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Ultra-large aluminum shape casting: Opportunities and challenges

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Abstract: Ultra-large aluminum shape castings have been increasingly used in automotive vehicles, particularly in electric vehicles for light-weighting and vehicle manufacturing cost reduction. As most of them are structural components subject to both quasi-static, dynamic and cyclic loading, the quality and quantifiable performance of the ultra-large aluminum shape castings is critical to their success in both design and manufacturing. This paper briefly reviews some application examples of ultra-large aluminum castings in automotive industry and outlines their advantages and benefits. Factors affecting quality, microstructure and mechanical properties of ultra-large aluminum castings are evaluated and discussed as aluminum shape casting processing is very complex and often involves many competing mechanisms, multi-physics phenomena, and potentially large uncertainties that significantly influence the casting quality and performance. Metallurgical analysis and mechanical property assessment of an ultra-large aluminum shape casting are presented. Challenges are highlighted and suggestions are made for robust design and manufacturing of ultra-large aluminum castings.

Keywords: ultra-large castings; aluminum; light-weighting; quality; microstructure; materials properties

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1 Introduction

The demands for reducing automobile weight for improved fuel efficiency in internal combustion engines and battery energy usage in electric vehicles have required the increasing applications of lightweight aluminum shape castings [1]. According to Ducker [2], the use of aluminum in the automotive sector has seen tremendous growth with at least 3.5% annual growth rate over past four decades; from 84 pounds per vehicle in 1975, to 459 pounds in 2020, and 556 pounds forecast for 2030, with majority (>50%) of the aluminum use being castings. This is because aluminum shape casting offers good combination of near-net-shape,

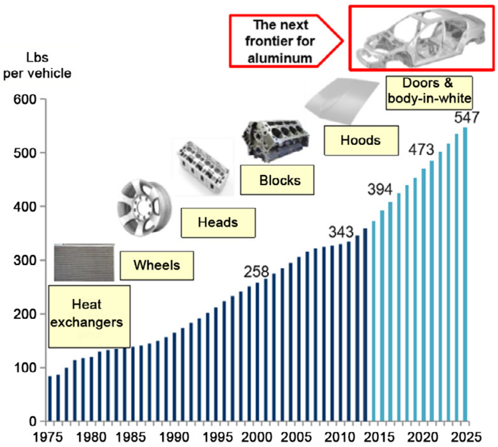

Fig. 1: Growth of aluminum in North American light vehicle [2]

high strength to weight ratio, excellent design flexibility for geometry complicity and integration, and low manufacturing cost.

As vehicle electrification advances and accelerates, the demand for aluminum, especially aluminum shape castings, continues to grow. This trend is driven by the need to offset the weight of large battery packs in order to extend the driving range of vehicles. Over the years, aluminum shape castings have mainly been used in the powertrain for engine and transmission components, such as engine blocks, cylinder heads, transmission housings and cases, and so on, primarily using secondary 319 and A380 alloys. Now, the aluminum casting growth has been shifting to the vehicle body and chassis, particularly for battery electric vehicles (BEVs), where it is used in battery trays and electric drive unit components, and in fuel cell propulsion systems, aluminum castings are utilized in frames, electronic shelves, and brackets, among other components, aiming to reduce both mass and manufacturing costs. For those applications, primary aluminum alloys that are less sustainable are primarily used due to their high ductility requirements.

Aluminum shape castings can be produced virtually by all kinds of casting processes and aluminum alloys. Nevertheless, high pressure die casting (HPDC) is the preferred production process for high volume production. For smaller production volumes, low-pressure die casting, permanent mold casting and sand casting are often used. For ultra-large aluminum shape castings, both HPDC and low-pressure sand-casting (LPSC) processes are used. The latest advances and developments in aluminum shape casting have been reviewed in Refs. [1, 3–4]. Among all cast aluminum alloys, the Al-Si-Mg and its variant alloys are widely used because of their excellent castability, high corrosion resistance and a high strength-to-weight ratio in the heat-treated condition. Both the as-cast and the heat-treated microstructures of these alloys strongly depend on their chemical composition and casting conditions, which in turn influence the size and distribution of casting defects, as well as the mechanical properties of alloys. Detailed reviews and reports on this subject can be found in the works of Wang et al. [5], Cáceres et al. [6], Taylor [7], and Wang et al [8].

Modern vehicles, especially hybrid and electric vehicles, are moving toward simpler vehicle body designs by casting ultra-large single-piece panels and components that serve as a load bearing structure of the vehicle body. These ultra-large single-piece castings are often referred to as mega-castings or giga-castings due to the huge size of the die casting machines used to make these castings. Ultra-large castings allow vehicle bodies to be lighter and less complex to manufacture by replacing the large number of stamped panels and welding parts required to form the vehicle body with a single-piece casting [9].

Furthermore, ultra-large single-piece castings often feature intricate design details with varying wall thicknesses throughout the casting, in addition to the increased local “hot spots” such as thick ribs and heavy bosses, which have a greater thickness than that of the cross-sectional area of the adjacent wall of the casting. During the casting process, the thicker “hot spot” sections will naturally cool and solidify much slower than their surroundings. When the thick sections start solidification and shrinkage, the surrounding sections have already solidified and cannot provide any metal feeding to the thick sections. As a result, more shrinkage porosity will form in the ultra-large castings. Furthermore, the huge sizes of ultra-large castings lead to a longer metal flow distance. This will result in more defects such as trapped air, oxides, cold shuts, and misrun in the giga castings.

Therefore, the increasing use of ultra-large aluminum shape castings in automobiles can pose even more challenges in quality control and performance prediction. The purpose of this paper is to provide a critical examination of the key factors that affect quality, microstructure, and materials properties to present some advanced technologies that improve casting quality and performance, and to demonstrate how the high integrity casting can be robustly designed and developed with the use of virtual casting tools.

2 Opportunities of using ultra-large aluminum castings

In the last few years, a new trend has started in aluminum shape casting. OEMs have introduced ultra-large light metal aluminum castings in critical structures to integrate many different parts into a single piece casting, significantly increasing the design flexibility of vehicle structural components. For instance, Tesla uses front and rear aluminum giga castings in the Model Y vehicles [10], as shown in Fig. 2. In comparison with the Model 3, these two castings replaced 171 parts (mostly sheet stampings along with some smaller castings), eliminated 1,600 welds, and removed 300 robots from the assembly line, significantly reducing required capital investment and floorspace [11]. Both front and rear giga castings are manufactured on a massive high pressure die casting (HPDC) machine, known as a giga-press, which can achieve 6,000 tons of locking force [12].

GM has used six (6) mega aluminum castings to form the entire lower body structure for the Cadillac Celestiq vehicle [13] (Fig. 3). Each mega casting has replaced 30+ individual parts. The mega castings have been made using a low-silicone variant of a 300 series alloy and low-pressure sand casting (LPSC) process [14].

