EXTRUSION: 1. MICROSTRUCTURES; 2. MODELING;
3. ALLOY MICROSTRUCTURES, CONSTITUTIVE ANALYSES; 4. MAGNESIUM ALLOYS

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(REPRINTS OF SELECTED ARTICLES IN SECTION LISTS INDICATED BY **'R'**)

OBJECTIVES:
Section 1.0 presents the transmission electron microstructures (TEM) observed in Al extrusions [7-10] and relates them to earlier analyses with polarized optical microscopy (POM) and X-ray diffraction (XRD). (TEM work was performed while H.J. McQueen was Associate Professor at Ecole Polytechnique, Montreal, on specimens extruded by Prof. J.J. Jonas, at McGill). The extrusion substructures in compression and rolling [18,19,30] were confirmed (work performed at Physical Metallurgy Labs of Energy Mines and Resources, Ottawa). The observations, over a wide strain range 0.7, 2.3 and 3.4, strongly indicated that in steady state ($\varepsilon > \varepsilon_S$) T, $\dot{\varepsilon}$, σ_S, constant, subgrains remained constant in size d_S misorientation ψ_S, internal dislocation density (mechanism dynamic recovery, DRV). Moreover, they remained equiaxed as grains elongated indicating that the subgrain boundaries (SGB) continually rearrange (repolygonization, McQueen, et al., ed.), as was confirmed by much higher strains in torsion [4,10,16,20,40,60] (such work was conducted on sabbaticals with Solberg, Nes and Ryum (Tronheim); Kassner (Lawrence, Livermore) and Blum (Erlangen) (Sections 3.1, 3.2, 3.3)

There are three extrusion reviews [191,228,290] covering Al, Al-Mg-Mn (5000), Al-Mg-Si (6000) and Al-Zn-Mg (7000, no Cu) that describe hot-strength constitutive equations, microstructural development and mechanical properties. The reviews also examine as-cast grain structure and impurity phases (constitutive particles) and in addition homogenization processing. The extrusion microstructures arising from the variations in T, $\dot{\varepsilon}$, and ε in the work zone near the die exit (Section 2.0) and in addition, the changes during cooling are also explained. (These publications were developed in association with a lecture series presented at the laboratory of COMALCO, Melbourne, while H.J. McQueen was on sabbatical there). In conjunction, many production alloys [132,322,341,342, 354,355,372] (with J. Belling) were tested in torsion at BHP Laboratory, with Peter Hodgson). After the reviews, later papers in Section 1.0 discuss various aspects of extrusion microstructures, as clarified through hot deformation by other techniques, often in relation to the modeling strain profiles (Section 2.0).

Extrusion modeling (Section 2.0) starts with the hot-torsion determination of constitutive equations and microstructure for a series of alloys 2618, 6061, 7075, A356 and their composites with Al_2O_3 or SiC, as prepared by DURALCAN through liquid-metal mixing. The data was then employed to model by DEFORM FINITE ELEMENT TECHNIQUEthe extrusion at several billet T, extrusion ratios and ram speeds, providing maximum load, t, ε and $\dot{\varepsilon}$. From the distributions in the intense deformation zone, estimates are made of microstructural evolution and the probability of failure.

In Sections 3.1, 3.2, the substructures in single-phase Al alloys from tests with uniform T, $\acute{\varepsilon}$ and ε are presented to confirm those from extrusion. The very high strains ε=60 in torsion lead into the complex structures arising from the grains thinning down to the point that grain boundary (GB) serration touch pinching off the grain. Insofar as this produces shorter grains containing substructures sot that more subgrains touch the GB, McQueen, et al. named it geometric dynamic recrystallization gDRX [70,115,116,145]; however, since there is only DRV defining the substructure, a better name is **g**rain-defining **gDRV**. The theory, **c**ontinuous **dDRX**, suggests all SGB are rising in ψ does not take account of transition boundaries developing between deformation bands that rise rapidly in ψ being permanent, unlike the SGB.

