Materials Science Forum Vols. 654-656 (2010) pp 574-579
Online available since 2010/Jun/30 at www.scientific.net
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doi:10.4028/www.scientific.net/MSF.654-656.574

Thixomolded® and Thermomechanically Processed Fine-Grained Magnesium Alloys

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Keywords: Magnesium, molding, thermomechanical processing, mechanical properties, composites

Abstract. Thixomolding of Mg alloys produces fine microstructure of about 5-10 micron alpha phase grain size, surrounded by divorced eutectic phases. During the period from 1995 to 2009, this process and microstructure has captured broad applications around the globe - in markets such as electronics (lap-tops, cameras and cell phones), autos, sports and hand tools. Thermomechanical processing has been applied recently to the Thixomolded precursor to further refine the grain size and eutectic phases - providing yield strength above 300 MPa, fatigue strength of 150 MPa along with elongation of 10%. Alloys studied include AM60, AZ61L and thixoblended alloys of higher Zn content. Microstructure is related to processing and properties. Metal/epoxy fiber composites based on this Mg product have demonstrated yield strength of 900 MPa, with E of 90 GPa.

Introduction

The purpose of this paper is to discuss Thixomolding® of Mg alloys and the derived added-value thermomechanical processing. Thixomolding is a commercial process for injection molding Mg alloys [1]. The principle of the process is illustrated in Figure 1 - being analogous to plastic injection molding; but with higher temperature and faster shot velocity. Shot cycles as short as 10 seconds have been recorded on smaller machines; the range of clamp tonnages being 100-1600 tons. About 400 machines exist at the 50 licensees of Thixomat in this global business in 13 countries.

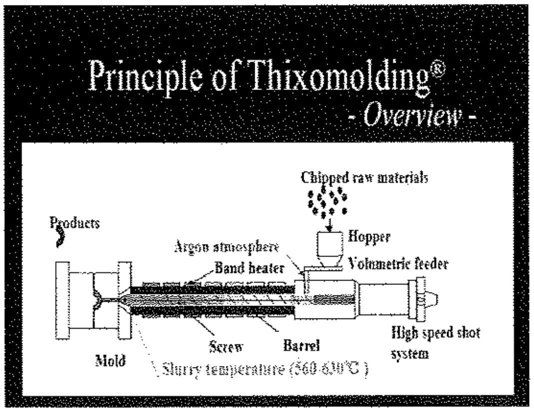

Figure 1 Schematic of Thixomolding Machine.

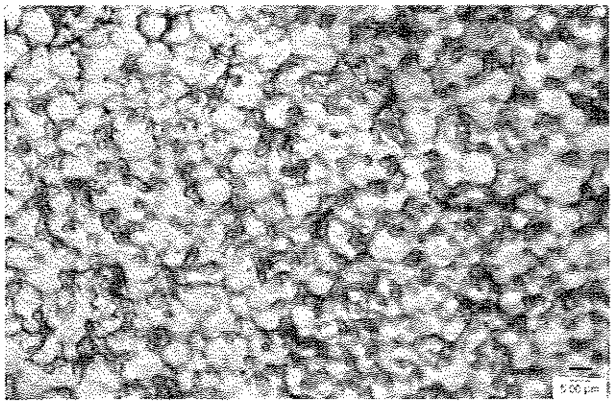

Figure 2 Optical micrograph of the as-thixomolded microstructure of AM60. Fine α phase (white) surrounded by divorced eutectic of dark β phase ($Mg_{17}Al_{12}$) and grey α phase.

Proven Advantages of Thixomolding

In the 15 year commercial experience with this process, the following advantages over conventional casting have been verified:

a. The most important is environmental friendliness, with no open foundry, no SF_6 gas, no sludge or dross - with worker comfort and safety.
b. Also of primary importance is net shaping of complex parts requiring little, if any, machining.
c. Tight dimensional control.
d. Longer die life, due to 80°C cooler metal temperatures.
e. Low porosity.
f. Higher ductility and fatigue strength.
g. Higher process yield.
h. Flexibility in part design.

History of Commercial Development

The electronic and communication (E/C) applications in Japan drove the early business in the 1990's – as in lap-top computers, cameras, projectors and cell phones. Following the recent intensive mode of globalization, much of this Thixomolding of E/C parts has moved to Taiwan, and now, China and Singapore. In the US, machine and hand tool parts, auto parts and sports equipment parts have supplemented the Thixomolding business in E/C parts. Table 1 summarizes applications of this technology.