Toyota plans to implement giga castings to significantly reduce the number of parts used in its front and rear body frames. Their goal is to integrate 175 different parts on its front and rear body frames, respectively with the help of

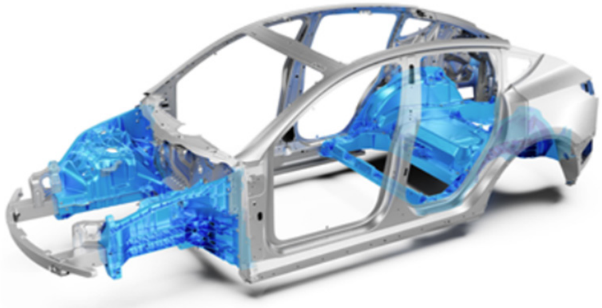

Fig. 2: A Tesla Model Y giga-casting [10]

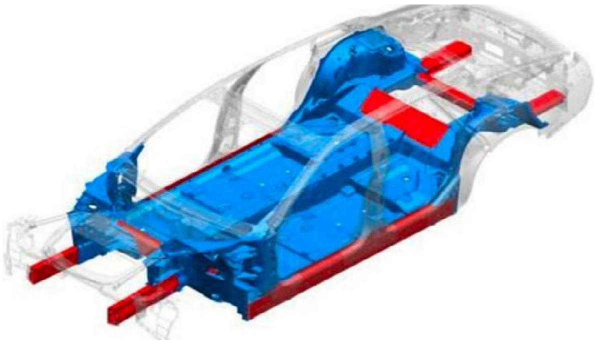

Fig. 3: Six mega aluminum shape castings forming the entire lower body structure for Cadillac Celestiq vehicles [13]

giga castings [15]. Volvo and its EV brand Polestar have also decided to follow the same path and invested in giga-press [9]. Volvo hopes to develop several vehicle models that can make use of the same mega-casting for its body-in-white (BIW) elements. The castings will integrate even mounting points for components such as suspension arms and electric motors [16]. Mercedes-Benz, Volkswagen, Ford, Hyundai, and Chinese electric vehicle start-ups Nio and Xpeng [17], are publicly known to be following this trend. Many other OEMs are at least looking at giga-castings or are already secretly working on it [9].

There are several benefits arising with the use of ultra-large aluminum shape castings, as shown in Table 1. For example, ultra-large castings reduce the number of components in a vehicle. Generally, the frame or underbody (usually composed of many stamped sheet components and some small castings) can be integrated into one large casting, which can in turn reduce the overall weight of the car. This is especially important for BEVs, as it increases the range and makes the car more efficient.

The utilization of ultra-large castings in vehicle manufacturing streamlines both the bill of materials and the manufacturing process [9], leading to a more efficient and accelerated production and assembly workflow. It also reduces the required capital investment for the tooling and equipment [9,18]. This is particularly true and beneficial for a brand-new facility. For an existing facility, some redesign and rearrangement of equipment and tooling might be needed. Nevertheless, the length of the assembly line and duration for assembling a vehicle should be significantly shortened, as the larger casting eliminates assembly and joining of many smaller pieces. As shown in Table 1, the use of giga-castings can cut costs by up to 40%. With the use of ultra-large aluminum shape castings, further cost can be reduced by using less labor-intensive ways to assemble parts, enabling the vehicles to be economically manufactured and assembled in high-cost countries. Additionally, the use of ultra-large castings should also reduce the number of suppliers and their logistics, creating a positive impact on costs and environment [9].

Table 1: Benefits of the use of ultra-large aluminum shape castings in automobiles

(1)	**Reduce number of parts (60+)**
	Replace 60 or more separate components, which previously had to be individually stamped, extruded, cast and sub-assembled into the desired body subsystem.
(2)	**Save tooling cost (40%)**
	a. Saves about 40 percent of its tooling investment. b. Saves a customer about 40 percent in costs over traditional casting operations because it can replace a series of tools and up to 650 feet of robotized welding lines typically needed to put together the individual parts of a complete front or rear platform.
(3)	**Save energy (30%)**
	a. Consumes about 30 percent less energy. b. Industry insiders believe this could eliminate up to 300 robots, which also helps an automaker reduce its energy consumption.
(4)	**Save mass (30%)**
	30 percent lighter than an all-steel solution and about 10 percent lighter than one that includes several parts in aluminum.
(5)	**Reduce lead time**
	Production time is slashed because it is faster to create a single casting than to produce the same part by welding together up to 60 pieces.
(6)	**Broader application**
	a. The giga press being used to make large battery cases for full-electric cars. A next step would be to include the battery case in the central platform, making it a structural part of the vehicle. b. A giga press could also cast an entire platform for a small battery-electric car.

3 Challenges with ultra-large aluminum castings

It should be noted that there are also challenges associated with the ultra-large aluminum shape castings despite the opportunities and benefits as mentioned. Some of them are related to the use of ultra-large shape castings and the others are about the production of quality large castings.

3.1 Difficulty in making quality ultra-large aluminum castings

The process of making quality ultra-large aluminum shape castings is extremely difficult not only because of the ultra-large size of giga casting (~1 m×1.5 m×0.5 m) but also the huge die or mold to make the giga castings. For example, in HPDC, the typical locking force is maintained at about 80 MPa to make good castings. For the giga casting with a projected area of 1.5 m^2 (including gating system), 12,000 t giga press will be needed to produce 80 MPa locking pressure. Dies for such giant castings are also huge (up to 100 t) [9], requiring the use of large equipment like cranes for handling. The size also makes die design and especially thermal management a challenge. Furthermore, die casting dies are extremely expensive particularly for the ultra-large castings and they do not last long with a typical die life of around 100,000 shots for structural components, as the dies directly contact with liquid aluminum with a melting temperature higher than 600 °C. In contrast, dies for stamping presses (for sheet-based components) can produce up to 6 million parts over their die life because the work piece temperature is much below 600 °C. Unless the die life is addressed, this makes ultra-large castings less suitable for very high-volume vehicles [9]. This is also true for sand casting no matter what kind of molding method is used. A large sand molding machine or 3D printing machine will be needed to make the mega/giga castings. Although sand casting process is more flexible than HPDC, there do exist limitations with the process including lower productivity, greater minimum wall thickness, less dimensional accuracy and tolerance, much slower cooling rates, and higher possibility of forming core gas porosity, etc.

It is generally accepted that it is very challenging to make quality HPDC parts due to extremely turbulent mold fill with entrapped air and surface oxides. In comparison with regular HPDC structural parts, mega/giga castings are many times bigger with very complex geometry designs such as large integrated bosses, deep ribs, and so on. Due to the variations in wall thickness and the extensive metal flow length needed to fill the entire cavity of a mega/giga casting die, there is a significant increase in hotspots prone to shrinkage and cold shuts. This especially makes the end of the filling process more susceptible to casting defects such as porosity and oxide formation. Figure 4 shows the examples of local macro shrinkage porosity seen in a giga casting. Additionally, for each shot it will take a longer time to pour nearly 100 kg liquid metal into a shot sleeve, which dramatically increases the possibility of forming externally solidified crystals (ESC) and cold flakes. Many other process aspects (e.g. vacuum, die lubrication, die thermal management, part ejection, etc.) also become more complicated when the size is increased to mega/giga castings. Therefore, it is extremely challenging to make an entire front/rear underbody or battery tray as a single giant high-quality casting. The casting scrap rate can be very high unless the right alloy and correct manufacturing process are used.

