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New Trends in Aluminum Die Casting Alloys for Automotive Applications

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Abstract: In order to provide ecological balance, new technologies are being developed to reduce fuel consumption. Within these new technologies, usage of light alloys such as aluminum and magnesium has gained great importance in the automotive applications. The advantages of aluminum alloys in terms of light weight, recycling, machinability and corrosion resistance led to increase application area of these alloys. Due to these characteristics of aluminum alloys, fuel-saving light-weight material selection plays an important role for automotive parts. Aluminum applications increase not only in automotive, but also in aerospace, space shuttle, marine, and defense applications. According to the production methods, aluminum alloys are generally classified as casting, sheet, forging and extrusion. Aluminum die casting alloys are generally used the production of suspension systems, engines and gears parts. However, with the developing aluminum casting technologies, the aluminum die casting method makes it possible to manufacture multiple body parts in one piece. It is predicted that number of aluminum die casting parts will increase, especially in electric vehicles. In this study, the importance of the use of aluminum die casting alloys in the automotive industry is emphasized. Research and trends so far of the development of aluminum die casting alloys are also summarized.

Keywords: Light weighting, Aluminum casting alloys, Fuel consumption.

Introduction

Recently, weight reduction through the use of light-weight materials plays an important role in improving fuel economy and reducing harmful emissions. The importance for reducing CO_2 emissions by lightweight structure design for automotive applications, lead to increase the usage of medium strength aluminum alloys (Taub et al, 2007). Replacing steel components with high strength aluminum alloys became a spot light in automotive industry for light-weighting (Baser, 2012). Aluminum can be assumed that the 2nd metal element which can be provided on earth. It is the most used material in today's industry after steel. Aluminum alloys are widely preferred due to their light-weight, low density, good formability and high corrosion resistance characteristics (Cuniberti et al, 2010).

In last decade studies on energy saving reveals that production of light and economical vehicles plays an important role for less fuel consumption. Aluminum alloys are widely preferred in passenger cars, buses, primarily in trains as well as the construction of marine applications (Zeytin, 2000). In fact, aluminum alloys have been used in the aviation and defense industry for a long time. The adaptation of aluminum to the automotive industry has started due to the advantages seen in aviation and defense applications.

Casting aluminum alloys are widely used in automotive industry (Baser et al, 2013). Aluminum casting is a variation of this that uses only aluminum and aluminum alloys as the liquid metal that is poured into the mold. Aluminum castings are used to make complex and detailed parts very efficiently (Engler et al, 2010). Casting aluminum alloys are quite widespread and find more and more applications in modern industry. According to different estimates, up to 20–30% of all aluminum products manufactured worldwide are used for aluminum die castings (Criqui et al, 2009).

Due to considerable improvements in casting technologies, now it is possible to produce high-quality aluminum die casting components with properties that are comparable to those of similar wrought products (sheet and extrusion). Moreover, this can be done not only for high-quality alloys, but also for those manufactured with substantial amounts of aluminum scrap (Brinkman et al, 2010). In the latter case the advantage, of course, is in lower production costs.

Significant improvements in the quality of aluminum die were achieved due to improved production processes. Today it is possible to employ advanced methods of molten metal handling, which result in dramatic reduction of harmful nonmetallic impurities. For instance, hot isostatic pressing is used to reduce shrinkage porosity. All these and many other innovations result in significant improvement of aluminum die casting quality as well as mechanical properties (Zolotorevsky et al, 2007). This study focuses on the importance of the use of aluminum die casting in the automotive industry. Research so far of the developments and global trends of aluminum die casting were also summarized.

