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Advanced casting technologies for lightweight automotive applications

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Abstract: This paper provides an overview of alloy and process developments in aluminum and magnesium castings for lightweight automotive applications. Wear-resistant aluminum alloys, creep-resistant and high strength/ductility magnesium alloys have been developed for automotive applications. On the process front, vacuum-assisted die casting and high vacuum die casting technologies have been developed for high-integrity body and chassis applications. Thin-wall and hollow casting components are being produced by low-pressure die casting processes for structural applications. Overcasting technology is gaining traction and has enabled mixed material designs for automotive sub-systems such as engine cradles and instrument panel beams. Simulation tools developed to predict the interfacial interactions of the dissimilar components and the structural integrity of the overcast systems are being validated in the casting trials.

Key words: lightweight; aluminum alloy; magnesium alloy; die casting
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Casting is a very efficient process used in the automotive industry to manufacture lightweight aluminum and magnesium components to near net shape. Although castings from these metal alloys have a long history in automotive applications, extensive use of these castings only began in the mid 1970s [1], due largely to increasing demands for greater vehicle fuel economy. Reducing the mass of a vehicle by 10% can increase fuel economy by up to 8% [2]. Depending on the application, aluminum castings can provide 30%–50% mass reduction compared with steel, while magnesium castings can provide 40%–60%. Recent work on mass decompounding for internal combustion (IC) vehicles, has quantified how additional secondary mass reductions can further increase fuel economy [3-5].

This paper summarizes the latest alloy and process developments for automotive aluminum and magnesium castings. New aluminum and magnesium alloys are being developed for automotive powertrain and other structural applications. Advanced casting processes such as vacuum die casting and low-pressure die casting technologies have been used to produce high-integrity body and chassis applications. Overcasting technology has enabled mixed material construction of automotive sub-systems such as engine cradles and instrument panel beams.

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1 Alloy development

1.1 Aluminum alloy development

Cast aluminum alloys used for automotive applications are mostly based on the Al-Si-Cu system. The two gravity-cast aluminum alloys, A319 (Al-6%Si-3.5%Cu-1%Fe-1%Zn) and A356 (Al-7%Si-0.25%Cu-0.2%Fe-0.4%Mg), account for most of the automotive applications, although each vehicle manufacturer has specific versions of these alloys. Similarly, there are two alloys that are widely used for high pressure die casting, A380 and A383. A380 (Al-8.5%Si-3.5%Cu-3%Zn) is used for valve covers, gear cases, and other housings, while A383 (Al-10.5%Si-2.5%Cu-3%Zn) is a higher strength alloy used in pistons and other demanding applications. Both the high pressure die casting alloys have 1.3% Fe to prevent soldering of the casting to the die steel. Magnesium alloys are less susceptible to soldering.

The commonly used Al-Si alloys described above do not have good wear resistance. As a result, engine cylinder blocks have bores which contain wear-resistant iron liners or coatings to withstand the severe tribology conditions of the moving piston and rings. In the 1960's a hypereutectic Al-Si alloy was developed to eliminate the need for liners [6]. A390 (Al-17%Si-4.5%Cu) was characterized by large primary Si particles which presented a wear-resistant surface to the rings, providing the surrounding aluminum was etched to expose the Si particles and prevent contact between the aluminum and the rings or pistons. The presence of the primary Si made machining the castings difficult and expensive.

In the 1990's General Motors began developing near-eutectic Al-Si alloys, which would provide wear resistance but without relying on the wear resistance of the primary Si and their machining challenges. Considerable understanding of the controlling microstructural features and their properties has resulted from this work [7]. While much of this work was done with sand cast, metal chilled alloys, more recently one version of these alloys GM396 (Al-12.5%Si-0.95%Cu-1.15%Ni-0.3%Mg) has been successfully high pressure die cast and shows promising wear resistance in engine testing [8].

