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Magnesium Die Casting:

Lubrication Technology & Trends

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Magnesium Die Casting: Lubrication Technology and Trends

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High-pressure die casting (HPDC) is a very popular process for making complex mechanical parts out of light metals like aluminum and magnesium alloys. It is capable of rapidly producing parts with high dimensional accuracy. HPDC growth paralleled that of the automobile industry, where the demands of assembly line manufacture spurred the demand for a quick, reliable way to make components. With the growth of JIT manufacturing, the automobile industry continues to be the dominant user of HPDC parts. Other end uses for die casting include recreational vehicles, power tools, electrical machinery, electronic components and housewares.

The rising cost of fuel and increasingly stringent environmental and fuel performance regulations are forcing the auto industry to seek novel ways to achieve these goals. Weight reduction of vehicles is a key step to reducing fuel consumption, so the industry is actively looking at replacing steel with lighter materials. According to Ducker International, the use of aluminum in the North American auto industry has grown to nearly 319 pounds per vehicle in 2006.

However, in recent times, another light metal has come to the forefront in the quest for lighter vehicles and improved fuel economy. Discovered by Humphrey Davy in 1808, magnesium was isolated in its pure state in 1828, but it was only in the 1960s that it gained popularity as an automotive component. The early Volkswagen Beetle comprised nearly 90 pounds of magnesium alloy parts.

Pure magnesium has a density of about two-thirds of aluminum and one-fourth of iron. It also has good vibration damping, dent resistance, machinability and provides shielding against electromagnetic waves. However, it also has shortcomings like insufficient strength, poor elongation and heat resistance and vulnerability to corrosion. Many of these limitations have been overcome through the development of special alloys.

The most commonly used magnesium alloy for die casting automotive components belongs to the Mg-Al-Zn family. AZ91D is a high purity magnesium alloy with good corrosion resistance, excellent mechanical properties and good castability. Mg-Al-Mn based alloys like AM50 and AM60 have better elongation and impact strength than AZ91 and, therefore, are mainly used for auto safety systems and wheel rims. Mg-Al-Si based alloys were among the earliest materials developed for high temperature applications. Typical compositions and properties of these alloys are shown in Tables 1 & 2[1].

Magnesium alloys have excellent thermal conductivity and low heat capacities. This translates into a tendency to solidify rapidly. To ensure complete filling of the cavities, alloy casting temperatures are typically 90˚F to 150˚F (50˚C to 80˚C) above the liquidus temperature. Gate velocities are typically between 100 to 150 ft/sec (30 to 50 m/sec), which are significantly higher than those used for aluminum casting.

As automakers start to make larger and more complex parts, the die caster is faced with an even bigger challenge. The complexity of these large parts makes it difficult to design internal cooling to adequately control the temperature of all parts of the die. A natural consequence of this is that the variation of temperature across the die surface has increased. Previously, the die surface temperatures before spray ranged between 250˚C to 350˚C. With the large

***Table 1** - Chemical composition of select magnesium alloys.*

Chemical Composition *All single values are maximum composition percentages unless otherwise stated.*							
Commercial name	**AZ91D**	**AZ81**	**AM60B**	**AM50A**	**AM20**	**AE42**	**AS41B**
	A	B	B	B	B	B	B
Aluminum	8.3-9.7	7.0-8.5	5.5-6.5	4.4-5.4	1.7-2.2	3.4-4.6	3.5-5.0
Zinc	0.35-1.0	0.3-1.0	0.22 max	0.22 max	0.1 max	0.22 max	0.12 max
Manganese	0.15-0.50^{C}	0.17 min	0.24-0.60^{C}	0.26-0.60^{C}	0.5 min	0.25^{C}	0.35-0.70^{C}
Silicon	0.10 max	0.05 max	0.10 max	0.10 max	0.10 max	–	0.5-1.5
Iron	0.005^{C}	0.004 max	0.005^{C}	0.004^{C}	0.005 max	0.005^{D}	0.0035^{C}
Copper, Max	0.030	0.014	0.010	0.010	0.008	0.050	0.020
Nickel, Max	0.002	0.001	0.002	0.002	0.001	0.005	0.002
Rare Earth, Total	–	–	–	–	–	1.8-3.0	–
Others (Each)	0.02	0.01	0.02	0.02	0.01	0.02	0.02
Magnesium	Balance	Balance	Balance	Balance	Balance	Balance	Balance

A: ASTM B94-03, based on die cast part. B: Commercial producer specifications, based on ingot. Source: International Magnesium Association. C: In alloys AS41B, AM50A, AM60B and AZ91D, if either the minimum manganese limit or the maximum iron limit is not met, then the iron/manganese ratio shall not exceed 0.010, 0.015, 0.021 and 0.032, respectively. D: In alloy AE42, if either the minimum manganese limit or the maximum iron limit is exceeded, then the permissible iron to manganese ratio shall not exceed 0.020. *Source: ASTM B94-94, International Magnesium Association.*

Table 2 - Physical properties of select magnesium alloys.