Table 1. Applications of thixomolding

Auto	Electronic/Communication	Sporting Goods	Hand Held Tools
Seat Backs	Lap-top Computers	Sun Glasses	Drills
Steering Column Brackets	Cell Phones	Gun Scopes	Saws
Mirror Parts & Brackets	Digital Project	Fishing Reels	Chain Saws
Lazy Susan Bins	Digital Cameras	Snow Board Clamps	Nailers
Foldable Car Tops	Cam Corders	Motorcycle Wheels	
Windshield Wiper Boxes	TV Surrounds	Go-Cycle Bicycle	
Lift Gate Mechanisms	Walkman	LED Maglite	
Cup Holders	"Dog Tag" MP3 Player		
Brackets for Trucks	Defense Detectors		
	Radar Detectors		
	Check Sorters		

Lightweighting has been the dominant incentive for use of Mg parts – supplemented by stiffness, electromagnetic shielding, thermal conductivity and damping virtues of Mg. On a strength/density basis, Mg compares favorably to Al and steel,but also in bending, torsion, oil canning and denting.

The history of Thixomolding is incomplete without mention of the role of design of parts. Thixomat and its licensees found that simple part-for-part replacement of die castings was not fruitful. Rather, redesign of parts to save machining or to replace many parts of an assembly with one net-shape Thixomolded part was the route to success and lower costs in the market place. For example, a 50 to 1 reduction in subassemblies was accomplished in an electronic card-sorting part.

Variety of Thixomolded Alloys

The selection of alloys for Thixomolding over the last decade has followed the traditional alloys of this field of metallurgy; i.e. AZ91D, AM60 and AM50. The first alloy has been selected for strength, castability and corrosion resistance; the latter two when better ductility was demanded by the application.

However, none of these alloys exhibit good creep resistance above 150°C. Certain auto applications demand creep resistance at higher temperatures, up to 200°C. Thus arose the intense alloy development efforts of many organizations aiming at this target. The Mg - Al alloy base has been fortified by additions of Sr, Ca and Rare Earths; whilst the Al content has been retained at 5-6% to retain ductility. Notable results emerged from Dead Sea Magnesium as the MRI alloys, from Noranda as the AJ alloys, from AMT as the AM-Lite alloys and from MEL as Rare Earth alloys.

On alloying theory, reducing the Al to 5-6% reduces the volume % and size of the brittle β phase inherent in solidification of AZ91D. Sr, Ca and Rare Earth elements differ in size and electronegativity from the Mg atom. Thus, these addition elements can harden the Mg grains at high temperatures; but, more importantly, modify the β phase and its detrimental effect on grain boundary creep. Higher Zn/Al ratio in the AM-Lite alloys replaces β by Zn Mg intermetallics and makes for enhanced surface quality and plateability.

The MRI, AJ, WE43 and AM-Lite alloys have all been Thixomolded successfully, as were AZ61, AZ62, AZ63, AZ64, AZ55, ZA64, ZA75, ZA84 and ZA10/4. Thixoblending [2] affords the chance for "same-day" agile production of novel alloys from master alloys blended in the feed hopper of Thixomolders – and for the change of composition within minutes.

Thixomolded Microstuctures

Commercially, Thixomolded parts are applied in the as-molded condition without heat treatment, with microstructure characterized by four components. These components are a) 50 μm α particles formed in the machine at about 5 to 15 volume fraction, b) proeutectic α grains of about 5-10 μm grain size formed on cooling in the mold, c) divorced eutectic α phase and d) divorced eutectic β phase. The latter 2 phases are arrayed around the second phase - with the β particles taking a coarse elongated form of about 10 μm dimensions. Typical properties as Thixomolded are yield strength of 130 MPa, tensile strength of 230 MPa and elongation of 6-10%. For subsequent TMP, large α phase is avoided in the Thixomolded precursor, thus providing fine proeutectic α and eutectic β (see Fig.2).

Adding Value by Thermomechanical Processing

Recently, Thixomat has redirected its R&D toward enhancing the mechanical properties of the as-molded product by microstructural refinement enabled by thermomechanical processing TMP). First, the machine is run hotter to minimize the volume % of large α particles formed in the machine. Then TMP reduces the proeutectic α grain size to sub-micron size; but also subdivides the β eutectic particles to sub-micron sizes and partially dissolves the β phase. Some nanometer size β precipitates within the grains. The subdivided β particles, as arrayed in grain boundaries, inhibit grain growth.

Inherent Deformation Problems of State-of-the-Art Commercial Practice

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. One cause is the prevalence of significant twinning during deformation that can lead to premature fracture, as described by Barnett [3-5] and Jain [6,7]. For these reasons, metal forming, which involves complex deformation paths to produce a component, is difficult for ordinary grain size Mg alloys at ambient or warm 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 [7-9] and it can cause fracture at low strains. Barnett [5] found 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 <a> type dislocations than the parent grains from which they form, and large strains in the twins can lead to incompatibility stress and fracture [7,10-13]. It has also been shown that activation of <c + a> slip rather than <a> slip on non basal planes is responsible in limiting ductility. Obara [14] has reasoned that this is because the <c + a> dislocations quickly dissociate into glissile <a> and sessile <c> segments greatly increasing work hardening and leading rapidly to fracture.