In addition, the huge size of one-piece ultra-large aluminum shape casting makes the casting material properties more non-uniform within a part. As an example, Fig. 5 shows the tensile properties tested at various locations in an aluminum giga casting. As can be seen, the tensile properties vary significantly from one location to another within the giga casting. The ultimate tensile strength (UTS) changes from 175 to 280 MPa and ductility (E) ranges from approximately 1% to 8%. The large property variation and particularly low strength and ductility are attributed to poor quality of the casting, especially to the presence of large casting defects such as porosity and oxides.

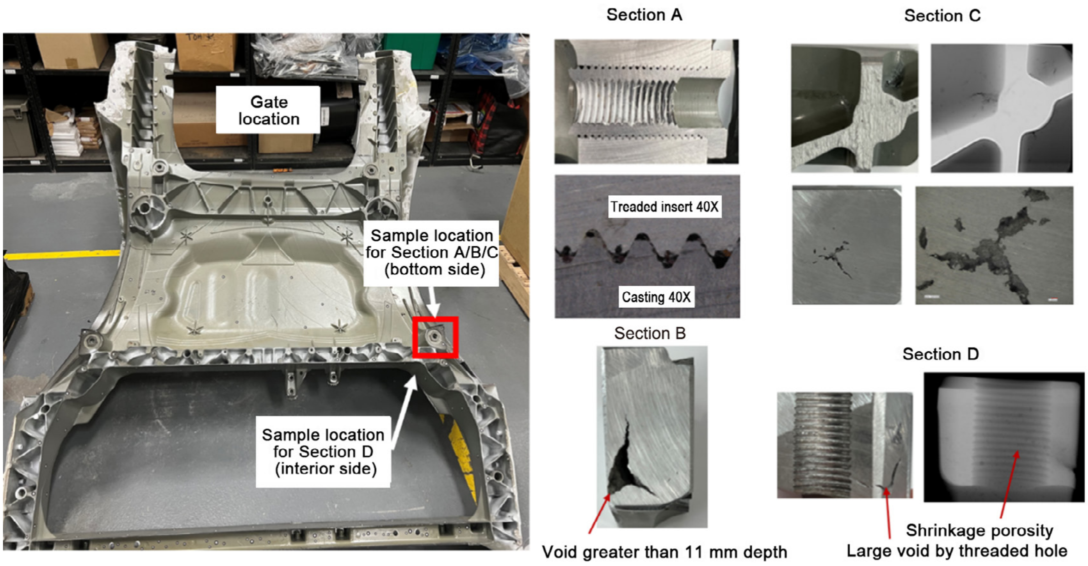

Fig. 4: Large macro shrinkage porosity observed in a giga aluminum casting

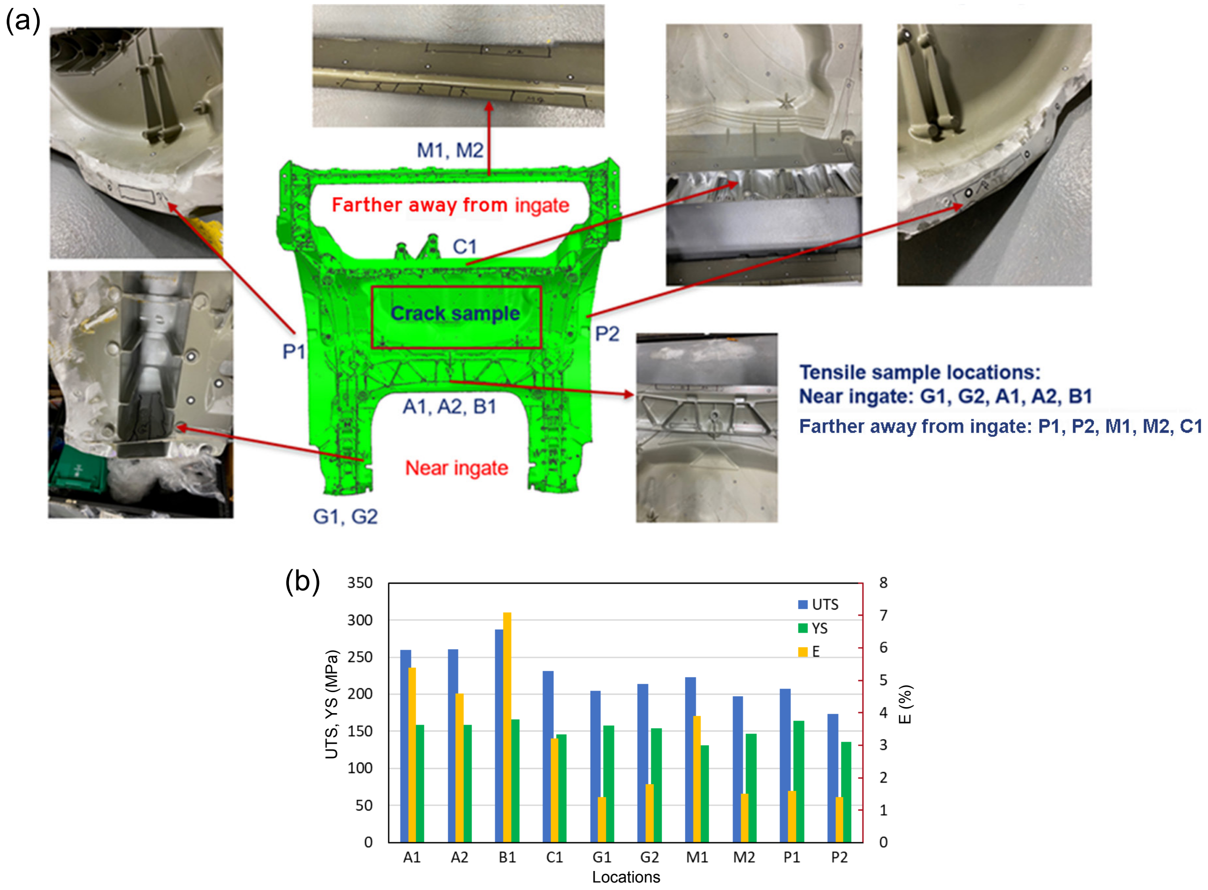

Fig. 5: Sampling locations (a) and tensile properties (b) of an aluminum giga casting in various locations

3.2 Dimensional stability

Ultra-large castings have different wall thicknesses throughout the part, each of which cools down differently within the die during HPDC process and subsequent cooling and quenching phases. This can lead to a significant amount of residual stress and distortions that are often difficult to handle. Typically, HPDC parts are not subjected to solution treatment because of blister concerns. For ultra-large HPDC aluminum castings, an over-aging process is not anticipated. The paint-baking process can be considered as just an under-aging treatment. As a result, continuous aging and dimensional growth during subsequent manufacturing process and assembly will significantly contribute to deviations and variations of tolerances in ultra-large castings compared to sheet metal assembly processes. Furthermore, thermal expansion of a single piece ultra-large casting can be very large. Table 2 shows the calculated linear dimension change of a giga casting with temperature as the part length is 2,000 mm at 0 K. Slight temperature variation during assembly can attribute huge dimensional variation and difficulty in assembly. In addition, ultra-large castings are not joined to other parts using standard spot-welding procedures, but rather use other methods that can also cause unexpected or unknown geometrical variations [9, 17]. Therefore, much more effort is necessary to get all the information about the part and understand its deviations. Otherwise, it is very difficult to produce quality ultra-large castings with the right dimensional tolerances. Even using alloys that require no heat treatment or may only need minor artificial aging (e.g. without quenching), it often requires complex straightening to achieve the correct tolerances [9].

