Advances in Semi-Solid Molding

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Thixomolding is the semi-solid molding of metal net-shape parts by a machine similar to a plastic-injection molding machine, but it is fed with granules of magnesium rather than plastic. The granules are melted and molded entirely within the machine, without the need for an external foundry. Parts can be molded in 20-second cycles, need no heat treatment, and in many cases need no machining. Thus, 1000 or more parts could be delivered the same day as ordered, if a mold is already available.

Other attractive features include environmental friendliness, fire safety, worker comfort, and the fact that the process does not require SF6 (a global warming gas) and does not produce hazardous slag or dross. Parts are generally net shape, requiring little or no machining, and have low porosity. The technology allows redesign of systems to consolidate many parts into one (Fig. 1), and parts can hold extremely tight tolerances, up to ±0.0005 in./in. The low-density magnesium parts also provide superior mechanical and physical properties and recyclability compared to plastics.

This article describes process improvements in second-generation machines, alloy blending technology, and alloy design resulting from alloy/microstructure/mechanical property studies.

Process improvements
Recent process improvements include machine design, induction heating, hopper heating, and hot sprues/hot runners.

• Machine design: Our machine builders, Japan Steel Works and Husky, recently introduced second-generation machines that offer notable improvements over the 264 current machines with capacities of 75 to 850 metric tons. Shot velocity has been boosted to 5.4-6 m/sec, and hydraulics have been modified to one-to-one pistons for enhanced shot control. This enables molding of larger and thinner parts, and flashless molding is made feasible. Husky’s 1000 metric ton version for larger auto parts is scheduled for prototype runs this spring.

• Induction heating: Low-frequency induction heating has proven to be very advantageous in transmitting heat to the incoming magnesium granules. This has recently been applied in the first sections of the barrel in preference to current-technology ceramic heater bands. With heater bands, thermal energy must be transferred to the granules by thermal diffusion through the barrel and liner, and then transferred to the granules by radiation and contact of granules with the liner surface. As a result, heater bands extend cycle time, especially in larger machines.

In contrast, low-frequency (such as 60 Hz) induction heating provides deep penetration of energy into the barrel; in fact, as much as 30% of the energy can be coupled directly into the feed stock and screw. Tests on a JSW 220 metric ton unit at Thixomat have proven that throughput can be doubled and cycle times cut in half, to 18 seconds on 325-gram parts. Today, one power source and two coils provide flexibility in setting heating profiles to the particular solidus-liquidus range of the magnesium alloy being processed and to the target volumepercent solids.

• Hopper heating: Granules have been preheated to 280°C in the feed hopper as another means to speed molding, and the technology can reduce cycle time by 10%. As in plastic molding, this also serves to dry the granules, enabling screw action to become freer and more consistent. The source of heat is an extra circuit of die heater oil through tubes in the hopper, an economic solution.

• Hot sprues/hot runners: In this technology, the metal slurry is maintained not only in the barrel, but also right up to the part. A sprue and runner (which become scrap) are not needed and are not molded with each shot (Fig. 2). Thus, process yield is boosted significantly, and control of slurry flow in the part is enhanced. Larger parts can be molded on smaller machines. Compared to conventional cold sprues, cycle time has been reduced by 42%.

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Fig. 1 — A one-piece Thixomolded fairing (center) for the Buell motorcycle replaced a first-generation 22-part steel assembly (left) and a second-generation ten-part plastic assembly (right). This saves cost and time, and reduces weight by 40% compared with the steel option. Image courtesy Phillips Plastics.

Fig. 2 — Benefit of hot sprue (right) vs. conventional cold sprue (left) on cycle time and yield for snowboard boot binding. Shot weight saving was 37 g (11%) and cycle time was reduced by 6 seconds (19%). Image courtesy Phillips Plastics.
and scrap savings have been 58% in recent commercial production.

**Alloy blending**

Flexibility in production has been enhanced with the granule mixing process of Thixoblending. This technology allows a variety of new alloy compositions to be blended at the hopper stage and molded within minutes. Inventory needs are reduced to a few master alloys, and lead times are shortened.

As a demonstration, AM71(7 Al) and AZ81(8 Al) were molded from blended feedstock of AM60(6 Al) and AZ91D(9 Al). The mechanical properties followed the rule of mixtures, providing test bars of excellent mechanical properties as seen in Table 1. In additional studies, the alloys blended were

- AM20(2 Al) and AM60(6 Al) to mold AM30(3 Al) and
- AZ91D and ZAC alloys to mold Mg-Al-Zn low-calcium alloys.

**Alloy design**

Many organizations are pursuing alloy design at an intensity level unseen in the last three decades. Alloy producers, part makers, and end users are all contributing to the drive to improve strength, ductility, creep resistance, and fatigue resistance, while at the same time retaining the corrosion resistance of the most common AZ91D alloy. To achieve these properties, alloy designers are targeting lower porosity, reduced percentage of eutectic phase, a tougher eutectic phase, a more creep-resistant eutectic phase, and intragranular strengthening.