Physical Properties

Typical values based on "as-cast" characteristics for separately die cast specimens, not specimens cute from production die castings.

Commercial Name	AZ91D	AZ81	Am60B	AM50A	AM20	AE42	AS41B
Ultimate Tensile Strength[B]							
ksi	34	32	32	32	32	27	33
(MPa)	(230)	(220)	(220)	(220)	(220)	(185)	(225)
Yield Strength[E B]							
ksi	23	21	19	18	15	20	20
(MPa)	(160)	(150)	(130)	(120)	(105)	(140)	(140)
Compressive Yield Strength[B]							
ksi	24	N/A	19	N/A	N/A	N/A	20
(MPa)	(165)		(130)				(140)
Shear Strength[B]							
ksi	20	20	N/A	N/A	N/A	N/A	N/A
(MPa)	(140)	(140)					
Impact Strength[D]							
ft-lb	1.6	N/A	4.5	7	N/A	4.3	3
(J)	(2)		(6)	(9.5)		(5.8)	(4.1)
Fatigue Strength[A]							
ksi	10	10	10	10	10	N/A	N/A
(MPa)	(70)	(70)	(70)	(70)	(70)		
Hardness[F]							
BHN	75	72	62	57	47	57	75
Elongation[B]							
% in 2 in. (51 mm)	3	3	6-8	6-10	8-12	8-10	6
Young's Modulus[B]							
psi x 10^6	6.5	6.5	6.5	6.5	6.5	6.5	6.5
(Gpa)	(45)	(45)	(45)	(45)	(45)	(45)	(45)
Poisson's Ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Density							
lb/in^3	0.066	0.065	0.065	0.064	0.063	0.064	0.064
$(g/cm^{3)}$	(1.81)	(1.80)	(1.79)	(1.78)	(1.76)	(1.78)	(1.78)
Melting Range							
°F	875-1105	915-1130	1005-1140	1010-1150	1145-1190	1050-1150	1050-1150
(°C)	(470-595)	(490-610)	(540-615)	(543-620)	(618-643)	(565-620)	(565-620)
Specific Heat[B]							
BTU/lb °F	0.25	0.25	0.25	0.25	0.24	0.24	0.24
(J/kg °C)	(1050)	(1050)	(1050)	(1050)	(1000)	(1000)	(1000)
Latent Heat of Fusion							
BTU/lb	160	160	160	160	160	160	160
(kJ/kg)	(373)	(373)	(373)	(373)	(373)	(373)	(373)
Coefficient of Thermal Expansion[B]							
μ in/in° F	13.8	13.8	14.2	14.4	14.4	14.5[G]	14.5
(μ mm/mm° K)	(25)	(25)	(26)	(26)	(26)	(26)	(26)
Thermal Conductivity							
BTU/ft hr° F	41.8[C]	30[B]	36[B]	36[B]	35[B]	40[BG]	40[B]
(W/m° K @)	(72)	(51)	(62)	(62)	(60)	(68)	(68)
Electrical Resistivity[B]							
% IACS @ 22°C	35.8	33	31.8	31.8	N/A	N/A	N/A
	(14)	(13)	(13)	(13)			

N/A=data not available. **A**: Rotating Beam fatigue test according to DIN 50113. Stress corresponding to a lifetime of 5×10^7 cycles. Higher values have been reported. These are conservative values. Soundness of samples has great effect on fatigue properties resulting in disagreement among data sources. **B**: At 68°F (20°C). **C**: At 212-572°F (100-300°C). **D**: ASTM E 23 unnotched 0.25 in. die cast bar. **E**: 0.2$ offset. **F**: Average hardness based on scattered data. **G**: Estimated. **H**: 0.1% offset. **I**: Casting conditions may significantly affect mold shrinkage. *Source: International Magnesium Association.*

components, the maximum temperature can be as high as 400°C, while the cooler portions of the die may be as low as 200°C. This leads to the development of localized hot spots which, in turn, create solder problems. This places a greater dependence on the die lubricant to provide cooling for the die surface. Yet, the higher temperatures encountered before the spray make this difficult to do because of the Leidenfrost effect. This requires greater quantities of die lubricant to be sprayed, which increase cycle times and costs.