Table 2: Calculated linear dimensional change with temperature for an aluminum giga casting

Temperature and dimension changes			
°F	55	85	120
°C	12.8	29.4	48.9
K	285.9	302.6	322.0
CTE (10^{-6}·K^{-1})	20.93	21.10	21.29
Absolute liner expansion (mm)	11.97	12.77	13.71
Liner dimension change (mm)	0	0.80	1.74
Note: alloy C611			

3.3 Sustainability

Sustainability has drawn considerable attention in the automotive industry. Incorporating more aluminum components to reduce a vehicle's weight can help reduce CO_2 emission during its operational lifecycle. However, this approach can also increase GHG (greenhouse gas) significantly due to the increase of primary aluminum alloy manufacturing for ultra-large castings. Figure 6 briefly illustrates the aluminum paradox from sustainability aspect [17]. Recycling is the solution to resolve the aluminum paradox. Using recycled aluminum instead of primary aluminum can lead to at least ~90% reduction of CO_2 emission, as shown in Fig. 7. Currently, aluminum auto body sheet is generally known to have a high recycled content [9], while structural aluminum castings have mainly employed primary alloys such as C611, Aural alloys, Silafont alloys, among others, due to the necessity for ductility and crashworthiness in these applications. Primary aluminum alloys generally have a high carbon footprint because of the tight Fe content limit (<0.2%) and no recycled aluminum used. Therefore, there is a need to increase the recycled content of structural aluminum die castings. Luckily, this change is already taking place, and structural aluminum die castings can now be made with high recycling contents. For example, Volvo states that its mega-casting project is helping the company achieve its sustainability goal of carbon neutrality by 2040, because it reduces the environmental footprint across production, allows for a high recycling content, and is made from a single alloy (thus, being easy to recycle). The weight reduction (especially since it replaced steel stampings) also helps to reduce the car's energy consumption during its use phase [9]. GM UniCAST aluminum alloy has a higher tolerance in Fe content which allows the use of 100% recycled aluminum alloys and scraps to make the alloy [19].

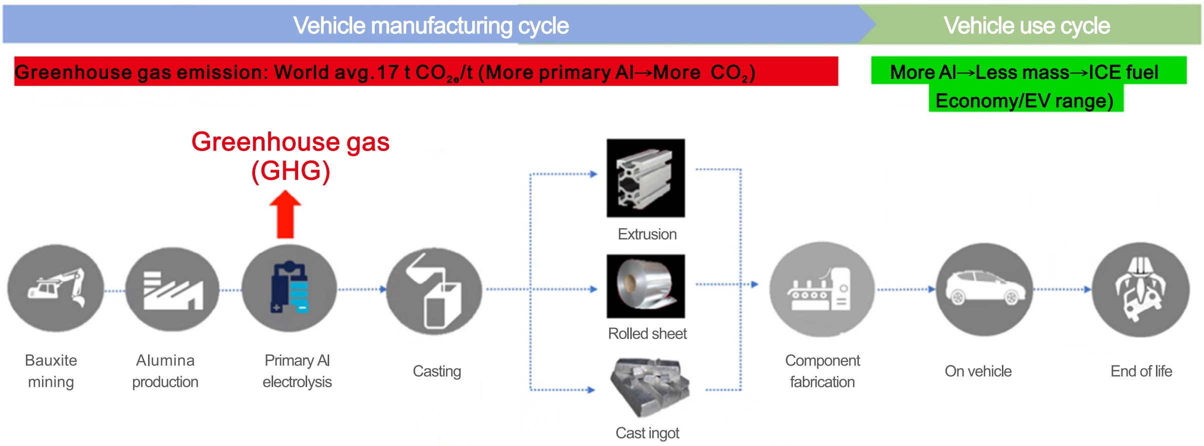

Fig. 6: Aluminum paradox from sustainability aspect [19]

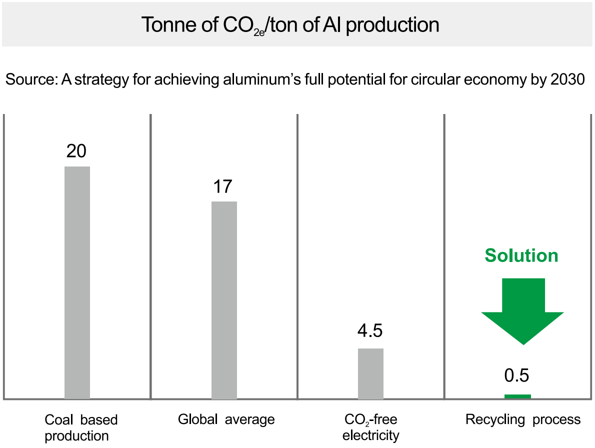

Fig. 7: Comparison of CO_2 production during various aluminum manufacturing processes [19]

3.4 Repairability and serviceability

As stated by Hartlieb [9], vehicles assembled with ultra-large castings make small repairs nearly impossible. This is because ultra-large castings have replaced tens and hundreds of small parts and they have also been joined with other components to form the entire body structure. The whole mega/giga casting would have to be replaced for any small damage to the casting. It would be very costly and time consuming to perform such a service and repair. In contrast to the assembly and vehicles without mega/giga castings, the mechanic can simply remove and replace the damaged or defective part [9,16]. To overcome the challenge is to design the ultra-large casting for repair. For example, GM engineers have proposed the design of the ultra-large single-piece casting with easy repair features including at least one predefined replaceable portion integrally cast with the main body portion, and a cut-guide delineating the predefined replaceable portion from the main body portion [20, 21]. The cut-guide includes a continuous channel defined on an exterior surface of the single-piece casting. The cut-guide further includes a rib extending from a channel wall on the main body portion. A damaged replaceable portion is excisable from the main-body portion by cutting through the single-piece casting along the cut-guide. The excised damaged replaceable portion may be replaced with the replacement part, which has substantially the same geometry, dimensions, and mechanical properties as an undamaged replaceable portion. The replacement part may be joined to the main body portion by mechanical means (e.g. bolting) or by welding.