1.2 Magnesium alloy development

There are currently two major alloy systems, Mg-Al-Zn (AZ) and Mg-Al-Mn (AM), used for automotive casting applications. AZ91 (Mg-9%Al-1%Zn) is used for strength-limited, non-structural parts used at ambient temperatures. These parts include brackets, covers, cases and housings; they provide essentially the same functionality as aluminum, but with significant mass savings. For structural applications such as instrument panels, steering systems and radiator supports, where crashworthiness is important, AM50 (Mg-6%Al-0.3%Mn) or AM60 (Mg-6%Al-0.3%Mn), offer unique advantages due to their higher ductility and higher impact strength compared with die cast A380 alloy.

(1) High strength/ductility alloys

With magnesium alloys expanding into more critical structural applications such as the Corvette Z06 engine cradle, there is a continuing need to develop new alloys with improved mechanical properties, especially fatigue strength and crashworthiness. A recent study on the effect of Al addition to Mg suggests a range between 7%–8%Al in the Mg-Al-Mn-based alloys (AM70) as offering the best balance of tensile properties (Fig. 1) and reasonable response to heat treatment [9].

It was also found that small additions (1%–3%) of tin (Sn) can increase the yield strength (11%–15%) and ultimate tensile strength (32%–37%) of the AM70 (Mg-7%Al-0.3%Mn) alloy without much loss in ductility [9]. This is due to the strengthening effect of the Mg_2Sn phase in these alloys.

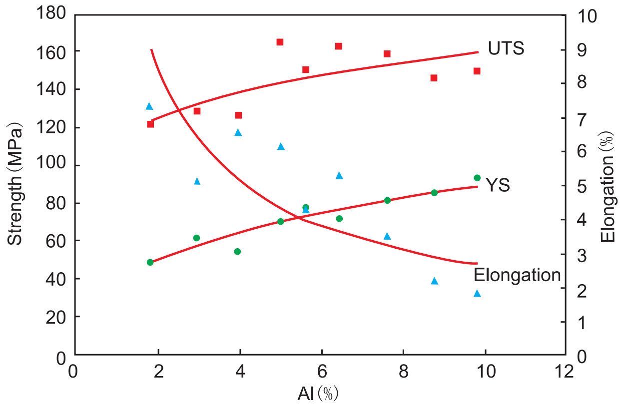

Fig.1: Tensile properties of Mg-Al-Mn alloys in the as-cast condition (gravity permanent mold casting) [9]

(2) Creep-resistant alloys

A major disadvantage of current AZ and AM alloys is their poor creep resistance at temperatures above 125 ℃ [10], which is inadequate for elevated temperature applications; automatic transmission cases can operate at up to 175 ℃, engine blocks up to 200 ℃, and engine pistons up to 300 ℃. Both diffusion-controlled dislocation climb and grain boundary sliding are reported mechanisms for creep in magnesium alloys, depending on the alloy system, microstructure, and stress and temperature regimes. The poor thermal stability of the $Mg_{17}Al_{12}$ phase and its discontinuous precipitation can result in substantial grain boundary sliding at elevated temperatures. The accelerated diffusion of aluminum solute in the magnesium matrix and the self-diffusion of magnesium at elevated temperatures can also contribute to creep deformation in the Mg-Al based alloys. Possible approaches for improving creep resistance in magnesium alloys include:

(a) Suppressing the formation of the $Mg_{17}Al_{12}$ phase;

(b) Pinning grain boundary sliding; and

(c) Slowing solute diffusion in the magnesium matrix.

Based on the above approaches, several new alloys containing Ca, Sr, RE and Si have been developed in the last decade [11-13]. These new creep-resistant magnesium alloys offer varying degrees of improvement in creep resistance and other properties. RE additions have shown to slow down creep due to the formation of $Al_{11}RE_3$ in the microstructure [11]; but should be controlled to the lowest possible level to minimize cost. Calcium and strontium can significantly improve creep resistance of magnesium alloys due to the formation of $(Mg,Al)_2Ca$ (Fig. 2 [12]) and Mg-Al-Sr intermetallic phase(s) [13]. However, Ca and Sr additions need to be carefully controlled to avoid potential castability problems such as die-sticking and cracking. Silicon additions below the Mg-Mg_2Si eutectic point (1.34%Si) offer very limited improvement in creep resistance. However, hyper-eutectic Mg-Si alloys offer potential for elevated temperature applications, but its high liquidus temperature makes it difficult for high-pressure die casting.