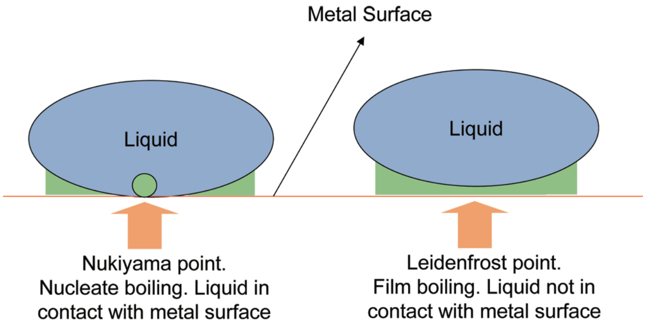


Figure 1 – Liquid vapor interaction at the surface under different conditions.

The Leidenfrost phenomenon is well-known to die casters. When water is sprayed on to a hot surface, which is at a temperature significantly above the boiling point of water, it is unable to make contact with the metal surface. Instead, the drops of water float on a cushion of water vapor and, thus, are unable to wet the surface (Figure 1). Die lubricant active materials are therefore unable to be laid down on the die surface. The highest temperature at which water, or a water-based die lubricant, can contact the metal surface is known as the Leidenfrost temperature.

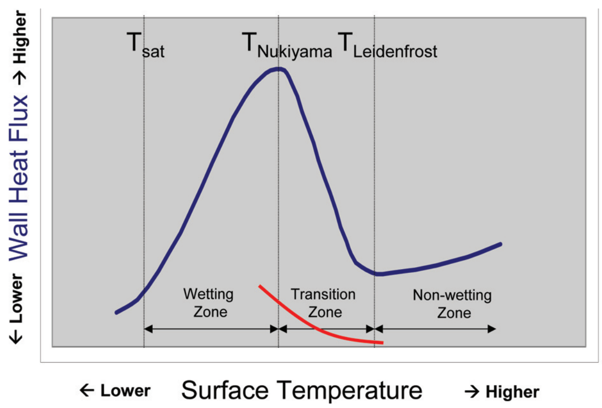


Figure 2 – Variation of heat flux and film thickness with surface temperature.

Today's high performance die lubricants utilize two separate approaches to address these issues. The first is to try to increase the Leidenfrost temperature. By allowing the die lubricant to wet the surface at a higher temperature, film formation begins earlier, allowing shorter spray durations. The second approach is to incorporate materials that would form a film rapidly on the die surface at elevated temperatures. The cooling curve of water shows the rate of cooling approaches at maximum at a temperature known as the Nukiyama point (Figure 2)[2]. By increasing the Leidenfrost temperature, the operating window to form a film is also increased. However, if the film formation was slow at the higher temperatures, any advantage gained by raising the Leidenfrost temperature would be lost. Many different factors affect the Leidenfrost temperature. Mechanical factors like the distance and angle of sprays, the size of the droplet and impact pressure all affect the wetting temperature. Last, but not the least, constituents in the spray can affect Leidenfrost temperature[3].

The benefit to a die caster is clearly seen. If a die is initially at a high temperature and needs to be cooled to about 250°C to get complete solidification, using these new materials could reduce the spray time by 20 to 30%. This directly translates into an increase in productivity, compared to conventional lubricant performance.

In magnesium casting, it is important to strike a balance between too little cooling, (which will cause soldering) and too much cooling (which can create a problem of poor fill). Modern engineered lubricants are able to achieve this balance by matching the needs of specific applications with unique product chemistries.

Regulating die surface temperatures is only one of the functions of the die lubricant. The primary function is release, and this can only take place if an adequate amount of the lubricant film is formed over the die surface. Lubricant components do not always adhere to very hot surfaces. The very high injection velocities in magnesium casting also aggravate the situation by abrading away the lubricant film particularly near the gate. In an actual die, there is wide variation in the temperature of the die surface. When die lubricant is sprayed on the surface, a film can be formed rapidly on the cooler parts of the die, but may not form very well on the hotter surfaces.

One method used to develop superior performing products involved measuring the amount of lubricant film formed at different temperatures and combining these measurements to develop a simple predictor of performance. Figure 3 shows the Hot Die Adhesion Index, which is ratio of the weight of film formed at 350°C and 250°C. This index is a measure of the uniformity of the film formed on a tool operating at different temperatures. A value of 100% means exactly the same amount of film is formed at all temperatures. In actual practice, this is very difficult to achieve. The results show that the new materials were at least two to three times more efficient than conventional die lubricants. They also showed higher lay-down rates as compared to standard products at all temperatures. While these data points were developed experimentally, they were validated by carrying out field trials on full-sized HPDC machines at customer sites. Field performance corresponded well with the experimental results.