4 Factors affecting quality of ultra-large aluminum castings

4.1 Cast aluminum alloys

With the long metal flow length in an ultra-large casting cavity, cast aluminum alloy shall have much better castability including high fluidity and low shrinkage and low hot tearing tendency. Fluidity is an important castability property of casting aluminum alloys, which affects the flowability and soundness of the cast products. If the fluidity of the alloy is satisfactory, which means that the alloy has good mold filling ability, it is easily accessible to obtain the castings with accurate dimensions, complete shapes and sharp outlines [9]. If the fluidity is not good, the mold filling ability is poor, and the casting defects easily form in the casting. The fluidity of cast aluminum alloys is affected by many factors, such as composition, pouring temperature, mold properties and mold structure [22, 23]. In Al-Si based cast aluminum alloys, Si is an important element affecting not only fluidity but also shrinkage. Near eutectic (10%–12% Si) composition helps both fluidity and lowering shrinkage, but significantly reduces tensile ductility even with the Sr modification and full solution and over-aging heat treatment (T7). Typically, HPDC parts are not subjected to a full T7 heat treatment, particularly for the mega/giga castings. To compromise, cast aluminum alloy with ~7% Si (e.g. C611, Aural 5, etc.) is currently used in HPDC mega/giga castings to have a balance of castability and tensile elongation as needed. For sand casting of ultra-large structural parts, even lower Si contents (~5% Si) need to be used for achieving the ductility. Table 3 shows the compositions of exemplary cast aluminum alloys currently used in HPDC mega/giga components. In addition to Si, a small amount of Mg is used for strengthening through natural aging and possible T5 artificial aging (e.g. through paint baking process). The addition of Mn is mainly for minimizing die soldering and meanwhile neutralizing Fe. Similarly, Sr addition is for modifying Si and at the same time to improve die soldering resistance. For the AA386 alloy Tesla uses, small amount of Cu (up to 0.8%) has significant detrimental effect on castability and casting corrosion resistance. The addition of Cu produces low melting point Cu-containing phases that increase the alloy freezing range and tendency of shrinkage porosity, as shown in Fig. 8 and Table 4. Cáceres et al. [24] reported significant increase of porosity when Cu content is in the range of 0.5%–1%, as shown in Fig. 9. Similarly, the amount of Cu addition in Al-Si based alloys leads to a high cracking susceptibility coefficient (CSC) and thus lower hot tearing resistance, as shown in Fig. 10 [26]. Additionally, presence of Cu in the aluminum alloys dramatically reduces material corrosion resistance. As shown in Fig. 11, the detrimental influence of Cu on the alloy corrosion resistance is much greater than other alloy elements such as Mg, Fe, and Sr. Therefore, it is not recommended to add Cu in the cast aluminum alloys for body structural applications.

Table 3: Composition comparison of alloys currently used in ultra-large castings

Alloy (wt.%)	Si	Cu	Mg	Fe	Mn	Ti	V	Sr
Aural 5 (Magna)	6.0–8.0	<0.03	0.1–0.6	0.2 max.	0.3–0.6	<0.08		0.014–0.017
C611 (EZCast, Alcoa)	6.0–9.0	<0.05	0.15–0.3	0.15 max.	0.4–0.8	<0.1		0.01–0.03
AA386 (Tesla used)	6.0–11.0	0.3–0.8	0.1–0.4	0.5 max.	0.3–0.8	0.15 max.	0.05–0.15	0.01–0.03

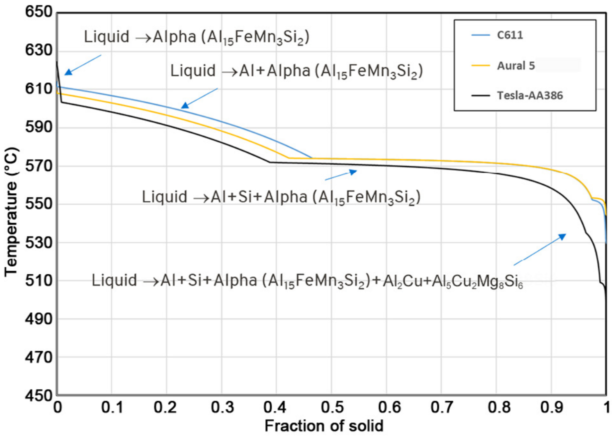

Fig. 8: Calculated friction of solid and solidification sequences of alloys currently used in ultra-large aluminum castings

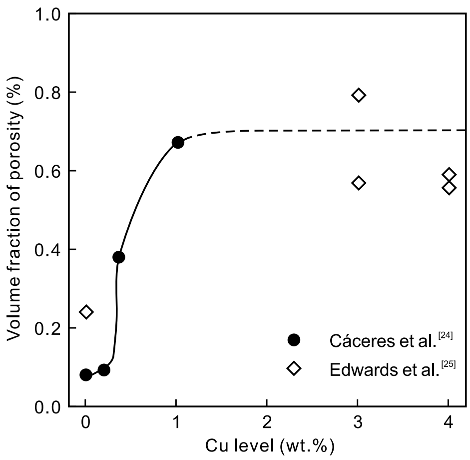

Fig. 9: Volume fraction of porosity as a function of Cu content in a cast Al-Si-Mg alloy [24]

Table 4: Comparison of alloy freezing range and solidification phases

HPDC alloy (wt.%)	Freezing range (°C)	Total eutectic particles (vol.%)	Si (vol.%)	Beta-Fe (vol.%)	Alpha-Fe (vol.%)	Al_2Cu (vol.%)	Mg_2Si (vol.%)	Q-Phase (vol.%)
Aural 5 (Magna)	87	8.2	6.2		1.8		0.2	
C611 (EZCast, Alcoa)	87	7.9	5.8		1.84		0.2	
AA386 (Tesla giga)	124	9.7	6.4	0.002	2.4	0.42		0.48

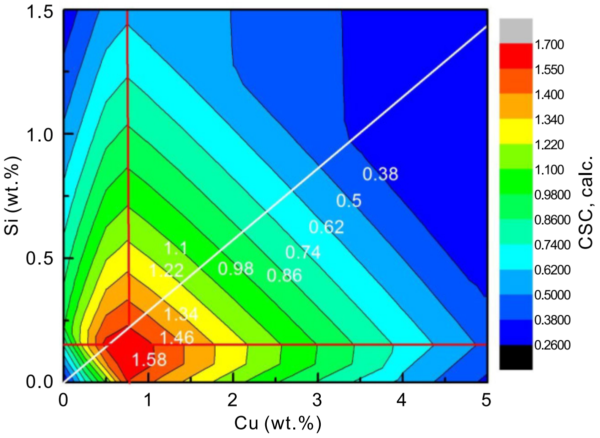

Fig. 10: Predicted cracking susceptibility coefficient (CSC) as a function of Cu and Si contents [25]

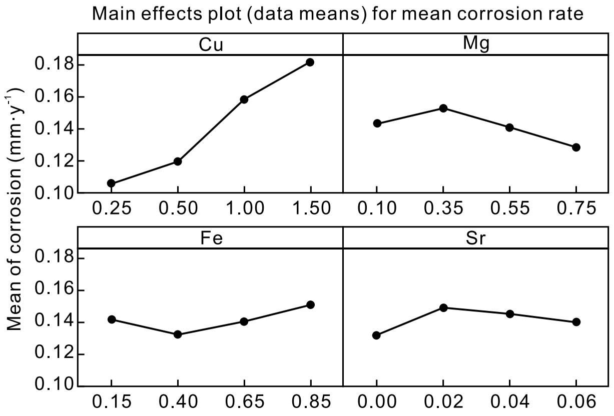

Fig. 11: Effect of Cu, Mg, Fe, and Sr contents on corrosion resistance of Al-Si-Mg alloy