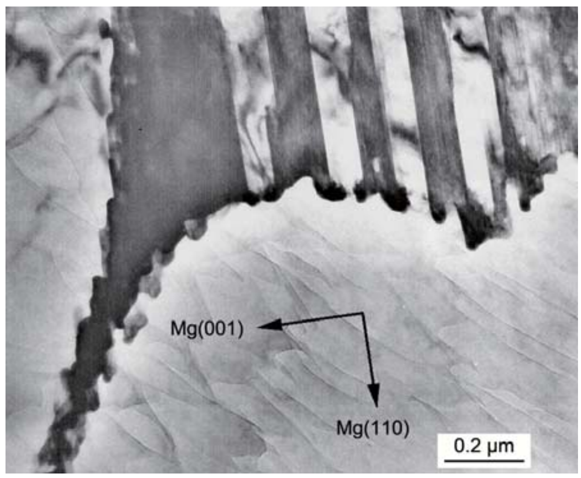

Fig.2: TEM micrograph showing the formation of $(Mg,Al)_2Ca$ phase in AX53 (Mg-5%Al-3%Ca) alloy (high pressure die casting) [12]

The discovery and development of potentially low-cost, creep-resistant magnesium alloys has resulted in their implementation in several powertrain applications; Mercedes 7-speed Tiptronic automatic transmission case [14], which uses AS31 (Mg-3%Si-1%Zn); and the BMW composite engine block [15], which contains a hypereutectic Al-Si alloy inner block around which is cast the AJ62 (Mg-6%Al-2%Sr) alloy. These applications are high pressure die castings. The inner aluminum portion of the BMW engine block is permanent mold gravity cast and contains the head bolts, wear-resistant bore, the cooling water jacket passages, and the bulkheads, and thus carries the major part of the engine function. The magnesium outer provides packaging for attachments, but neverless reduces the overall mass of the engine.

Magnesium Powertrain Cast Components Project is an USCAR (United States Council for Automotive Research) collaboration sponsored by the United States Department of Energy and led by GM, Ford, and Chrysler, aiming at replacing the major aluminum components of a V block engine with magnesium [16]. The cylinder block using a creep-resistant magnesium alloy achieved a mass reduction of 14 kg (8%) for the fully dressed engines (~29% for all of the cast aluminum components which were replaced by magnesium). The prototype engine contained a low pressure, sand cast cylinder block, a Thixo-molded rear seal carrier, and high pressure die cast oil pan and front cover, with all other parts carried over from the baseline aluminum engine. The prototype engines were dynamometer tested for durability.

