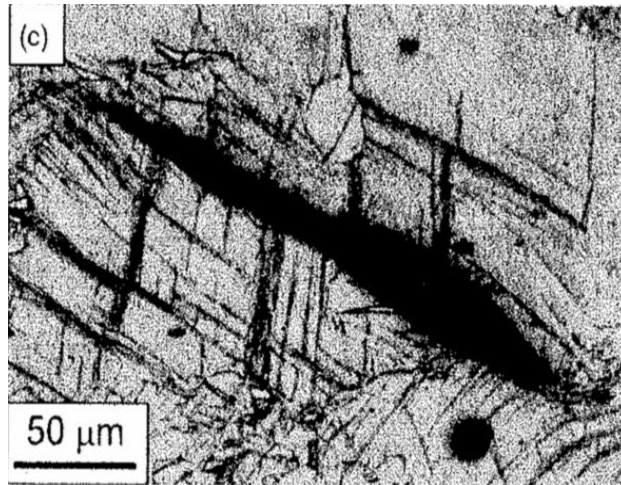




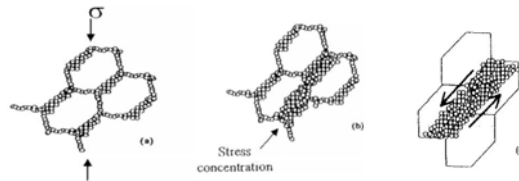
## Inherent Deformation Problems of State-of-The-Art Commercial Practice

Light weight Mg sheet would be in high demand in the automobile, aerospace, truck / trailer, battery, military and electronic/communication markets were it not for two factors, 1) high cost, and 2) poor formability. If cost could be reduced and if formability could be enhanced, the aforementioned markets could enjoy the benefits of lightweight Mg on fuel economy and reduction of pollutants.

Despite significant efforts and the ever increasing need for light weight magnesium wrought products, limited commercial application of forming processes for magnesium alloys has been realized. This can be attributed to: (1) limited operative slip systems at room temperature in the hcp crystal structure [Hart1968, Ree1960, Kel1968, Bart1980, Kim2003, Bar(2007a, 2007b, 2004), Koi(2005a,2005b), Agn(2001,2003,2004,2005, 2006), Jai(2007,2008)], where for Mg the CRSS for basal slip has been shown to be significantly less than for prismatic or pyramidal slip, as reviewed by Koike [Koi2003b]; (2) the tendency to form strong textures during deformation as described in recent years by Agnew and others [Agn(2001,2003,2004,2005,2006), Jai(2007,2008), Kim2003]; (3) the highly anisotropic deformation behavior of textured microstructures that lead to macroscopically anisotropic mechanical properties [Kel1968, Agn2006, Kle2004, Koi2005a]; and (4) the prevalence of significant twinning during deformation that can lead to premature fracture, as described by Barnett [Bar2007a, 2007b,2007c), Jai(2007,2008)]. For these reasons, metal forming, which involves complex deformation paths to produce a component, is virtually impossible for ordinary grain size Mg alloys at ambient temperatures and at strain rates that are commercially viable. Microscopically, it has been shown that twinning becomes more prevalent as grain size increases, temperature decreases and strain rate increases [Yan2006, Jai2008) Mey2001] and it can cause fracture at low strains. An example of this is illustrated from the work of Barnett [Bar2007c]. Figure 1 shows crack formation associated with  $\{10\bar{1}1\}$  double twins in room temperature deformation of rolled and annealed sheet derived from DC (direct cast) billet. Double twins are more favorably oriented for slip of  $\langle a \rangle$  type dislocations than the parent grains from which they form, and large strains in the twins can lead to incompatibility stress and fracture [Hart1968, Ree1960, Bar2004, Yoo1981, Jai2008]. It has also been shown that activation of  $\langle c + a \rangle$  slip rather than  $\langle a \rangle$  slip on non basal planes is responsible in limiting ductility. Obara [Oba1973] has reasoned that this is because the  $\langle c + a \rangle$  dislocations quickly dissociate into glissile  $\langle a \rangle$  and sessile  $\langle c \rangle$  segments greatly increasing work hardening and leading rapidly to fracture.