4.2 Melt cleanliness control

Liquid aluminum cleanliness is vital to produce high-quality castings since most defects in final casting are usually related to inclusions and gases coming from the liquid metal [27-29]. The liquid metal should be cleaned to the highest level possible before it is introduced into mold cavity. The highest-level quality of liquid metal means that the oxide inclusions and the dissolved gases are minimized to the point that they will not cause casting defects during solidification. To ensure the highest possible quality of liquid metal, the starting point is the cleanliness of furnace charge that could be made up from a mixture of primary ingot, secondary (recycled) ingot, bought-in scrap, and in-house returns from the gating system and scrap parts. In general, scrap parts and particularly return charges tend to have higher impurity contents and higher level of oxides and dissolved gases in comparison with primary ingots, especially those supplied from continuously cast billet. When a great quantity of scrap return is used, a special caution should be taken to avoid liquid metal contamination, because all scrap return surfaces are full of oxides and possibly contain moisture and other contaminations. One technology was reported from GM to reduce liquid metal contamination with scrap and return charge [30]. The method comprises preheating a scrap charge to remove moisture and contaminants. The scrap charge is then coated on all free surfaces with a layer of flux. Subsequently, the scrap charge is melted in a furnace to form a melt bath of liquid aluminum suitable for casting. The flux layer removes the naturally occurring oxide film from the scrap charge surfaces as well as provides a cover flux to protect the melt bath from oxidation.

The mechanism of oxide film removal can be explained by the interfacial tension forces between the molten aluminum and oxide film. For removal of the oxide film to occur, the sum of the interfacial tensions of molten Al/molten salt and oxide film/molten salt should be less than the interfacial tension between molten Al and oxide films, as given in following equation:

$$\gamma_{\mathrm{Al/salt}} + \gamma_{\mathrm{oxide/salt}} < \gamma_{\mathrm{Al/oxide}} \qquad (1)$$

where $\gamma_{\mathrm{Al/oxide}}$, $\gamma_{\mathrm{Al/salt}}$, and $\gamma_{\mathrm{salt/oxide}}$ are the interfacial tensions at the aluminum-oxide, aluminum-salt and salt-oxide interfaces.

Thermodynamically, this criterion is never satisfied. Based on the interfacial turbulence phenomena, however, it can be proposed that at the initial stage of oxide detachment, the molten salts first penetrate to the fresh aluminum surface through small cracks in the oxide film. These small cracks were raised during heating since the underlying aluminum expands more than the oxide films. As long as the oxide layer is no longer compact, the liquid aluminum tends to become a spherical shape and meanwhile the molten salt starts to react with fresh aluminum chemically in many small crevices, as shown in Fig. 12 [29].

When molten salts react with fresh aluminum, surface-active elements such as sodium and potassium may be

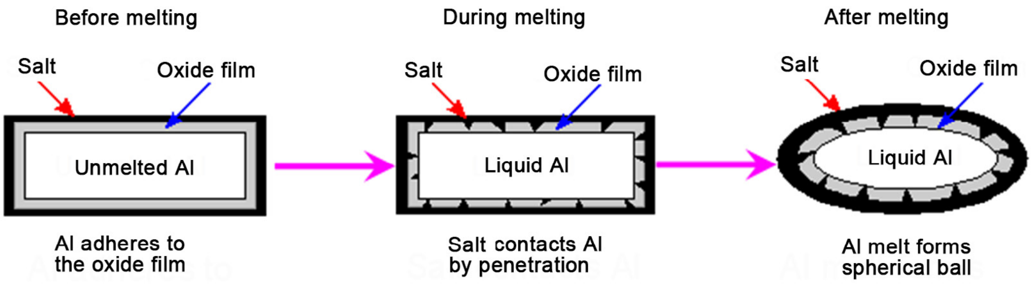

Fig. 12: A schematic illustrating aluminum oxide detachment process [29]

absorbed onto the aluminum surface, leading to the decrease of interfacial tension between aluminum and molten salt. Since the adsorption of salt ions such as sodium and potassium is not uniform along the entire surface of the aluminum droplets, due to non-uniform distribution of small crevices (cracks), a concentration gradient exists along the surface. As a result, the aluminum liquid tends to spin (interfacial movement). This creates a stripping force that separates the oxide layer from the liquid aluminum. For instance, in the equimolar NaCl-KCl salt system, the interfacial tension between aluminum and salt is 710 $\mathrm{mN{\cdot}m^{-1}}$. When NaF is added to this system, this value decreases to 450 $\mathrm{mN{\cdot}m^{-1}}$. The liquid aluminum will spin towards the area where the interfacial tension between aluminum and salt is higher (710 $\mathrm{mN{\cdot}m^{-1}}$), and this will lower the overall energy of the entire system.

Supposing that there is an aluminum liquid droplet setting on a flat oxide film in molten salt, three interfacial tension forces will act on the wetted aluminum droplet (Fig. 13). These three interfacial tensions will have following relationship when an equilibrium condition is obtained:

$$\gamma_{\mathrm{Al/oxide}} = \gamma_{\mathrm{oxide/salt}} - \gamma_{\mathrm{Al/salt}} \times \cos\theta \tag{2}$$

where the contact angle (θ), a measure of wettability, is the angle between the tangent at the three-phase contact line and the solid oxide interface. Assuming that a thin oxide film of area (S) was stripped away from an aluminum droplet, leaving the droplet to have an area (S) in contact with salt, the change in free energy of the system (ΔG) is given by:

$$\Delta G = S(\gamma_{\mathrm{oxide/salt}} + \gamma_{\mathrm{Al/salt}} - \gamma_{\mathrm{Al/oxide}}) \tag{3}$$

After replacing $\gamma_{\mathrm{Al/oxide}}$ with Eq. (2), the above equation can be rewritten as:

$$\Delta G = S\gamma_{\mathrm{Al/salt}}(1+\cos\theta) \tag{4}$$

To separate the oxide film from aluminum droplet or in other words to dewet the aluminum droplet from oxide film, the free energy of the system should be reduced. This can be done by either lowering the aluminum/salt or oxide/salt interfacial tensions or raising the aluminum/oxide interfacial tension. If the interfacial tension between oxide and aluminum is increased, the change in free energy becomes negative and the oxide film removal is more spontaneous. According to Eq. (4), however, the removal of oxide film is not spontaneous since the interfacial tension between aluminum and salt is impossible to be negative. Therefore, what can be done is to reduce the $\gamma_{\mathrm{Al/salt}}$ value as low as possible and to increase the contact angle θ as large as possible.