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 [15-18] as illustrated from Ion's work in Figure 3. 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 μm, strong texture and brittle behavior well above ambient temperature. Hence formability and mechanical properties suffer.

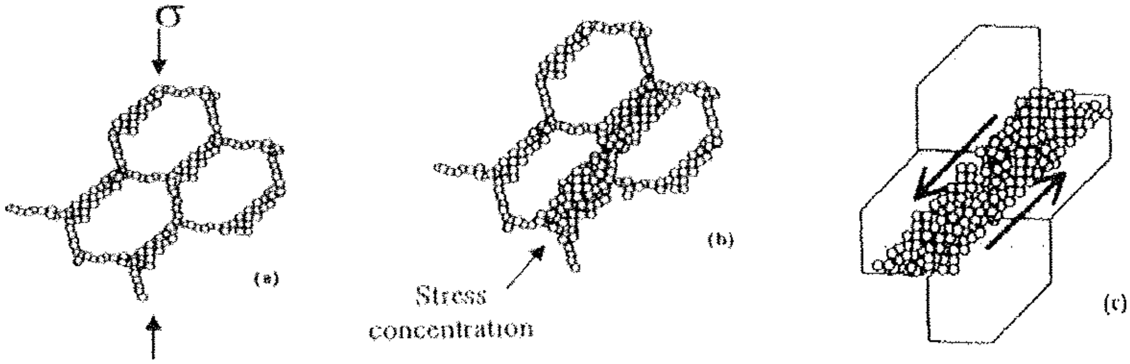

Figure 3 Twin induced heterogeneous recrystallization leading to shear banding and hot cracking in coarse-grained commercial Mg alloys [15].

The process, Thixomolding Thermal Mechanical Processing (TTMP), builds upon the fine grained, isotropic, low porosity of Thixomolded Mg alloys which contain eutectic phases (see Figure 2). Intense thermomechanical processing is applied to further refine the grain size and eutectic phases Furthermore, additional thermal treatments can be applied to optimize strength, ductility and formability

Tensile Properties of TTMP Mg Alloys

The mechanical properties of Thixomolded and TTMP AM60 are listed in Table 2, as are those of AZ61L in Table 3. Yield strength is more than doubled by TMP for both alloys - to exceed 300 MPa, without significant loss of ductility. Post-TTMP direct aging improved the combination of yield strength (320-340 MPa) and elongation (8-11 %) for the Zn containing AZ61L; but had little effect on low Zn AM60. Annealing of the two alloys improved elongation to 14-21 %, at the expense of strength of 226-240 MPa. Subsequent aging of AZ61L recovered some of the strength that was lost during annealing.

Table 2 Effect of processing on properties of thixomolded AM60

Condition	YS, MPa	UTS, MPa	Elong .%
As Thixomolded (T)	135	240	10
T+TMP	316-320	368-370	9-11
T+TMP+Direct Age	311-328	358-375	8-11
T+TMP+Anneal	218-244	302-312	18-21

Table 3 Effect of processing on properties of thixomolded AZ61L

Condition	YS, MPa	UTS, MPa	Elong., %
As Thixomolded (T)	130	220	7
T+TMP	305	362	6
T+TMP + Direct Age	326-340	372-378	5-8
T+TMP + Anneal	219-227	307-314	14-20
T+TMP + Anneal + Age	288	350	10

Table 4 broadens the survey of the effects of TMP on tensile properties – to Thixoblended alloys of higher Zn alloys of 1.5 to 7 % Zn. Of these alloys, the Mg-6 Al-1.5 Zn had the best combination of strength and ductility. As Thixomolded, the higher Zn alloys were stronger than AM60 and AZ61L. In general, TMP was effective in raising strength while gaining ductility. In Table 5, it is apparent that neither TRC nor DC+extruded stock of AZ31 responded to TMP strengthening to the magnitude that

Thixomolded AM 60 and AZ61L did. This is related to the large grain size of the starting commercial DC and TRC stock that predestined a final grain size of 10 μm in DC+TMP and 45 μm in the TRC+TMP materials.

Furthermore, edge cracking during TMP was minimal in Thixomolded material compared to medium edge cracking at 45° angles in DC extruded material and severe deep edge cracking in TRC stock.