The alloying shopping list includes aluminum, zinc, calcium, strontium, yttrium, and rare earth elements. High aluminum content contributes to corrosion resistance, but aluminum forms the intergranular β Mg17Al12 eutectic component that is brittle and has a low melting point.

The benefit of lower aluminum on ductility is apparent in Table 1. Aluminum fails to precipitate in fine coherent particles within the grains. Hence, recent design tends toward lowering aluminum from 9%, while complexing with other candidate elements.

Strontium and calcium additions make for a more ductile and higher melting-point eutectic phase, justifying their complexing in lower-aluminum alloys such as the Noranda and General Motors candidates. For example, Noranda’s AJ52 and AJ62 with strontium processed well in our Thixomat machine. Tensile test results for AJ52 are tabulated in Table 1, demonstrating good elongation and hot strength.

- The complexing with yttrium and zinc generates surprising intragranular strengthening by stacking faults.
- Alloying with rare earth elements contributes nanosized coherent precipitates within the grains, very effectively stacked across the basal slip planes to resist dislocation motion and to boost strength.

As to fatigue resistance, low porosity and smaller pores are critical. Cooperative testing on Thixomolded AZ91D at the Materials Science & Engineering Department of The University of Michigan showed run-out times. Inventory needs are reduced to a hopper stage and molded within minutes. Mechanical properties are yet to be optimized at the solid contents of 25% and higher. The better-filling mode of hot sprues/hot runners and heat treatment may provide improved mechanical properties at these higher percentage solids. Table 2 lists some of the many parts made via Thixomolding.

**Table 1 — Tensile properties of Thixomolded magnesium alloys**

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Room-temperature composition, wt. %</th>
<th>Yield strength, MPa (ksi)</th>
<th>Ultimate tensile strength, MPa (ksi)</th>
<th>EL, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91D</td>
<td>Mg-9 Al, 1Zn</td>
<td>158 (23)</td>
<td>256 (37)</td>
<td>6.1</td>
</tr>
<tr>
<td>AZ81</td>
<td>Mg-8 Al, 1 Zn (Blended)</td>
<td>144 (21)</td>
<td>255 (37)</td>
<td>8.2</td>
</tr>
<tr>
<td>AM71</td>
<td>Mg-7 Al (Blended)</td>
<td>131 (19)</td>
<td>257 (37)</td>
<td>12.2</td>
</tr>
<tr>
<td>AM60</td>
<td>Mg-6 Al</td>
<td>121 (18)</td>
<td>252 (36)</td>
<td>15.9</td>
</tr>
<tr>
<td>AJ52</td>
<td>Mg-5 Al, 2 Sr</td>
<td>144 (21)</td>
<td>244 (35)</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>At 175°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AJ52</td>
<td>Mg-5 Al, 2 Sr</td>
<td>111 (16)</td>
<td>164 (24)</td>
<td>17</td>
</tr>
</tbody>
</table>

Very thin complex parts, such as small chip coolers, have been molded at 0.3 mm, and electronic covers have been molded at 0.6 to 0.7 mm. For such parts, solid fractions of 5% are preferred in commercial production, and ductility is excellent.

For intermediate thicknesses of 1 to 4 mm and good properties, solids are optimized at 15%.

To date, strength and ductility trend lower at solids of 25% and higher in the normally non-heat treated moldings. Solids at more than 25% can be molded in thicker sections such as 12 to 25 mm. For example, 15-mm thick military parts were molded at 42.5% solids.

To demonstrate the versatility of the process, Husky recently molded 4 mm by 190 mm shapes at 70% solids. However, mechanical properties are yet to be optimized at the solid contents of 25% and higher. The better-filling mode of hot sprues/hot runners and heat treatment may provide improved mechanical properties at these higher percentage solids. Table 2 lists some of the many parts made via Thixomolding.

**Table 2 — Applications for Thixomolding**

<table>
<thead>
<tr>
<th>Electronics/ communication</th>
<th>Autos</th>
<th>Sports equipment</th>
<th>Hand-held tools</th>
<th>Other products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mini-Notebook PC’s (21 models), Digital projectors, Cameras, VCR’s, Palm devices, Mini disks, Cellular telephones, Chip coolers, Barcode and check readers, Virtual vision devices, Copier gears, Connectors</td>
<td>Seat backs, Transmission parts, Brackets, Motor housings, Electronic boxes, Fuel rails, Oil pump housings, Door locks, Mirror brackets, Valve covers, Convertible car top components</td>
<td>Snowboard clamps, Fishing reels, Bicycle brake handles, Motorcycle fairings</td>
<td>Nailsers, Saws, Drills, Chain saws, Hedge trimmers, Leaf blowers, Hair clippers</td>
<td>Sunglasses, Microscopes, Fans, Laser scopes</td>
</tr>
</tbody>
</table>