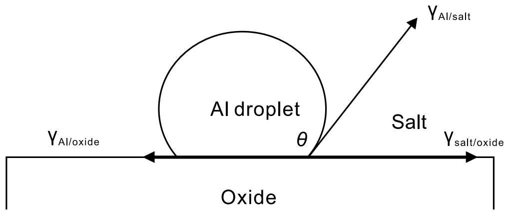

Fig. 13: Interfacial tension forces acting on the aluminum liquid droplet and aluminum oxide substrate [29]

The dissolved hydrogen in aluminum liquid can produce a lot of gas porosity if the melt is not properly degassed. This is because of the large difference in hydrogen solubility between liquid and solid. To make high integrity aluminum castings, the hydrogen level in the liquid aluminum should be controlled below 0.15 mL per 100 g aluminum and preferably below 0.1 mL per 100 g aluminum. The detailed degassing principle and practice have been reviewed and reported in Ref. [4].

4.3 Gating system design

The design of the gating system is very critical to the casting because it will affect the subsequent design procedures and influence the overall quality of the cast products. Irrespective of the shape of the castings, the casting quality is always determined by the gating system [31]. The optimal design of the gating system can significantly reduce the turbulent flow of the molten metal, minimizing the amount of gas and trapped impurities. For production of quality aluminum castings, the design of a naturally pressurized gating system shall be used no matter what kind of casting process is. The cross-sectional dimensions of individual parts of the gating system can be calculated from the dimensions and weight of the casting. In general, the melt velocity at any time during mold filling should be kept below the critical velocity of 0.5 $\mathrm{m{\cdot}s^{-1}}$ [4, 32] to avoid melt front turbulence and oxide film entrainment. For HPDC, however, mold filling needs to be completed within 100–200 milliseconds to be able to fill up the thin walls without causing cold shuts or misrun defects. The minimum melt velocity at ingates is usually controlled around 40 $\mathrm{m{\cdot}s^{-1}}$, which is 80 times greater than the critical velocity. Therefore, it is vital to correctly design HPDC gating system and particularly ingate locations and sizes to avoid converging melt fronts and keep melt flow as smoothly as possible.

Figure 14 shows an example of two gating designs for a large HPDC structural casting. Small changes in the runners and ingates between Designs 1 and 2 can lead to a different amount of air entrainment during mold filling, as shown in Fig. 15. The air entrainment is calculated through casting mold filling process simulation based on computational fluid dynamics. Design 2 seems to reduce trapped air during fill stages through the use of wide, thin runners and connected ingates.

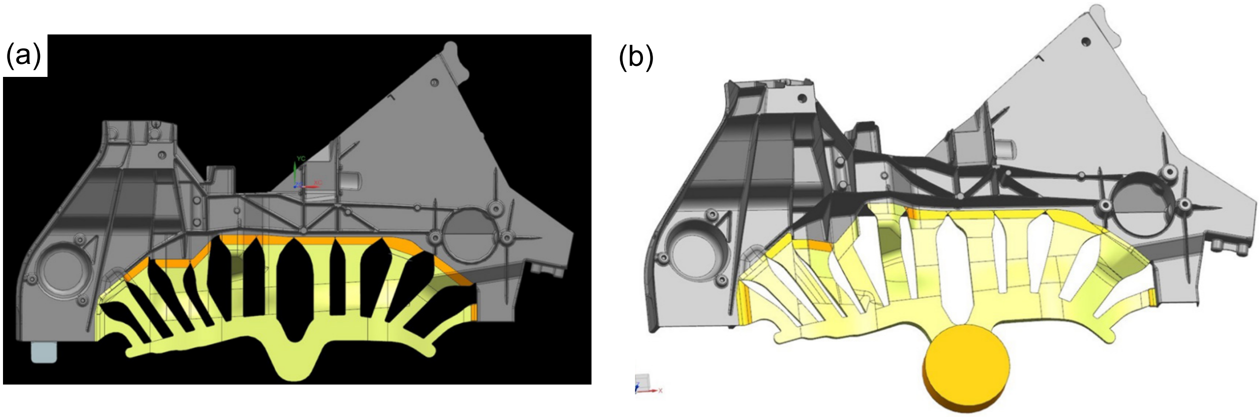

Fig. 14: Two gating designs for a large HPDC structural part: (a) Design 1; (b) Design 2

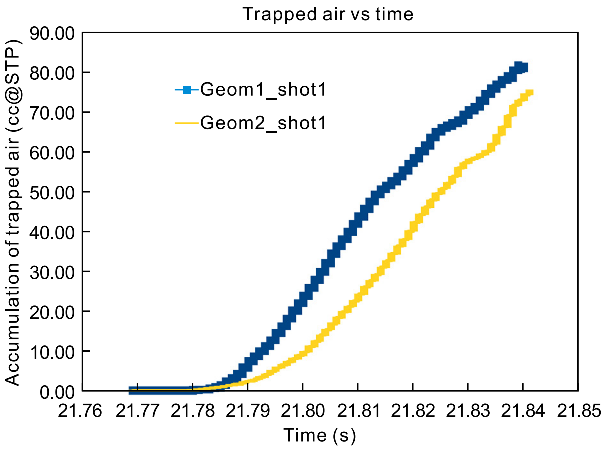

Fig. 15: Trapped air integral comparison between two gating designs (in casting only)

4.4 Mold surface treatment

Mold surface condition determines not only the quality of the surface finish but also the quality of the casting skin layer that can significantly affect casting durability performance as fatigue cracks usually form from the casting surfaces. For instance, if the coating material applied on the die surface is of bad quality, the casting will not have a smooth surface finish. Moreover, if too much coating is applied, it may lead to excessive buildup that can affect the dimensional accuracy. If a ceramic-based material coating needs to be used, the coating thickness should be maintained between 0.15–0.3 mm to ensure the casting dimensional accuracy and meanwhile to make it easier to remove the casting from the mold.

Castings with relatively large flat surfaces can experience excess surface appearance and quality issues due to the formation and entrapment of young oxides in the melt front during mold filling. In the final product, oxides at or near the subsurface can significantly reduce mechanical properties and particularly fatigue performance in addition to the bad surface appearance. A chemical etching method or an alternative surface treatment approach can be applied to metal die surface to make rough patterns or texture, so that the oxide film in the metal front can be peeled off during mold filling and the surface appearance and quality issue can be solved. Figure 16 shows an example of cast surface defects eliminated with the proper die surface treatment [33].

4.5 Casting process

Like gating system design, optimal casting process control is so important to the casting quality particularly for ultra-large aluminum castings. Casting process parameters should be closely controlled and aligned with the calculated gating analysis for optimal results as a given gating design literally determines process parameters.