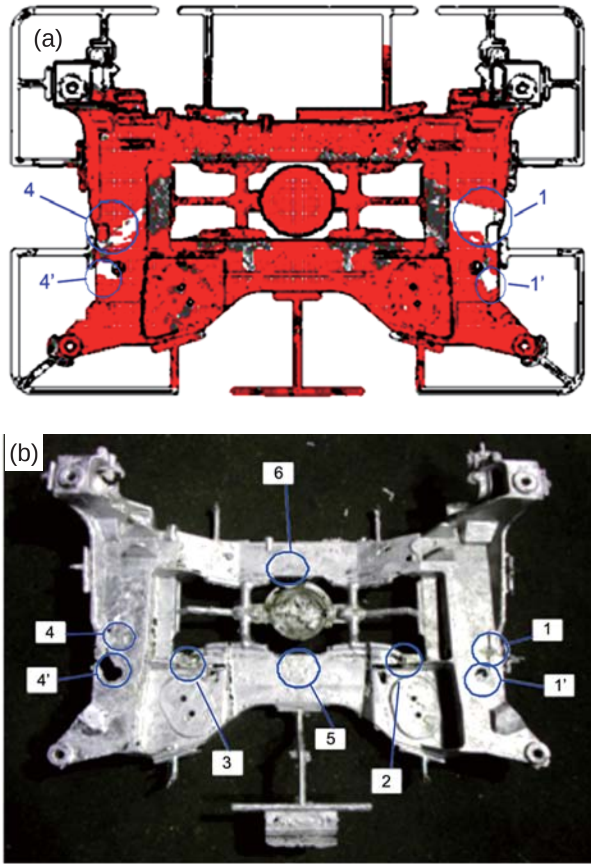

Fig.3: Advanced simulation for high-pressure die casting (Mg cradle for Corvette Z06)

2 Casting process development

High-pressure die casting (HPDC) is the most common process used for casting magnesium since it offers much flexibility in design and manufacturing. The excellent die filling characteristics of both magnesium and aluminum alloys enables large, thin-wall, and complex castings to be economically produced and have replaced several steel subsystems that are manufactured by welding numerous stampings and reinforcements. The first-in-industry one-piece magnesium die-cast cradle for the Chevrolet Corvette Z06 weighs only 10.5 kg, and demonstrates a 35 percent mass savings over the aluminum cradle it replaced [17]. As is shown in Fig. 3, advanced simulation of die fill and solidification have proved to be very useful in guiding design and process control for large and small die castings.

Despite its high productivity, the biggest drawback of conventional high-pressure die casting of light metals is the porosity that results due to entrapped gases becoming included in the casting during injection of the molten metal at a high velocity. The porosity issue is less serious for thin-wall sections (< 2.5 mm), where the mechanical properties are largely provided by the fine-grain pore-free skin on the casting surface. When thicker walls are needed for stiffness and/or durability in chassis and body applications, the effect of porosity on mechanical properties (especially ductility and fatigue strength) becomes more serious. The following alternative processes can produce castings with less porosity, but often at higher costs or lower productivity.

2.1 Vacuum die casting

Vacuum die casting is an innovative process, where the reduced pressure created in the injection chamber and die cavity just prior to injection, leaves no entrapped air in the casting, and enables the manufacturing of relatively large thin wall castings with significantly improved properties. Castings produced with this process are currently targeted for components require pressure tightness and good mechanical properties via heat treatment. Vacuum die casting thus stretches the capabilities of conventional die casting while preserving its economic benefits. Vacuum die casting of aluminum alloys is very popular in North America, with over 20% of all die casters having vacuum die casting capabilities [18].

(1) Vacuum-assisted die casting

While vacuum die casting of aluminum is widely practiced, there is only one company in North America, Gibbs Die Casting (Henderson, KY), that uses vacuum in vertical die casting of magnesium components. A simple vacuum system, such as Fondarex vacuum valve and pump, can be used in vacuum-assisted horizontal die casting process, and is sufficient in reducing gas porosity in magnesium castings [19]. Conventional HPDC parts are not heat-treatable due to the formation of blisters upon heating to solutionizing temperatures when entrapped air in the porosity expands. The much reduced gas porosity in vacuum-assisted die casting allows those castings to be heat-treated without blisters. Figure 4 shows the surfaces of T4 solution heat-treated castings from both conventional and vacuum-assisted die casting processes [19]. Extensive blisters were observed on the surfaces of the conventional die cast parts after heat treatment, while no blisters were observed on the surfaces of the vacuum-assisted castings.