Table 4 Benefit of TMP on yield strength and elongation of thixomolded Sheet Bars of AZ and ZA Alloys

Alloy	Thixom-old YS, MPa	Thixom-old El,%	TMP Red, %	TMP YS, MPa	TMP El.,%
AZ6/.5	181	6	76	303	10
AZ62	157	8	67	283	11
AZ63	145	8	72	299	7
ZA55	176	4	74	231	9
ZA64	194	4	77	256	8
ZA75	165	5	74	263	10

Table 5 Effect of composition and processing on mechanical properties of TMP Mg alloys (50% Reduction in one pass)

Alloy	Processing	YS, MPa	UTS MPa	El., %
AZ31	TRC+TMP	187	291	10
AZ31	DC+Extrude +TMP	174	282	17
AM60	Thixomold + TMP	316	368	9
AZ61L	Thixomold + TMP	305	362	6

Table 6 Average R values of TTMP + annealed

Sheets	No. of Samples	Direction	R Value
6	29	Transverse	1.0
6	27	45°	1.3
6	30	Longitudinal	1.2

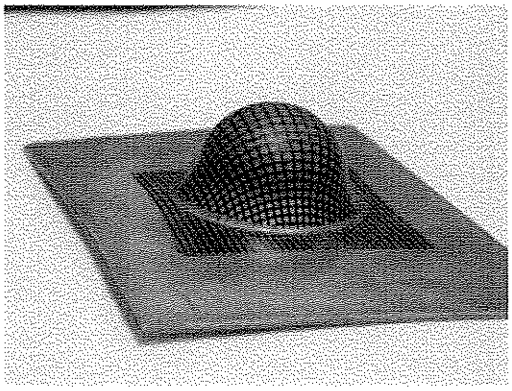

Figure 4 TTMP AZ61L sheet (1mm), formed at 300°C at 0.5 in/min.

Table 7 Comparison of reinforced metal alloys

	TTMP, AZ61/C Fiber Composite	TTMP AZ61L/C Fiber Composite	GLARE, 2024Al/Epoxy S Glass Fiber
Array	Mg/C/Mg	C/Mg/C	Multi-Al/S
YS, MPa	820	910	317
UTS, MPa	820	910	580
E, GPa	63	97	55
Density, ρ (g/cm^3)	1.70	1.70	2.38
YS/ρ	482	535	133
UTS/ρ	482	535	244
E/ρ	37	57	23
Bending Rigidity,E$^{1/3}$/ρ	2.34	2.70	1.60
Dent Resist., YS$^{1/2}$/ρ	16.8	17.7	7.48
Crash Resist., E$^{1/5}$/ρ	1.35	1.47	0.94

Formability

Annealing increased room temperature bendability of TTMP AM60 and AZ61L as well as Thixoblended/TTMP AZ6-1.5, AZ62, AZ63, AZ64, AZ55, ZA 65 and ZA 75. R values for multiple samples from 6 sheets of AM60 in the TTMP plus annealed condition are listed in Table 6. These average values range from 1.0 to 1.3, with the 45° samples on the high side of this range. A cup formability test is shown in Figure 4.

Laminate Composites

For the most demanding structural applications Mg alloys fall short on strength and stiffness. Likewise polymer matrix fiber composites fall short on fatigue, denting and damage resistance. It is hypothesized that a composite of Mg/polymer bonded fiber would overcome the shortcomings of each component. Thus, laminate composites of Mg alloy AZ61L and epoxy bonded carbon fibers were fabricated in order to test this idea. As seen in Table 7, three layer TTMP Mg/Epoxy C fiber/TTMP Mg exhibited an increase of yield strength (from 300 to 820 MPa) and E (from 45 to 63) over the Mg alloy base level. The reverse configuration with C fiber on the exterior of AZ61L was even stronger and stiffer.

This new TTMP composite is compared in Table 7 to GLARE, a commercial Al/epoxy S glass composite that is used in the Airbus A380 [19]. The TTMP composite test material demonstrated YS/ρ, UTS/ρ and E/ρ about twice that of GLARE. Furthermore, bending rigidity, dent resistance and crash resistance of TTMP composites should be superior to GLARE.

Conclusions

1. The fine (<10 μm) grain structure of Thixomolded Mg alloys is advantageous for thermomechanically processing (TMP) to finer grain sizes.
2. Twinning, shear banding and cracking during such TMP processing is minimized.
3. Yield strength can be doubled to 300 MPa by TMP of Thixomolded Mg alloys, without sacrifice of ductility.
4. Post-TMP thermal treatments can generate attractive combinations of strength, ductility and R values – to improve formability.
5. Thixomolded Thermomechanically Processed (TTMP) Mg alloy/epoxy bonded fiber composites can offer further strengthening and stiffening – to levels of yield strength of 900 MPa and modulus of elasticity of 90 GPa.

Acknowledgement

The authors are pleased to honor the support of NSF under Phase I & II STTR Contract 0847198.

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