In Sections 3.2,8,9 the substructures of alloys (5000, 3000 can-stock, Al-Fe-Co conductors) with stable particles Al6Mn and Al3Fe are presented. Precipitation hardening alloys (6000, 7000, 2000, 8000) rre explained in section3,3,4,5,6,7 and composites in 3.10. Microstructures for Mg alloys are in section 4.0. READING ORDER FOR FASTEST LEARNING IF ACQUAINTANCE WITH MICROSTRUCTURES IS LIMITED (Appendix A)

Reprints of 50 entire articles are provided for more significant, older papers and for more recent proceedings papers. Recent journal papers are omitted, since available on the publishers' websites. Those reprinted are indicated by **'R'** directly under the Paper number. They are distributed in folders, numbered/named after Sections, such as **R**1.1, **R**1.2; however, Sections 3.1,3.2,3.8 and 3.9 are grouped in **R**3.1,2,8,9 and sections on precipitation alloys are grouped in **R**3. 3,4,5,6,7. Mg alloys, both extrusion modeling and microstructures are in **R**4.0

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1.0 Extrusion Microstructures:

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8.**R** DYNAMIC RECOVERY DURING THE EXTRUSTION OF ALUMINUM, J.J. Jonas, H.J. McQueen and J.J. Jonas, Deformation Under Hot Working Conditions, Iron Steel Inst., London, (1968), pp. 49-59.

9.**R.** INTERPRETATION OF EXTRUSION SUBSTRUCTURES AS REVEALED BY ELECTROLYTIC ETCHING OF ALUMINUM, J.J. Jonas, H.J. McQueen and D.W. Demianczuk, ibid. 8, pp. 97-99.

10.**R.** DEFORMATION OF ALUMINUM AT HIGH TEMPERATURES AND STRAIN RATES, H.J. McQueen, W.A. Wong and J.J. Jonas, Can. J. Phys., 45, (1967), 1225-1234.

191**R.** APPLICATION OF HOT WORKABILITY STUDIES TO EXTRUSION PROCESSING: PART I, EXTRUSION CONTROL PARAMETERS AND CONSTITUTIVE EQUATIONS, H.J. McQueen and O.C. Celliers, Materials Forum (Australia), 17, (1993), 1-13.

193. EFFECT OF HOMOGENIZATION AND PRECIPITATION ON EXTRUDABILITY, MECHANICAL PROPERTIES OF AA2024, M.E. Kassner, X. Li, and H.J. McQueen, Mat. Sci. Eng., 169, (1993), 9-17.

228**R.** APPLICATION OF HOT WORKABILITY STUDIES TO EXTRUSION PROCESSING PART II, MICROSTRUCTURAL DEVELOPMENT AND EXTRUSION OF Al, Al-Mg AND Al-Mg-Mn ALLOYS, H.J. McQueen and O.C.Celliers, Can. Metal. Quart., 35, (1996), 305-319.

270. K MICROSTRUCTURAL EVOLUTION OF ALUMINUM AND ALLOYS AT HIGH STRAINS, M. Richert and H.J. McQueen, Hot Workability of Steels and Light Alloys-Composites, H.J. McQueen, E.V. Konopleva and N.D. Ryan, eds., Met. Soc. CIM, Montreal, (1996), pp. 15-26. *(COLD)*

290**R.** APPLICATION OF HOT WORKABILITY STUDIES TO EXTRUSION PROCESSING PART III: PHYSICAL AND MECHANICAL METALLURGY OF Al-Mg-Si AND Al-Zn-Mg ALLOYS, H.J. McQueen and O.C. Celliers, Can. Metal. Quart., 36, (1997), pp. 73-86.

303. MICROBAND FORMATION IN CYCLIC EXTRUSION COMPRESSION OF ALUMINUM, M. Richert,

H.J. McQueen and J. Richert, Can. Met. Quart., 37, (1998), 449-457. *(COLD)*

309. MECHANICAL FORMING OF ALUMINUM MATRIX COMPOSITES, H.J. McQueen and E. Evangelista, Materials for Lean Weight Vehicles, Inst. Materials, London, P15, (1997), pp. 323-332.