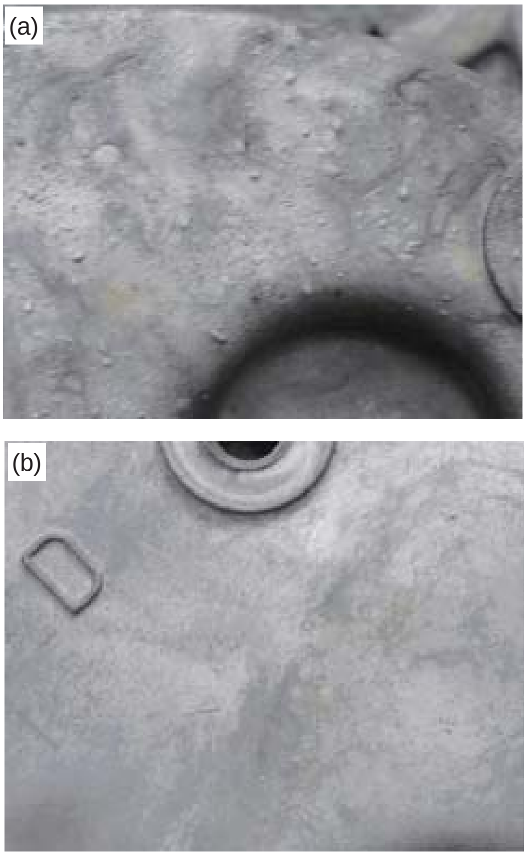

Fig.4: Casting surfaces after T4 treatment: (a) conventional die casting; and (b) vacuum-assisted die casting [19]

(2) High vacuum die casting

The high vacuum die casting (HVDC) process is considered an enhanced version of the vacuum-assisted HPDC process. The key features of the HVDC process include the die and gating design, powerful vacuum system, vacuum valves and control system, monitoring systems, and die cast process settings. The main differences among conventional HPDC, vacuum-assisted HPDC and the HVDC process are shown in Table 1. For aluminum alloys, Alcan's patented High-Q-Cast process has been used in production of automotive body parts such as the B-pillar. New aluminum alloys, such as AURAL-2 and Magsimal 59, have been specifically developed for this process and enables response to heat-treatment, while also mitigating die-sticking problems observed in the HPDC processes [20, 21]. Recently, a similar process has been developed for magnesium alloys and termed "super vacuum die casting" (SVDC) [22]. Automotive shock towers have been made using AM60B and AZ91D alloys. Although SVDC provides a limited improvement in yield strength, which is primarily determined by alloy chemistry and grain size; the much lower porosity in these castings significantly improves the ductility and ultimate tensile strength of both AZ91D and AM60B alloys compared with conventional HPDC castings (Table 2).

Table 1: Comparison of conventional HPDC, vacuum-assisted HPDC and high/super vacuum die casting

Process	Conventional HPDC	Vacuum-assisted HPDC	High/Super vacuum die casting
Vacuum level	None	60 – 300 Mbar	< 60 Mbar
Advanced vacuum monitoring and controls	No	No	Yes
Sealed die surfaces	No	Yes	Yes
Susceptibility to gas porosity	High	Low	Very low
Heat treatable	No	Yes	Yes

Table 2: Tensile properties of as-cast SVDC shock towers compared to HPDC components of similar sizes

Alloy	Yield strength MPa	Ultimate tensile strength MPa	Elongation %
AZ91D-SVDC	158.7	227.7	3.6
AZ91D-HPDC	150	200	2.5
AM60B-SVDC	123.7	226.6	9.1
AM60B-HPDC	120	210	6.0

2.2 Low pressure casting

A low pressure casting (LPC) machine usually includes a pressurized crucible located below the mold table with a feeding tube running from the crucible to the bottom of the mold (sand or permanent mold). Dry gas is normally used to pressurize the surface of the molten metal in the crucible with relatively low pressure, which is sufficient to force the molten metal to rise through the feed tube, feeder and gating system into the die cavity. When the mold cavity is filled, the exerting pressure is increased to continue feeding metal into the risers to compensate for shrinkage of the casting during solidification. The external pressure is released after the casting has completely solidified. With proper design of the feeding system, the metal in the feed tube is still molten, and flows back into the crucible. The total cycle is repeated for the next casting. Since a quiescent fill and design of complex internal passages are possible, the solidified casting can be virtually free of internal porosity. Although the LPC process is associated with lower capital investment compared to the HPDC process, it cannot produce wall thicknesses below 4 mm for aluminum or 3 mm for magnesium, and is also associated with a longer cycle time; about 2–4 times longer compared to HPDC depending on part complexity. However, the LPC process can produce hollow castings that cannot be produced by the HPDC process. Hollow castings are desirable since they provide efficient structures from the boxed sections they can provide.