**Figure 1. Crack initiation and voids in coarse grained commercial AZ31 sheet (Bar 2007c).**



**Figure 2. Twin induced heterogeneous recrystallization leading to shear banding and hot cracking in coarse-grained commercial Mg alloys (Ion1982).**

Attempts to produce finer-grained stock from commercially cast alloys as a means to avoid twin-induced fracture are fundamentally limited by the microstructure and deformation behavior described above. In particular, warm deformation of coarse grained material can, through both basal slip and twinning, cause local dynamic recrystallization to form fine grains favorably oriented for deformation while at the same time leaving large grains between these soft regions where shear bands form and cause catastrophic cracking [Ion1982, del(2003, 2005b, 2008)], as illustrated from Ion's work in Figure 2. To avoid this inherent propensity, many small reductions and reheats are required to gradually coax the original coarse-grained cast material down to sheet. These small increments of reduction of large grained stock limit the ability to refine grain size and to refine eutectic intermetallic size. Such wrought commercial stock retains a grain size of 15 to 90  $\mu\text{m}$ , strong texture and brittle behavior well above ambient temperature. Hence formability and mechanical properties suffer.

## References

- Agn2001** S.R. Agnew, M.H. Yoo and C.N. Tome, *Acta Materialia* 49 (2001) 4277–4289.
- Agn2003** S.R. Agnew, C.N. Tome, D.W. Brown, T.M. Holden, S.C. Vogel, *Scripta Materialia* 48 (2003) 1003–1008.
- Agn2004** S.R. Agnew, J.A. Horton, T.M. Lillo, D.W. Brown, *Scripta Materialia* 50 (2004) 377–381.
- Agn2005** S. R. Agnew and O. Duygulu, *Int. J. Plast.* 21 (2005)1161.
- Agn2006** S.R. Agnew, D.W. Brown, C.N. Tome, *Acta Materialia* 54 (2006) 4841–4852.
- Al-S2008** T. Al-Samman, G. Gottstein, *Materials Science and Engineering A* 490 (2008) 411–420.
- Bar2003** M.R. Barnett, *Metall Mater Trans* 34A(2003)1799-1806.
- Bar2004** M.R. Barnett, Z. Keshavarz, A.G. Beer, D. Atwell, *Acta Materialia* 52 (2004) 5093–5103.
- Bar2007a** M.R. Barnett, *Materials Science and Engineering A* 464 (2007) 1–7.
- Bar2007b** M.R. Barnett, *Materials Science and Engineering A* 464 (2007) 8-16.
- Bar2007c** M.R. Barnett and N. Stanford *Scripta Materialia* 57(2007)1125-1128.
- Bart1980** C. Barrett and T.B. Massalski, Structure of Metals, 3<sup>rd</sup> Ed. Oxford: Pergamon Press, 1980 p. 768.
- Bie2002** N.E. Biery, Ph.D. Dissertation, Carnegie Mellon University, Pittsburgh 2002.
- Bie2003** N.E. Biery, M. De Graef and T.M. Pollock, *Metall. Mater. Trans.* 34A, 2301, (2003).
- Dec2008** R. Decker and S. LeBeau, *Advanced Materials & Processing* 166 (2008) No. 4 28-29.
- del2003** J.A. del Valle, M.T. Perez-Prado and O.A. Ruano, *Materials Science and Engineering A* 355 (2003) 68-78.
- del2005a** J.A. del Valle, M.T. Perez-Prado and O.A. Ruano, *Materials Science and Engineering A* 410-411 (2005) 353-357.
- del2005b** J.A. del Valle, M.T. Perez-Prado and O.A. Ruano, *Metall Mater* 36A (2005)1427-1438.
- del2008** J.A. del Valle and O.A. Ruano, *Materials Science and Engineering A* 487 (2008) 473-480.
- Doh1997** R.D. Doherty, D.A. Hughes, F.J. Humphreys, J.J. Jonas, D. Juul, Jensen, M.E. Kassner, W.E. King, T.R. McNelley, H.J. McQueen, A.D. Rollett, *Materials Science and Engineering A*238 (1997) 219 – 274.
- El-M2008** A.El-Morsy, A.Ismailb, M.Waly, *Materials Science and Engineering A* 486 (2008) 528–533.
- Eml1966** E. Emley; Principles of Magnesium Technology, Pergamon Press, London,1966.
- Gal2001** A. Galiyev, R. Kaibyshev and G. Gottstein, *Acta Metall* 49 (2001)1199-1207.
- Har2007** K. Hirai, H. Somekawa, Y. Takigawa and K. Higashi, *Scripta Materialia* 56 (2007) 237–240.
- Hart1968** W. Hartt, R. Reed-Hill, Trans. Metall. Soc., AIME, 242 (1968), p.1127.
- Ion1982** S.E. Ion, J.F. Humphreys and S.J. White, *Acta Metallurgica*, 30 (1982)1909-1919.
- Jai2007** A. Jain and S.R. Agnew, *Materials Science and Engineering A* 462 (2007) 29–36.
- Jai2008** A. Jain, O. Duygulu, D.W. Brown, C.N. Tome and S.R. Agnew, *Materials Science and Engineering A* 486 (2008) 545-555.
- Jia2007a** L. Jiang, J.J. Jonas, A.A. Luo, A.K. Sachdev, S. Godet *Materials Science and Engineering A* 445–446 (2007) 302–309.
- Jia2007b** L. Jiang, J.J. Jonas, R.K. Mishra, A.A. Luo, A.K. Sachdev, S. Godet, *Acta Materialia* 55 (2007) 3899–3910.
- Kel1968** E.W. Kelley and W.F. Hosford, *Trans. Metallurgical Society of AIME* 242(1968)654-.
- Kim2001** W. –J. Kim, S.W. Chung, C.S. Chung and D. Kum, *Acta Materialia.* 49 (2001) 3337–3345.
- Kim2003** W.-J. Kim, S.I. Hong, Y.S. Kim, S.H. Min, H.T. Jeong and J.D. Lee, *Acta Materialia* 51 (2003) 3293-3307.
- Kim2007** W.J. Kim, J.D. Park, J.Y. Wang and W.S. Yoon, *Scripta Materialia* 57 (2007) 755–758.
- Kle2004** S. Kleiner, P.J. Uggowitzer, *Materials Science and Engineering A* 379 (2004) 258–263.