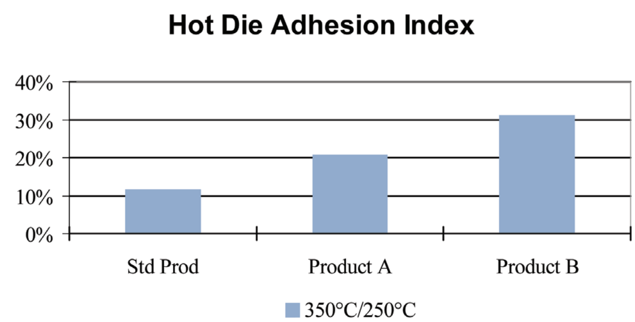


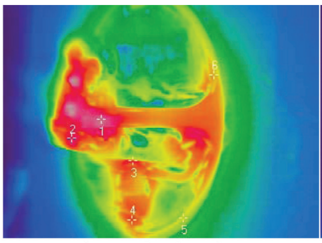
Figure 3 – Relative performance of different products on hot die adhesion.

The following case is from a North American die caster making magnesium steering wheels. The customer was getting acceptable overall performance in release, casting appearance, solder protection and in-cavity build-up with their conventional die lubricant. They were awarded a new job that had several design challenges. The biggest challenges were the small cores and very thin ribs that would bend easily and cause wheel distortion.

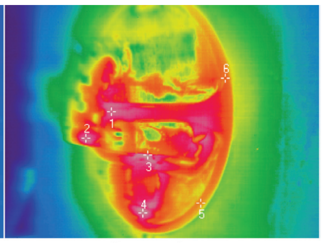
Anticipating release issues, the customer first attempted to run with their conventional die lubricant at a richer-than-normal dilution. The first attempt lowered the dilution by 25%. When this did not improve the problem, they then lowered the dilution to half of the original concentration. The two adjustments did not influence the problem favorably. They did see an increase in staining, overspray and in-cavity build-up.

Chem-Trend collected thermal images from the problem tool. When the images were evaluated, the one thing that the conventional die lubricant could not overcome was the thermally unbalanced tool. The temperatures before the spray varied from about 425°F to 640°F (218°C to 338°C) across the surface area of the tool. The conventional die lubricant was unable to cope with this wide variation without giving release issues in the hot zones or build-up in the cold areas of the die.

The new die lubricant technology was able to provide higher protection in the high temperature regions without causing the excess cooling that leads to flow or build-up issues. This allows proper filling of the casting, yet provides adequate release so it can be extracted without distortion. Figure 4 shows the after-spray thermal profiles with the two different products.



Conventional product
Temp range 325 – 500°F (163 – 260°C).



New product
Temp range 365 - 471°F (185-244°C).

Figure 4 – Die thermal profiles after spray.

The current trend in magnesium alloy development is to make alloys that can operate in a high temperature environment. Creep resistance is a very important mechanical property for components that operate under continuous stress situations at high temperatures. Creep is a phenomenon in which a metal part subject to a tensile stress at an elevated temperature is slowly elongated in the direction of the maximum tensile stress, even though this applied tensile stress is at a level that would not result in plastic deformation at room temperature. The creep elongation speed is dependent on the stress level, the temperature, the time the part has been in service at this temperature and stress level. It is also dependent on the chemical composition and structure of the metal.

Table 3 shows the creep values of standard aluminum and common magnesium alloys[4].

Newer alloys incorporate alkaline earth or rare earth elements to provide improved creep resistance trying to meet the performance of A380 aluminum alloy. In some cases, this results in a higher casting temperature and/or a greater tendency toward hot tearing. Thermal issues are likely to be greater with these new alloys. The role of a release agent is even more critical with these newer materials. Experiments are currently being run with these new alloys.

Table 3 – Tensile creep elongation of select magnesium alloys.

	Tensile Creep Elongation of Die Cast Alloys			
	% Creep at 50 MPa 200 h		% Creep at 50 MPa 500 h	
Alloy	150°C	175°C	150°C	175°C
A380	0.08	0.04	0.10	0.05
AZ91D	2.70	failed after 80 hrs	6.35	–
AS21x	0.19	2.27	–	–
AS41	0.05	2.48	0.07	–
AE42	0.06	0.33	0.08	0.44

The die casting industry is rapidly changing to meet the new demands of their customers, and new alloys are being developed to meet the ever-increasing demands of a high strength-to-weight ratio. We continue to develop new technology so we can maintain our position as partners to the die cast industry.

About the Author

G. Natesh heads the marketing & technology functions for the die cast product line within Chem-Trend. He is a chemical engineer with more than 25 years experience in a variety of sales, marketing and engineering roles within the chemical specialty industry. He is based in Howell, MI.

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