Aluminum Die Casting

Aluminum Die Casting Alloys

In recent years, aluminum die casting alloys have become one of the crucial alloy groups in many industrial applications. Features of aluminum alloys such as energy and fuel saving and light weight properties were underlined since CO_2 in the automotive has become an important issue to achieve. Aluminum die casting alloys have a classification system consisting of 3 digits and decimal places (Tanwir et al, 2017). Heat treatment can be also applied to aluminum casting alloys (Kaufman et al, 2004). Master alloy additions can be made to improve the properties of aluminum casting alloys according to customer needs. Grain refinement is one of the most common process in order to obtain fine micro structure in cast aluminum alloys. Within the grain refinement process, the grain morphology of coarse grained Al-Si alloys is refined and the mechanical properties are increased (Kaufman et al, 2004). Titanium-boron, titanium and boron alloys such as $AlTi_5B_1$, Al_3B, $TiAl_3$, and AlB2 are widely used as grain refiners (Spittle et al, 2006). Among the aluminum casting alloys, 300 series is mostly preferred especially in parts such as housing and bracket in the automotive applications. 300 aluminum casting alloys especially aluminum-silicon based with an additional copper or magnesium elemental percentage (Kaufman et al, 2004).

The highest volume of aluminum components in vehicles are aluminum castings, such as engine blocks, cylinder heads and chassis parts (Graf, 2021). New aluminum die casting techniques came up with improved material properties and functional integration that enables aluminum to meet the desired requirements. This trend is driven by the needs of the automotive manufacturers to substantially reduce weight of the power train and chassis components. Additional features for achieving a better vehicle performance gain an unacceptable increase in vehicle weight (Baser, 2012). Already well-established in high class automobile engines, a significant weight reduction can be obtained by aluminum die casting usage-smaller but high volume compact-size vehicles (Kaufman et al, 2004).

Aluminum Casting Methods

Among aluminum casting methods sand mold casting, precision casting and high pressure die casting methods are most common used aluminum casting methods in the literature (Kaufman et al, 2004). However, in recent years, when the geometric difficulties in the parts, the porosity in their internal structures and the expectations in the casting cavities are revealed, it is noticed that the demands for the high pressure casting method have increased. In the automotive industry, aluminum alloys are classified according to their production methods as in Figure 1.

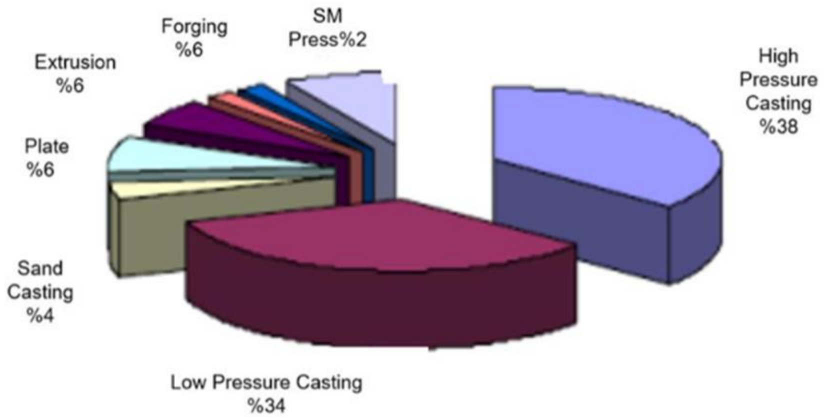

Figure 1. Classification of aluminum alloys in automotive by production method (Ozcomert, 2006).

Sand casting method is one of the most preferred production methods when not only the automotive sector is considered. (Dalquist et al, 2004). Sand mold castings are handled in two ways. It is classified as removable and perishable. While the perishable model is not very common, the removable model is widely used. There are many parameters that are important in the sand mold casting method. These can be listed as follows; molding process, pattern, sand quality, cores. The molding process is a very important parameter in the sand mold casting method. The process using molding sand creates the compacted sand model cavity. Thanks to the runner system, it is aimed to give the desired geometry by pouring the melted metal alloy into the mold cavity. After the hardened parka is removed from the mold, the final piece is obtained after the excess parts such as burrs, runners and feeders are cleaned. (Wang et al, 2010).