- Koi2003a** J. Koike, T. Kobayashi, T. Mukai, H. Watanabe, M. Suzuki, K. Maruyama and K. Higashi, *Acta Materialia* 51 (2003)2055-2065.
- Koi2003b** J. Koike, R.Ohyama, T. Kobayashi, M. Suzuki and K Maruyama, *Materials Transactions*, 44 (2003) 445-451.
- Koi2005a** J. Koike and R. Ohyama, *Acta Materialia* 53 (2005) 1963-1972.
- Koi2005b** J. Koike, *Metall Mater Trans* 36A (2005)1689-1696.
- Liu2008** J. Liu, Z. Cui and c. Li, *Computational Materials Science* 41 (2008) 375–382.
- McQ2004** H.J. McQueen, C.A.C. Imbert *Journal of Alloys and Compounds* 378 (2004) 35–43.
- Mey2001** M.A. Meyers, O. Vohringer, and V.A. Lubarda,
- Miy2006** Y. Miyahara, Z. Horita, T.G. Langdon, *Materials Science and Engineering A* 420 (2006) 240–244.
- Muk2001** T. Mukai, N. Yamanoi, H. Watanabe and K. Higashi, *Scripta Materialia* 45 (2001) 89-94.
- Mys2002** M.M. Myshlyaev, H.J. McQueen, A. Mwembela and E. Konopleva, *Material Science and Engineering A* 337 (2002) 121-133.
- Nan2007** T. K. Nandy, R. M. Messing, J. W. Jones' T. M. Pollock, D. M. Walukas and R. F. Decker, *Metall. Mater. Trans.* 37A (2007) 3725-3736.
- Oba1973** T. Obara, H. Yoshinga, S, Morozumi, *Acta Metall.* 21(1973)845-853.
- Per2004** M.T. Perez-Prado, J.A. del Valle and O.A. Ruano, *Scripta Materialia*, 50 (2004)667-671.
- Ree1960** R. Reed-Hill, *Metall Trans Soc AIME*,218 (1960), p.554.
- Sad2008** N. Saddock, Ph.D. Dissertation, University of Michigan, Ann Arbor, MI 2008.
- Tu2008** W. Tu and T.M. Pollock, *Superalloys 2008*, TMS, 2 Warrendale, PA, in press, (2008).
- Wu2006** A. Wu, M. De Graef, T. M. Pollock, *Philosophical Magazine*, 86, 25-26, 3995 – 4008, (2006).
- Yam2001** A. Yamashita, Z. Horita, T.G. Langdon, *Materials Science and Engineering A* A300 (2001) 142-147.
- Yan2006** Q. Yang and A.K. Ghosh, *Acta Materialia* 54(2006) 5147-5158.
- Yoo1981** M.F. Yoo, *Metall Mater Trans A* 12 (1981) 409.