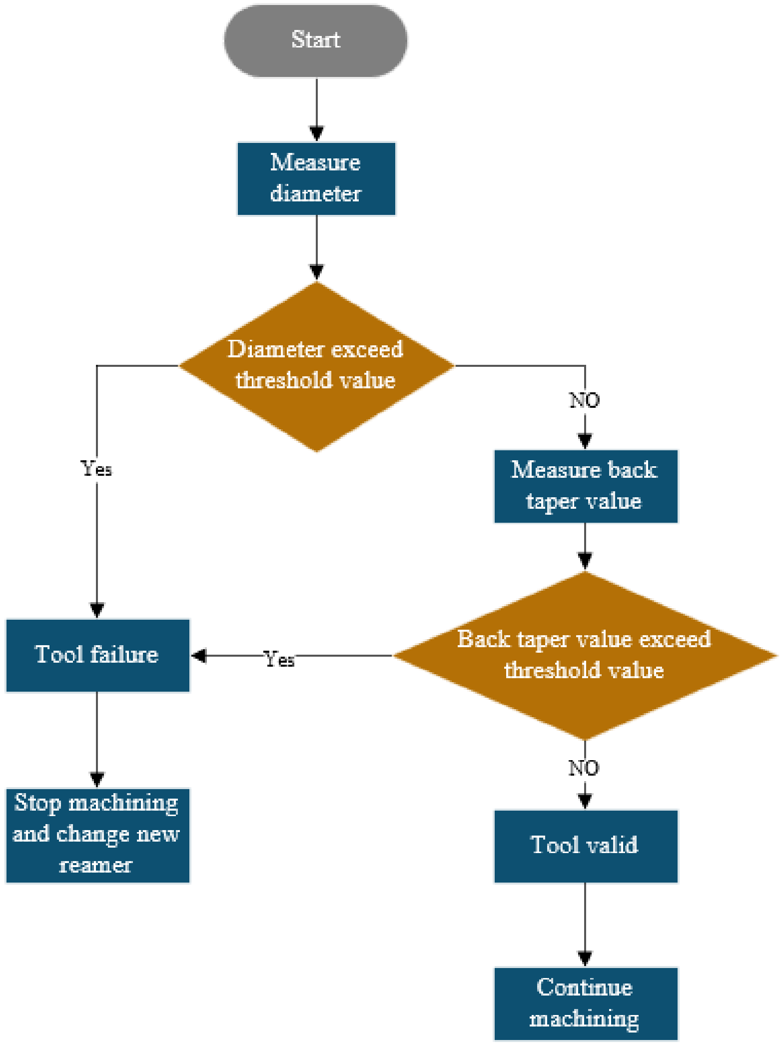


Figure 4.4 Flow chart for monitoring reamer life based on OMM.

Chapter 5 Experiments

5.1 Experimental objective

In the previous chapters, based on the cutting principle of reaming, the diameter of the reamer and the back taper value are chosen as the judgment factors for determining whether the reamer had failed or not.. Thus, the objective of this experiment is to establish an On-Machine Measurement system to monitor the changes in the diameter and back taper of a reamer during continuous reaming operations. The aim is to investigate the effects of reamer diameter and taper deviations on the quality of machined holes. Specifically, the experiment focuses on observing whether the quality of the machined holes meets the required standards when the reamer's diameter and back taper values exceed specified tolerances.

5.2 Experimental setup

The experiments are conducted to achieve the objectives. Here, the experimental setup is introduced. A machine reamer D10*70 is adopted (see Figure 5.1). The workpiece material is 35CrMo alloy steel. Figure 5.2 shows the experimental setup. A three-axis CNC milling machine is employed, and a laser tool setter is set up on the machine Table. A 50 by 50 by 30 mm workpiece is clamped with a vise, as shown in Figure 5.3. Some holes with a diameter of 9.8 mm were machined on the workpiece using a drill as a pre-reaming hole.