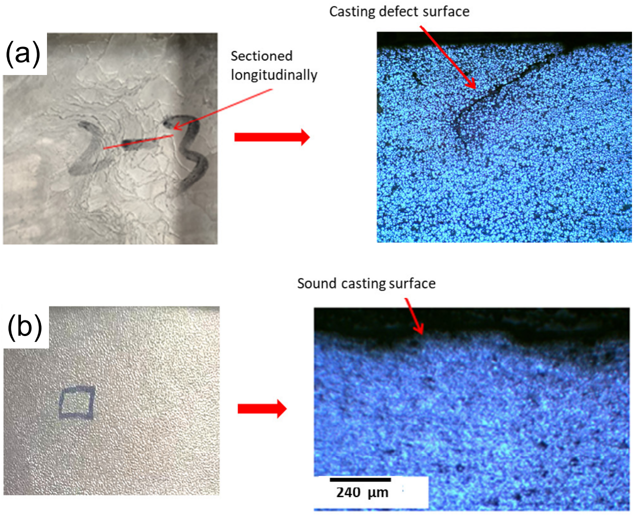

Fig. 16: An example showing cast surface defects eliminated with the proper die surface treatment [32]: (a) casting surface defects; (b) surface defect eliminated with die surface treatment

4.5.1 Mold temperature

The mold temperature at the time of pouring significantly affects the mold filling, solidification, residual stress, distortion, casting dimensional accuracy, and die life. If the mold temperature is too low, the casting will not fill well with cold shuts, flow marks, and misrun defects. When the mold temperature is too high, however, defects like surface bubbles, welding, and shrinkage may form. For a given size of casting, there is an ideal/optimal mold temperature to achieve a good combination of best casting quality and prolonged die life although it is generally accepted that the ideal die temperature should be kept about one third of the melt pouring temperature of the alloy selected. The actual ideal mold temperature should be determined and optimized using a casting process simulation code incorporating with a thermal imaging technique to measure the die cavity surface temperature before and after casting. Because of the casting geometry complexity and varying wall thickness throughout the part, ideal mold temperature should not be uniform throughout the entire mold cavity either. Therefore, conformal heating/cooling system is needed to achieve the ideal mold temperature distribution. For ultra-large mega/giga castings, local thermal management inserts may be used to help control the mold temperature and casting quality.

4.5.2 Pouring temperature

In metal casting, pouring temperature is an important process parameter as it not only affects the metal fluidity and viscosity, but also determines the cooling rate, microstructure fineness, and the distribution of alloying elements. Therefore, pouring temperature influences both metal flow and casting quality and mechanical properties. Low pouring temperature leads to incomplete casting, cold shuts, misrun, and surface defects. High pouring temperature results in coarse microstructure, high solidification shrinkage and porosity, more dross formation, and low mechanical properties. High pouring temperature may also cause damage to the mold, leading to other defects. To achieve the optimal casting quality and mechanical properties in HPDC, it is important to choose the right pouring temperature. Although typical pouring temperature is adapted to be around 50–100 °C higher than the liquidus temperature of the alloy, comprehensive casting process simulations are needed to determine the optimal pouring temperature, particularly for ultra-large mega/giga castings. This is because ultra-large castings have a much longer metal flow distance from the ingates in comparison with regular castings, and determination of an optimal pouring temperature becomes much more critical to ensuring smooth and complete metal flow into the mold cavity without risking damages to the die.

4.5.3 Pouring velocity and time

Pouring velocity is the speed at which the molten metal is injected into the die in HPDC. Pouring time is the time required for the molten metal to be injected into the die-casting mold until it is filled. Both are interdependent. For a given size of casting, high pouring velocity results in a short pouring time. The filling speed is mostly affected by the pouring temperatures. If the pouring temperature is high, the viscosity of the molten metal is low, and the fluidity increases. When the fluidity increases, the filling speed also increases. The filling speed is also a determining factor in casting quality. When the filling speed is low, the casting is unclear and cannot be formed. When the filling speed is right, castings with high surface quality can be achieved even with low injection pressure. Too high mold filling speed can result in undesired results, such as high air and oxide entrainment casting defects. Thus, an optimal pouring velocity and time should be determined using casting process simulation tools coupling with experimental validation.

In HPDC, the pouring velocity and pouring time constitute the shot profile. In other words, the shot profile determines the mold filling velocity and time. Thus, the shot profile should be optimized and well controlled to achieve the quality casting as it is one of the most important process parameters that control casting quality such as trapped air and oxide entrainment. As an example, two shot profiles (shown in Fig. 17) were computationally analyzed with both gating system designs as illustrated in Fig. 14. The accumulation of the trapped air calculated for four combinations (two gating designs and two shot profiles) is shown in Fig. 18. The delayed plunger fast speed stage and pressurization (Shot profile 2) significantly reduce the trapped air when it is combined with Design 2 of the gating system. Clearly, shot profile in HPDC plays a critical role in determining casting quality and thus mechanical properties.

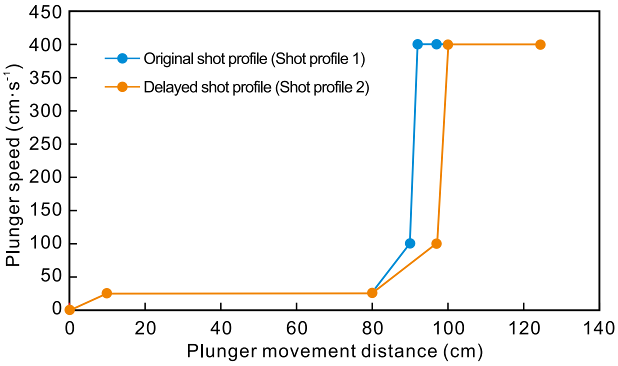

Fig. 17: Two shot profiles for a large HPDC structure casting

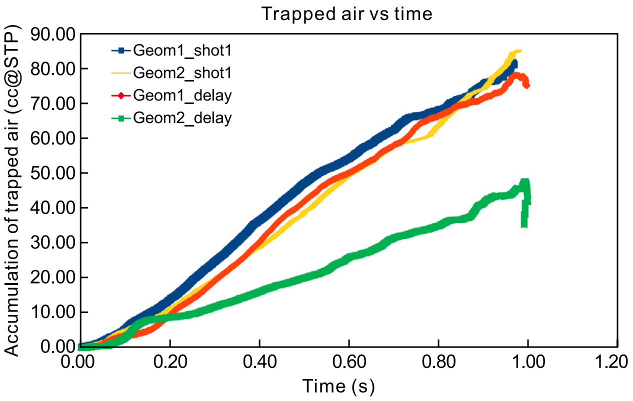

Fig. 18: Accumulation of the trapped air calculated for the four combinations of two gating designs and two shot profiles

5 Summary

Ultra-large mega/giga aluminum shape castings have drawn great attention in the automotive industry, as they can revolutionize vehicle body structure designs and manufacturing. Currently, ultra-large aluminum castings are mainly used for underbody structures to replace tens and hundreds of stamps, extrusions, small castings, and welding parts, simplifying structure design and manufacturing, reducing mass, and saving cost and lead time. Despite many appealing advantages, application of ultra-large castings poses some challenges such as difficulty of achieving casting quality and dimensional tolerances, part serviceability, and materials sustainability. The repairability and sustainability of ultra-large aluminum castings can be enhanced through the adoption of a design for repair concept and the use of sustainable cast aluminum alloys. The casting quality and mechanical properties can be enhanced using castable aluminum alloy, clean molten metal, optimal gating system design, and casting process optimization using virtual casting tools. Ultra-large casting's dimensional tolerances and stability can be assured through residual stress and distortion minimization with robust manufacturing and assembly process control.

Conflict of interest

Dr. Qi-gui Wang is an EBM of *CHINA FOUNDRY*. He was not involved in the peer-review or handling of the manuscript. The authors have no other competing interests to disclose.

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