375 HOT DEFORMATION MODE AND TMP IN ALUMINUM ALLOYS, H.J. McQueen and M.E. Kassner, Light Weight Alloys for Aerospace Application, K. Jata, et al., eds., TMS-AIME, Warrendale, Warrendale, PA, (2001), pp. 63-75

381**R.** EXTRUSION DESIGN AND MODELING OF Al ALLOYS, H.J. McQueen, D.S. Salonine and E.V.
K Konopleva, Multidisciplinary Design in Engineering, R.B.Bhat, et al.,eds.,CSME-MDE,(2001)(electr, pub.)

385**R.** ANALYSIS OF EXTRUSION CONDITIONS FOR 6063, 6061, 5083, 2024, 7075, D. Salonine and H.J. McQueen, Enabling Technologies for Light Metals and Composite Materials, T. Lewis and M. Charron, Met. Soc. CIM, Montreal, (2002), pp. 931-947.

405. REDUCTION OF TEMPERATURE EXTREMES AT THE DIE EXIT IN ALUMINUM ALLOYS EXTRUSION, D.S. Salonine and H.J. McQueen, Aluminum Alloys: Physical Mechanical Properties, ICAA9, J.F. Nie, et al., eds., Monash Univ. Melbourne, Australia, (2004), pp. 1086-1091.

408. STUDIES ON HOT WORKING AND MICROSTRUCTURE EVOLUTION OF ALUMINUM ALLOYS IN RUSSIA, D.S. Salonine and H.J. McQueen, Light Metals/Metaux Legers 2004, D. Gallienne and R. Ghomaschi, eds., Met. Soc., CIM, Montreal, (2004), pp. 57-69.

418**R.** EXTRUSION OF TUBES AND HOLLOW SHAPES FROM Al ALLOYS, D.S. Salonine and H.J. McQueen, Light Metals 2005 Métaux Legers, J-P. Martin, ed., Met.Soc.CIM, Montreal, (2005),pp.305-317.

422 HISTORICAL EVOLUTION OF THERMOMECHANICAL PROCESSES APPLIED TO ALUMINUM ALLOYS, H.J. McQueen, (ICAA10 2006, Vancouver), Mat. Res. Forum, 519-523, (2006), 1493-1498.

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435 MODEL FOR FRICTION STIR WELDING FROM PIERCING/EXTRUSION, H.J. McQueen, M. McQueen, M. Cabibbo and E. Evangelista, Light Metals in Transport Applications, Met Soc. CIMM Soc. CIMM, Montreal, (2007), pp. 141-155.,

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297. CONSTITUTIVE ANALYSIS AND EXTRUSION MODELING OF ALUMINUM MATRIX COMPOSITES, H.J. McQueen, J. Charlton and E. Herba, Light Metals 1998 Metaux Legers, M. Sahoo, C. Fradet, eds., Met. Soc. CIMM, Montreal, (1998), pp. 47-59.

307**R.** EXTRUSION MODELLING OF 6061 ALLOY AND PARTICLE REINFORCED MMCs, E.M. Herba and H.J. McQueen, Mat. Sci. Tech., 14, (1998), 1057-1064.

310**R.** MODELING OF THE EXTRUSION OF 2618 Al ALLOY AND OF 2618/10% Al_2O_3 AND 2618/20% Al_2O_3 COMPOSITES, M. Sauerborn and H.J. McQueen, Mat. Sci. Tech., 14, (1998), 1029-1038.

316. COMPARISON OF EXTRUSION MODELING OF AA7075 WITH OTHER ALLOYS AND COMPOSITES, E.V. Konopleva, H.J. McQueen and M. Sauerborn, Hot Deformation of Al Alloys, T.R. Bieler, et al., eds., TMS-AIME Warrendale, PA., (1998), pp. 397-406.