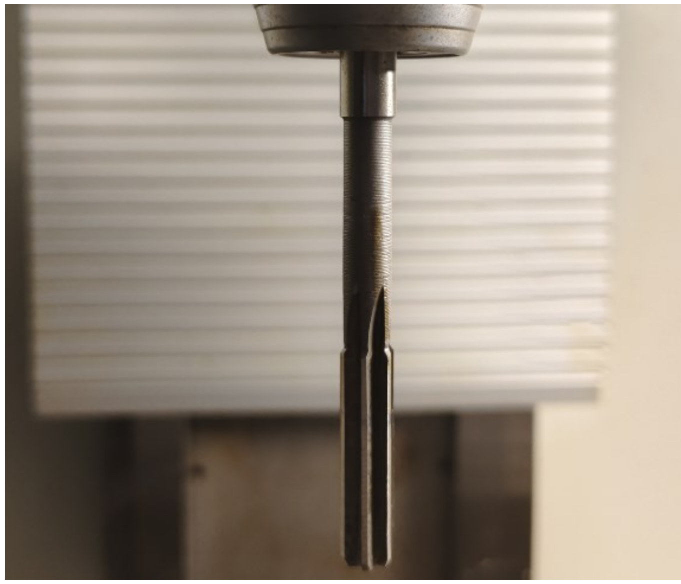


Figure 5.1 D10*70 machine reamer.

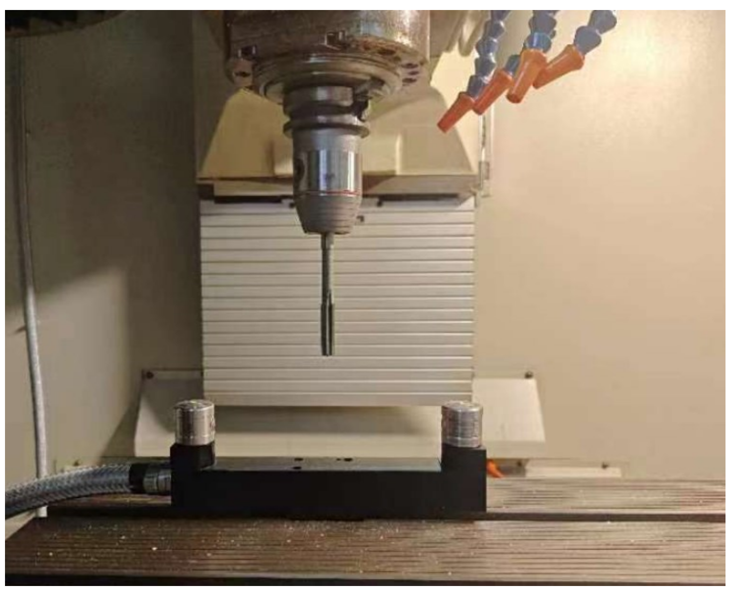


Figure 5.2 The experimental environment is set up.

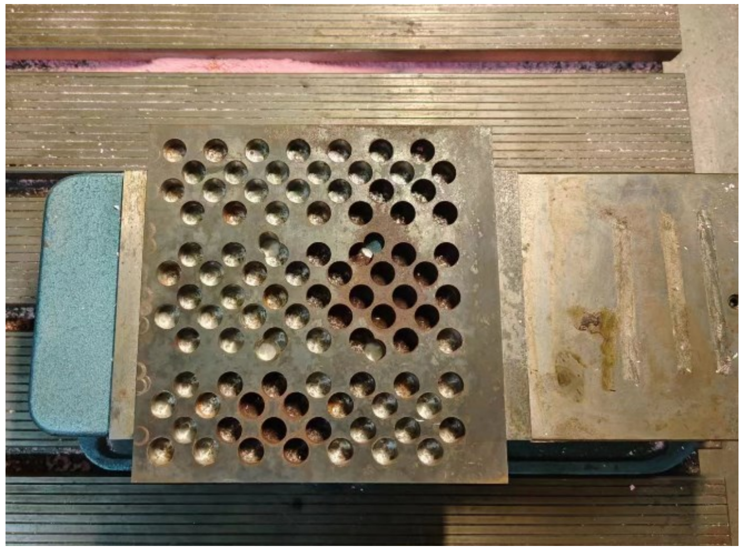
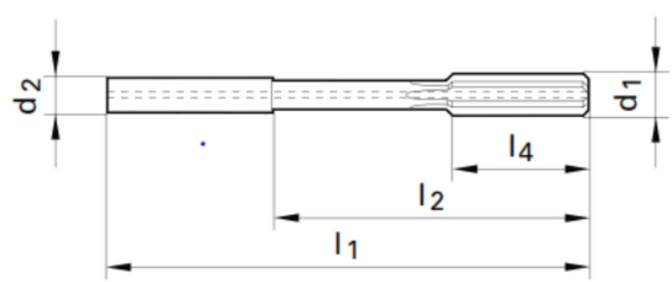