A significant advantage of the LPC process is its capability to produce large and thin-wall castings of high strength and structural efficiency. A good example is the hollow casting/extrusion welded cradle for the Cadillac CTS, Fig. 5, which is on the primary load path, and is critical to the stiffness, durability and crash energy management of this vehicle. This cradle is the industry-first welded cradle of a large hollow casting and extrusions, and achieved a mass reduction of 10 kg (or about 35%) and a part reduction of 40 from the current production steel cradle. The casting itself resulted in a mass reduction of about 9.5 kg (or about 40%) and a part consolidation of 32 to 1 from the steel design.

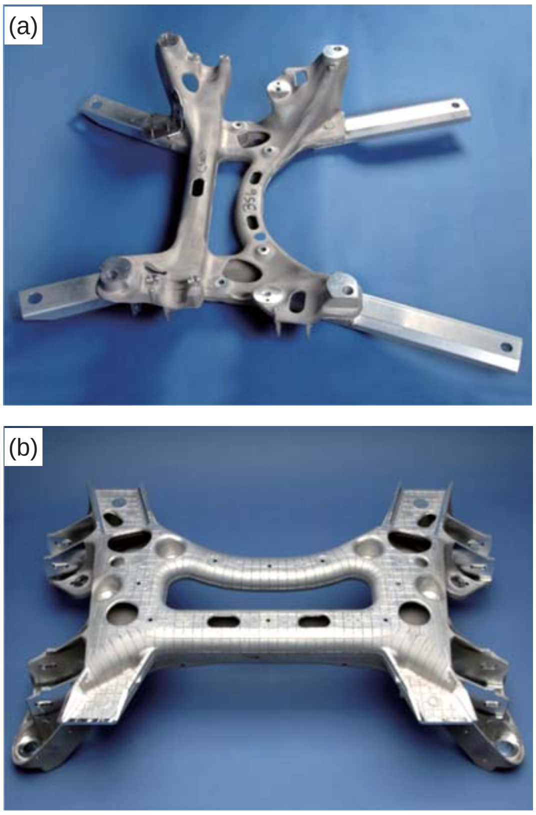

Fig.5: (a) Hollow aluminum casting; and (b) welded engine cradle for Cadillac CTS

The key in making this large hollow casting, Fig. 5(a), is the VRC/PRC (vacuum riserless casting/pressure riserless casting) process and the use of precision sand cores. The casting thickness is limited by the control of sand core shifting during solidification, which would result in uneven wall thickness around the core. While the design analysis suggested a nominal wall thickness of 4 mm for the hollow casting, the minimum thickness accepted by the casting industry was 5 mm. A high-strength core binder and improved design and location of core prints were used to achieve a 4 mm wall in the production cradles, which led to an additional mass saving of 1 kg and made the welding easier (4 mm casting to 2.5 mm wall extrusions). The casting design had to be modified to enable castability and to fit the casting machine for a two-cavity operation, producing two parts with a cycle time less than 4 min. Specifically, there was an extensive use of thin ribs to improve the cavity fill in the upper die of the large hollow casting and provide stress relief near the weld zones. To correct for any distortion, a straightening step was added after the water-quench and prior to aging, after which the casting strengthens and makes this operation more difficult.