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378**R.** DISTRIBUTIONS OF ε, $\dot{\varepsilon}$, T and σ IN EXTRUSION MODELING OF Al ALLOYS AND COMPOSITES, H.J. McQueen, E.V. Konopleva, H. Farah and E. Herba, Design, Manufacturing and Application of Composites, CANCOM 2001, S.V. Hoa, A. Johnston, J. Deneault, eds., Technomic Pub., Westport, CT., (2001), pp. 435-444.

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385 ANALYSIS OF EXTRUSION CONDITIONS FOR 6063, 6061, 5083, 2024, D. Salonine and H.J. McQueen, Enabling Technologies for Light Metals and Composite Materials, T. Lewis and M. Charron, Met. Soc. CIM, Montreal, (2002), pp. 931-947. **(in R.1)**

404 EXTRUSION ANALYSES BY FEM AND BY TRADITIONAL METHODS FOR 7075 MATERIALS, H.J. McQueen and Y. Yao, Aluminum Alloys: Physical Mechanical Properties, ICAA9, J.F. Nie, et al., eds., Monash Univ., Melbourne, Australia, (2004), pp. 610-615.

409**R.** COMPARISON FOR 6061 MATERIALS OF EXTRUSION ANALYSES BY FEM AND BY TRADITIONAL METHODS, H.J. McQueen and Y. Yao, Light Metals/Metaux Legers 2004, D. Gallienne and R. Ghomaschi, eds., Met. Soc., CIM, Montreal, (2004), pp. 213-224.

419. HOT WORKABILITY AND EXTRUSION MODELLING OF MAGNESIUM ALLOYS, H.J. McQueen and M. Sauerborn, Z. Metallkd. 96, (2005), 638-644.

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19**R.** MICROSTRUCTURES OF ALUMINUM COMPRESSED AT VARIOUS RATES AND TEMPERATURES, H.J. McQueen and J.E. Hockett, Met. Trans., 1, (1970), 2997-3004.

30**R.** THE DEFORMATION OF METALS AT HIGH TEMPERATURES, H.J. McQueen and W. J. McG. Tegart, Scientific American, 232 [4], (1975), 116-125.

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104. INITIATING NUCLEATION OF DYNAMIC RECRYSTALLIZATION PRIMARILY IN POLYCRYSTALS, H.J. McQueen, Mat. Sci. Eng., 101, (1988), 149-160.

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(For gDRX = gDRV see: 115, 116, 226, 234, 250*, 259*(*Al-Mg), 324, 337, 338, 403, 413, 423, 426, 430, 440. (cDRX multiphase 135 Al-Cu,143*,227 Al-Li) (not cDRX single phase: 338,403, 413);*

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401**R.**Al, Al-Mg, Mn, PART 2: HOT DUCTILITY AND EXTRUSION, Aluminium 80, [11], (2004), 1263-1270.

402**R.**Al, Al-Mg, Mn, PART 3. STATIC RESTORATION AND ROLLING SCHEDULES, Aluminium 80, [12], (2004), 1347-1355.

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132. STATIC RECRYSTALLIZATION OF Al-Mn-Mg ALLOYS AFTER HOT TORSION, B. Crawford, J. Belling, H.J. McQueen and A.S. Malin, Recrystallization '90, Intnl. Conf. Recrystallization in Metallic Materials, T. Chandra, ed., TMS-AIME, Warrendale, PA., (1990), pp. 655-660.
322. CONSTITUTIVE RELATIONSHIPS FOR THE HOT WORKING OF AA 3004 (A1-1.0Mn-1.2Mg), H.J. McQueen, J. Belling, Innovations in Processing, Manufacturing of Sheet Materials, M. Demeri, ed., TMS-

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185. THE HOT WORKING CHARACTERISTICS OF EUTECTIC-ROD STABILIZED CONDUCTOR ALLOYS (Al-0.65Fe, Al-0.5Fe-0.5Co), H.J. McQueen, K. Conrod and G.Avramovic-Cingara, Can. Metal. Q., 32, (1993), 375-386. (Best Materials Science Paper CIM.)