Figure 5.3 The 35CrMo alloy steel workpiece with some holes is fixed in a vise.

The reamer tool specifications selected for the experiment are listed as Table 5.1. The material of this reamer is carbide. The highest grade of accuracy that can be achieved with this reamer is H7.

Table 5.1 Main dimensions of reamers



Tool	**d1**	**L4**	**L2**	**L1**	**d2**
Reamer	10mm	30mm	050mm	100mm	10mm

5.3 Experimental process and results

The experimental process can be described as follows. Firstly, prepare the machining setup with the reamer, workpiece, and laser tool setter. As a baseline reference, perform initial dimension measurements on a new, unworn reamer. As shown in Figure 5.4, the diameter of point P1 on the reamer is initially measured, denoted as d01. Subsequently, the diameter of point P2 is measured, designated as d02. Point P2 is located at a distance of 10mm from the rear end of the reamer. By obtaining measurements of the diameters at these two points, the back taper value of the reamer can be calculated. These parameters collectively form the initial measurements for a new reamer before its utilization in machining operations.

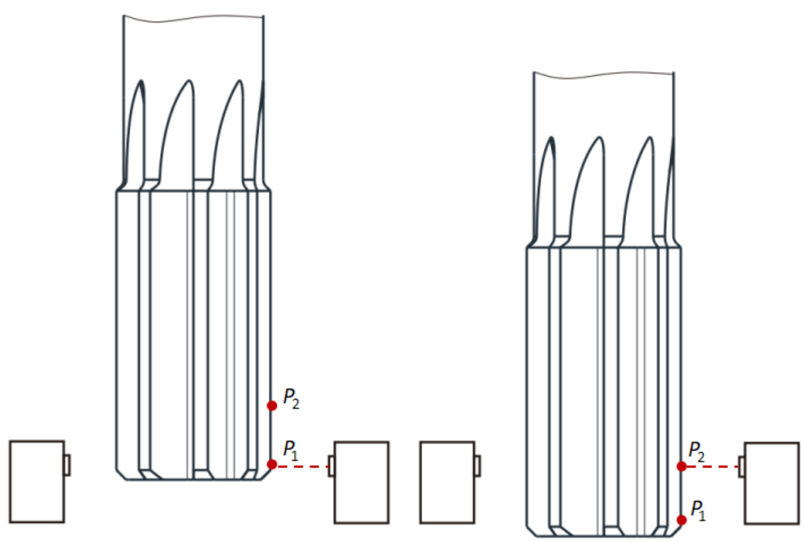


Figure 5.4 Measuring the diameter of the reamer on two positions in the OMM system.

The reamer tool cuts the workpiece with a feed of 0.2 mm/rev, cutting speed of 200 m/min. Measurements are taken every 15 holes machined to obtain the reamer diameter and back taper values at this point. If both values are within acceptable limits, record them and continue the manufacturing process. However, if either of these values exceeds the specified tolerance, the machining was continued for another 30 holes,and stop machining, then the experimental data was summarized in a Table 5.2.