While LPC is well established for aluminum, this is not the case for magnesium alloys, although some recent studies report of developments in this area [23–27]. Table 3 compares the mechanical properties of AZ91 and AM50 castings of similar thicknesses of ~10 mm produced by low pressure die casting (LPDC), gravity permanent mold casting (PMC) and high pressure die casting processes [27]. The results suggest that the LPDC castings showed improved properties compared to similar thickness castings that can be made with the gravity process, mostly due to controlled casting filling and the application of pressure, and also the lower porosity due to the application of pressure during the entire solidification process. The LPDC is considered to be the preferred process to produce thick-walled magnesium castings (~10 mm thick) that cannot be produced without porosity even with the use of vacuum in high pressure die casting (HPDC). The LPC parts are also heat-treatable and a T6 heat treatment (18 hours at 420 ℃, hot-water quench and 16 hours at 175 ℃) can improve the yield and ultimate strength of LPDC AZ91 castings by about 50% and 24%, respectively, but with a reduction in elongation. The age-hardening effect in AZ91 alloy is due to the precipitation of the $Mg_{17}Al_{12}$ phase in the microstructure. Due to its lower aluminum content, AM50 alloy does not show any significant age-hardening effect upon heat treatment. However, the grain size in LPDC castings are an order of magnitude larger compared to HPDC castings, due to the faster cooling rate in the latter, which also translates into higher yield strength in the HPDC castings. Grain refinement is needed in the LPDC process to improve the strength while maintaining its superior ductility. New high strength alloy systems that respond to age-hardening need to be explored to expand the use of magnesium castings in structural applications.

Table 3: Tensile properties of low pressure die casting (LPDC) AZ91 and AM50 samples compared to gravity permanent mold cast (GPMC) and high pressure die cast samples of similar thickness of ~10 mm [27]

Alloy	Casting	Temper	Yield strength MPa	Ultimate tensile strength MPa	Elongation %
AZ91	LPDC	As-cast	92.2	180.4	3.4
AZ91	LPDC	T4	76.9	218.5	6.6
AZ91	LPDC	T6	138.2	228.1	1.7
AZ91	GPMC	As-cast	82.7	178.4	3.9
AZ91	HPDC	As-cast	110–130	130–175	0–1
AM50	LPDC	As-cast	57.8	192.3	8.7
AM50	LPDC	T6	68.3	210.6	9.5
AM50	LPDC	T4	66.4	200.3	8.6
AM50	GPMC	As-cast	53	173.4	8.1
AM50	HPDC	As-cast	102–122	132–215	0–5

2 Overcasting development

Magnesium die casting offers significant mass saving and part consolidation compared to welded steel stampings. Figure 6 shows a 6.9 kg magnesium HPDC instrument panel (IP) beam for the Buick LaCrosse, which provided about 40% mass saving and significant part consolidation compared to the traditional sheet steel design.

The use of magnesium in IP beams is, however, facing strong competition. IP designs using aluminum or steel tubes are only slightly heavier than magnesium die castings but can be significantly less expensive. Tubular designs using magnesium overcasting technology are being explored for future IP development. Figure 7 shows an example of an overcast IP beam section (Fig. 7a), full beam design (Fig. 7b); casting simulation (Fig. 7c); and die arrangement (Fig. 7d) where a tube (steel, aluminum or magnesium) can be inserted before molten magnesium or aluminum is overcast onto the tube. Such hybrid IP designs offer multi-material design flexibility, mass efficiency, structural integrity and reduced joining and assembly [28]. Simulation tools have been developed to predict the interfacial interactions of the dissimilar components (Fig. 7c) and the structural integrity of the overcast systems, which has been validated in the casting trials. Overcasting technology can be applied to many other structural and non-structural applications with improved design flexibility, mass saving and manufacturing efficiency.