The precision casting method is a production method used especially in the production of parts that are very difficult to manufacture (Pattnaik et al, 2012). Prototype productions are completed faster because the final part is obtained faster. In order to meet the expectations in the final parts, it is preferred especially because of its advantage in the machining process. Allowing freedom in design selection, obtaining detailed parts in good quality with high measurement precision, providing surfaces with high quality and roughness levels specific to the application method and the mold used, production can be carried out from parts with very little weight to parts with heavy weight. It also stands out with its features such as processing on complex parts, providing dimensional accuracy, obtaining parts with high production numbers in a short time, reducing costs, reducing machine operations and the number of processes (Pattnaik et al, 2012).

Die casting is an efficient, economical process offering a broader range of geometry and components for automotive industry as well as other applications than any other manufacturing technique. Parts have long service life and may be designed to complement the visual appeal of the surrounding part. Automotive parts designers can gain a number of advantages and benefits by specifying aluminum die casting parts (Cheșa, 2019).

High-speed production – Die casting is able to manufacture automotive parts with complex geometries in minimum tolerances respect to rest of the mass production processes. Machining is not required and over thousands of automotive die casting parts can be produced before repairing the molds (Cheșa, 2019). Dimensional accuracy and stability – Die casting produces automotive parts that are durable and dimensionally stable, while maintaining close tolerances (Cheșa, 2019).

Strength and weight – Thin wall castings of aluminum die cast automotive parts includes high strength and lighter respect to other casting methods. In addition, because aluminum die castings do not consist of separate parts welded or fastened together, the strength of automotive components after die casting is that of the alloy rather than the joining process (Cheșa, 2019). Multiple finishing techniques – Aluminum die cast automotive parts with smooth or textured surfaces can be obtain by aluminum die casting. They are easily plated or finished with a minimum of surface preparation (Cheșa, 2019).

High pressure aluminum die casting (Figure 2a) is a manufacturing process in which molten metal (aluminum) is injected with a die casting machine under force using considerable pressure into a steel mold or die to form products (Kaufman et al, 2004). In addition, short cycle times are feature advantage of high pressure casting in the production of thin-walled parts with complex and difficult geometric structures (Kridli et al, 2021). High pressure die casting production is rather fast relative to other aluminum casting processes (Zolotorevsky et al, 2007). Aluminum die casting applications also allow to offer aggressive casting delivery times (Kridli et al, 2021). Because of the excellent dimensional accuracy and the smooth surfaces, most of components which are manufactured by high pressure die casting do not require machining except the removal of flash around the edge and possible drilling and tapping holes (Zolotorevsky et al, 2007). High pressure casting method has also disadvantages such as higher investment costs and process fees compared to other aluminum casting methods. Complex shape and high-cost aluminum injection molds are used (Zolotorevsky et al, 2007).

Low pressure aluminum die casting (Figure 2b) can be also preferred for the components without concern for high quality (Kridli et al, 2021). Since the low pressure casting method is longer in terms of cycle time, it is generally preferred for parts with lower annual numbers as well as the production volume. Low pressure casting is the preferred method of manufacturing components such as engine blocks, wheels and suspension parts.

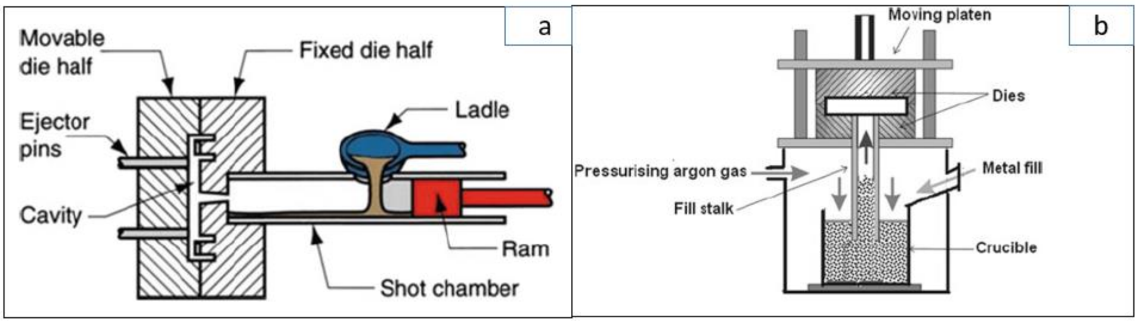

Figure 2. Illustration of; high pressure die casting (a), low pressure die casting (b) methods (Bonollo et al, 2015).