Table 5.2 The Diameter measurements at points P1 and P2 of the reamer

Machined holes	**0**	**10**	**20**	**30**	**40**	**50**	**60**
d01 (mm)	10.012	10.011	10.010	10.008	10.004	10.0	9.996
d02 (mm)	10.007	10.006	10.006	10.005	10.002	10.001	9.999
Δd=(d01-d02) (mm)	0.005	0.005	0.004	0.003	0.002	-0.001	-0.003

The reaming accuracy requirement is H7, then the hole accuracy requirement is $10_{0}^{+0.015} mm$, according to the previous section of the study, the reamer diameter accuracy tolerance requirement is $10_{+0.006}^{+0.012} mm$. The material of workpiece is 35CrMo alloy steel, belongs to the medium hardness of the alloy steel, reamer back taper requirement is form 0.003mm to 0.007mm. Based on the above machining requirements, the required effective dimensions of the reamer for this experiment are provided in the Table 5.3.

Table 5.3 The required effective dimensions of the reamer for this experiment

	Standard value	**Lower limlit**	**Upper limit**
Diameter of reamer (d01)	10mm	0.006mm	0.012mm

Back taper (Δd)	-	0.003mm	0.007mm

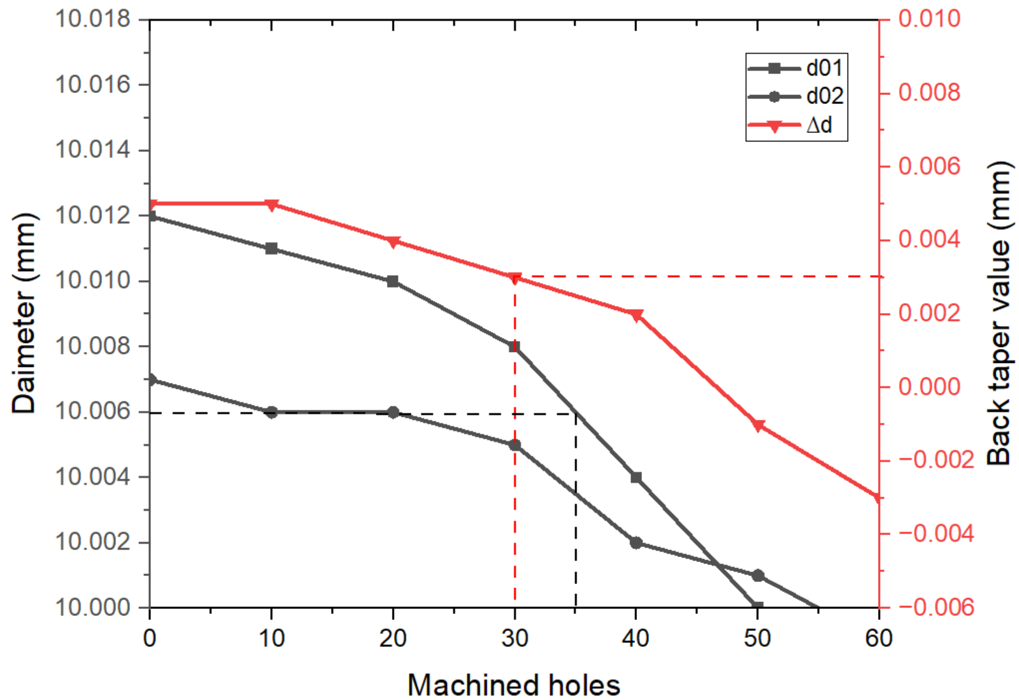


Figure 5.5 Measured data of reamer diameter and back taper value during hole reaming process.

Figure 5.5 shows that as the quantity of machined holes increases, the diameters measured at points P1 and P2, denoted as d01 and d02, respectively, gradually decrease. The back taper value of reamer ,denoted as Δd, decreases correspondingly. Upon machining the 30th hole, the back taper value reaches the lower limit of the effective tolerance, with a value of 0.003 mm. Continuing the hole-machining process, around the 35th hole, the diameter of reamer reaches the lower limit of the diameter's effective tolerance, at 10.006 mm. According to the method proposed in this article for determining the lifespan of the reamer, if either the diameter or the back taper value deviates beyond specifications, the reamer tool is considered to have failed. Therefore, in this experiment, reamer tool failure is indicated upon reaching the 30th hole.