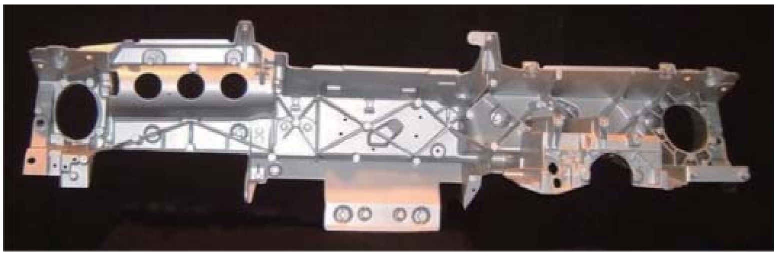

Fig.6: Magnesium die cast instrument panel beam for Buick LaCrosse

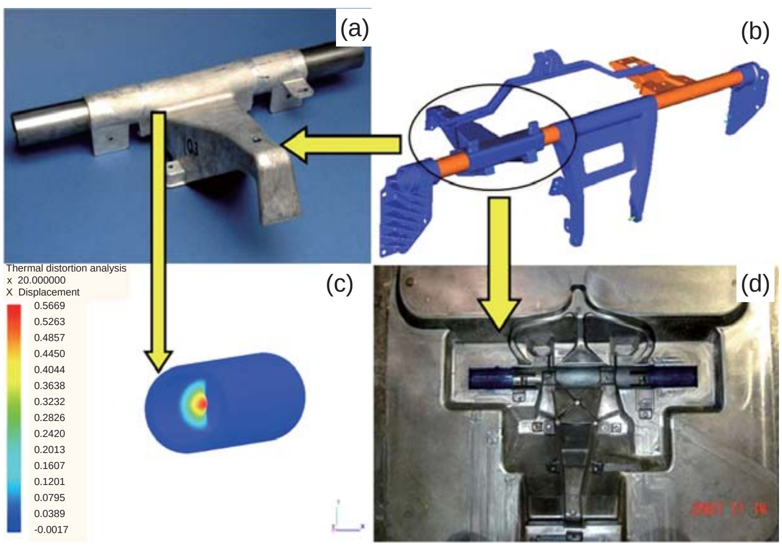

Fig.7: Lightweight instrument panel beam of magnesium overcast onto a steel tube

3 The future

Advanced casting alloys and process technologies have played a key role in enabling changes in materials and processes in automotive manufacturing; the future promises to be even more exciting as rapid advancements in materials science and engineering introduce new automotive materials, novel vehicle designs, and improved fabrication technologies [1].

The Chevrolet Corvette Z06 already contains some of these next generation materials. In addition to a lightweight aluminum frame (at 129 kg, 30 percent lighter than the steel frame it replaced), the Corvette Z06 also uses many advanced materials such as a first-in-industry magnesium engine cradle, magnesium steering column, steering wheel and brake module support bracket, carbon fiber floor pan (with a “unique in the industry” sandwich structure), front fenders and wheelhouses, and titanium valves and connecting rods. The use of these advanced materials, in combination with the use of efficient hydroforming and die casting processes, made this vehicle the fastest production car in the world (e.g., 60 mph acceleration in 3.7 s).

Another example of developments looking into future application of castings is the Magnesium Front End Research and Development Project [29, 30] that is an effort jointly sponsored by the United States Department of Energy, the United States Automotive Materials Partnership (USAMP), the Chinese Ministry of Science and Technology and Natural Resources Canada (NRCan). The goal of this project is to develop enabling technologies and demonstrate the technical and economic feasibility of a magnesium-intensive automotive front end body structure, which offers improved fuel economy and performance in a multi-material automotive structure. The USAMP team has achieved 38.2 kg (45%) mass saving and 56% part consolidation in a Mg-intensive front end body structure compared with the baseline steel design for a mid-sized unibody construction [29]. The international project team has developed many enabling technologies including the super-vacuum die casting technology, which led to producing the first-in-the-world weldable magnesium die castings [30]. Projects such as these are good examples of international collaborative projects that are advancing alloy and process development for lightweight automotive applications.

One trend is clear; vehicles will consist of a balanced use of many materials in the future, incorporating more lightweight materials such as aluminum, magnesium and composite materials. Overcasting technology will further develop to expand its capability of integrate multi-material subsystems, although specific attention needs to be paid to galvanic corrosion mitigation in the multi-material applications. Additionally, the types of materials employed in automobile manufacture will depend on both materials and manufacturing innovations. Tools being developed in the computational materials disciplines will be needed to design new lightweight alloys that are strong and tough for use in structural applications in the primary load path. Manufacturing innovations will be needed in die design and mold filling methods to produce large thinner wall castings including hollow sections.

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