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3.10 Aluminum Matrix Composites: (See also 308 in 1, 237 in 3.3 and many in Section 2)

229**R.** HOT DEFORMATION, DYNAMIC RECOVERY AND RECRYSTALLIZATION BEHAVIOUR OF A SiC_p/6061 Al COMPOSITE, X.Xia, P.Sakaris and H.J. McQueen, Mat. Sci. Tech., 10, (1994), pp. 487-494.

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306**R.** HIGH TEMPERATURE MECHANICAL AND MICROSTRUCTURAL BEHAVIOR OF A356/15 VOL.% SiCp AND A356 ALLOY, H.J. McQueen, M.M. Myshlyaev, E. Konopleva and P. Sakaris, Can. Met. Quart., 37, (1998), 125-139.

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4. Magnesium Alloys: (In extrusion modeling 326 in **R.2**, 419)

289. MICROSTRUCTURAL DEVELOPMENT IN Mg ALLOY AZ31 DURING HOT WORKING, A. Mwembela, E.V. Konopleva and H.J. McQueen, Scripta Metal. Mat., 37, (1997), pp. 1789-1795.

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312. HOT WORKABILITY OF FIVE COMMERCIAL MAGNESIUM ALLOYS, A. Mwembela, H.J. McQueen, E. Herba and M. Sauerborn, ibid. 311, pp. 215-222.

366. TWINNING, DYNAMIC RECOVERY AND RECRYSTALLIZATION IN HOT WORKED Mg-Al-Zn ALLOY, M.M. Myshlyaev, H.J. McQueen, A. Mwembela and E.V. Konopleva, Mat. Sci. Eng., A337, (2002), 121-133.

374. MICROSTRUCTURAL EVOLUTION AND STRENGTH IN HOT WORKING OF ZK60 (Mg), M.M. Myshlyaev, A. Mwembela and H.J. McQueen, Can. Metal. Quart., 42, (2002), 97-112.

428**R.**K HOT WORKABILITY OF Mg ALLOYS - INSIGHTS FROM Al ALLOYS, H.J. McQueen, Magnesium in the Global Age, M.O.Pekguleryuz, L.W.MacKenzie,eds.,Met. Soc. CIM Montreal, (2006), pp. 399- 420.

Appendix A:::

READING ORDER FOR FASTEST LEARNING IF ACQUAINTANCE WITH MICROSTRUCTURES IS LIMITED

For the bibliography, advice is needed for the best sequence to study them; although they are arranged in logical groups, the order of publication is somewhat arbitrary relative to theory development. Those not listed below are best left for specialized consultation
Reading order for fastest learning if acquaintance with microstructures is limited::

MICROSTRUCTURES AND MECHANISMS

30R. elementary description of DRV, DRX
7R,8R. first descriptions of extrusion substructure (hydrostatic pressure/diffusion not important)
10R. third in extrusion sequence giving the most advanced interpretation
18R good microscopy rolling
19R. good micros compression
70R. simple microscopy to high strain
104R. tables comparing DRV, SRV, DRX, SRX.
145R clear review of Al alloys without precipaitation
146R clear review of Al precipaitation alloys could be left until later
235R....Al detailed review clarifying limitations of EDE
288 advanced TEM, SEM of Al
NOW WELL PREPARED TO LOOK AT EXTRUSION
324R, focused review on TEM, OIM, XRD
334R,390R good reviews on TEM
115-6R. detailed results oof very high strain
368R simple presentation of SEM of 6060, compares gDRX and cDRX. … .185R.
POM, TEM micros, stability of Al-0.65Fe

EXTRUSION PROCESSING
228R Al, Al-Mg micros., constitutive, segregation
290R Al-Mg-Si, Al-Zn-Mg micros., properties
191R. constitutive good, modeling old fashioned
307R,377, modeling 6061/composites (best student)
359R. reviews modeling of all composites
375R. TMP, extrusion , rolling, forging
381R extrusion design simplified
378R. emphasis on distribution

Al-Mg ALLOYS
71. simple introduction, (effects of particle less valuable) … . 209R,213.
comparisons in mechanisms of Al and Al-5Mg
400-1-2R micros, ductility, rolling, extrusion