After the reaming process is completed, measure the diameter of the hole using an internal micrometer, and consolidate the data in the Table 5.4.

Table 5.4 The Diameter of finish holes

Machined holes	0	10	20	30	40	50	60
Hole diameter	10.009	10.008	10.004	10.001	9.997	9.991	9.984

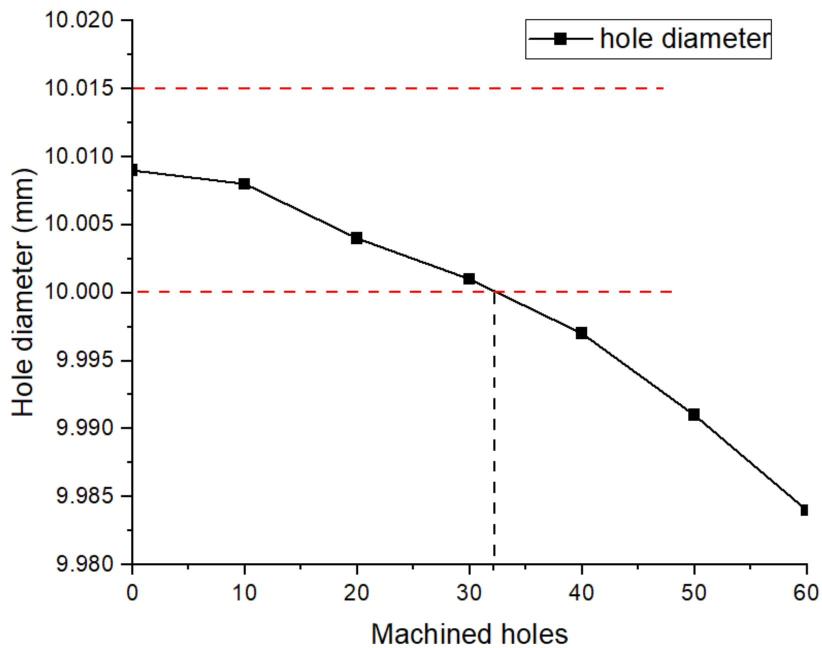


Figure 5.6 As the number of reamed holes increases, the diameter of the holes changes.

The tolerance of a 10mm diameter hole with an H7 tolerance grade is (0, +0.015mm). Figure 5.6 shows the variation in hole diameter dimensions as the number of reamed holes increases. With the rise in the number of reamed holes, the diameter of the hole gradually decreases. Eventually, upon reaching the 33rd hole in the machining process, the aperture exceeds the lower tolerance limit.

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Based on the data presented in Figure 5.5, it can be inferred that the reamer becomes ineffective after machining up to the 30th hole, utilizing the proposed in-process measurement method for reamer lifespan assessment, as outlined in this study. Figure 5.6 further illustrates that upon reaching the 33rd hole, the hole diameter exceeds tolerance limits defined by the lower specification of H7 grade. Thus, this experiment effectively validates the feasibility of employing the reamer's diameter and back taper measurements to ascertain its operational lifespan.

Conclusions

There are three primary objectives accomplished in this research. It has introduced new models for predicting reamer diameter reduction and reamer back-taper change. Furthermore, the study has proposed an innovative approach for identifying critical values of reamer diameter reduction and back-taper change crucial for determining tool life. A verification experiment was conducted to validate this approach, and the results unequivocally confirmed the effectiveness and reliability of the proposed methodology.

This research presents an innovative approach to predict the tool life of reamers, tackling the complex challenges of integrating on-machine measurement and tool condition monitoring. By thoroughly analyzing the impact of wear on reamer dimensions and understanding wear patterns, the study aims to precisely predict tool life by identifying wear-induced indicators of reamer failure. A vital advantage of this method lies in using a laser tool setter on the machine tool for direct tool size measurement, enabling accurate tool life predictions and facilitating real-time wear detection. This holistic approach enhances machining precision and efficiency by guiding timely tool replacement or maintenance decisions. In summary, this research offers a practical and valuable solution for improving machining processes, making a significant contribution to the field of mechanical engineering.

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