Aluminium Die Casting Applications & Trends for Automotive Industry

Automotive industry is at the forefront of this trend looking for effective alternatives to cut down on weight without sacrificing durability, which is under constant pressure to adhere to increasingly strict fuel economy standards, while addressing the efficiency in production, understanding of minimizing operating costs is dominant (Cheșa, 2019). Although the most important parameters are safety, it is also aimed to produce fuel-saving vehicles. Therefore, aluminum casting parts have entered a rapidly rising trend in the automotive industry in recent years. According to calculations in literature, 0.6 liters of fuel consumption is obtained in every 100 kg of weight reduction per 100 km. within the aluminum casting parts usage (Kelly et al, 2015).

Figure 3. Examples of aluminum die casting components (Cheșa, 2019).

Use of aluminum casting parts in a 1400 kg vehicle, approximately 300 kg of weight gain can be achieved. This corresponds 20% of weight reduction that provides the fuel saving is 1.8 liters per 100 km. (Palencia et al, 2012). According to literature, aluminum when replacing steel in today's vehicles, could save approximately 44 million tons of CO_2 emissions per year (Palencia et al, 2012). The recycling application of aluminum can be carried out without sacrificing the material quality. Nearly 90 % percent of the aluminum used in vehicles is recycled at the end of its life cycle. (Ozcomert, 2012).

Fasteners, brake systems, engine system, pistons can be examples for aluminum die casting vehicle parts in automotive applications. Figure 3 shows of engine parts produce through aluminum die casting as an example. (Cheșa, 2019). The stator is generally also made through aluminum die casting. Stators have many variations in size. This is why using die casting is such a good method, because it allows for different sized mechanical parts to be created with the highest degree of accuracy every time (Figure 3). Brackets are also manufactured through the process of aluminum die casting. Brackets are used in the electrical part of the motors. Also, stepper motors also use die casted brackets and these are generally created as per the specifications of the customers (Figure 3). Electronic covers are created in many parts of vehicles, for instance, gearbox but also the shades pole, the motor and on the stepping motor. These are but a few examples of where electronic covers are used through die casting processes (Figure 3). Heat sinks manufactured using the casting methods are primarily suitable for forced ventilation systems. This type of heat sink is usually made of cast aluminum (Smith et al, 2014).

Aluminum casting producers have been perfecting and improving their methods and techniques to streamline the production processes to increase output at a reasonable cost. Structural die casting components (Figure 4, a-c) are increasingly popular for the automotive industry (Hirsch et al, 2011, Baser, 2012, Hartlieb, 2013). Currently, they are proving their strengths above all with upper class cars such as the new Jaguar I-Pace, the BMW series 8 Coupé or the Mercedes-Benz C class (Hirsch et al, 2011, Baser, 2012). In automobile manufacturing, an increasing number of structural components such as shock towers (Figure 4, d) are being implemented. They can be used to replace multiple individual components, thereby substantially lowering the weight of a vehicle. Lightweight construction is significant for hybrid and electric vehicles coming to market: the additional weight of batteries and the electric motor for hybrids can be substantially offset by replacing steel structures with aluminum die castings. The market for structural components has already multiplied over the past five years. At the same time, manufacturing costs were decreased by approximately 20 %; however, OEMs suggest that an additional 20 to 30 % cost reduction is required to make these parts viable for high volume vehicles (Ducker Worldwide, 2017).

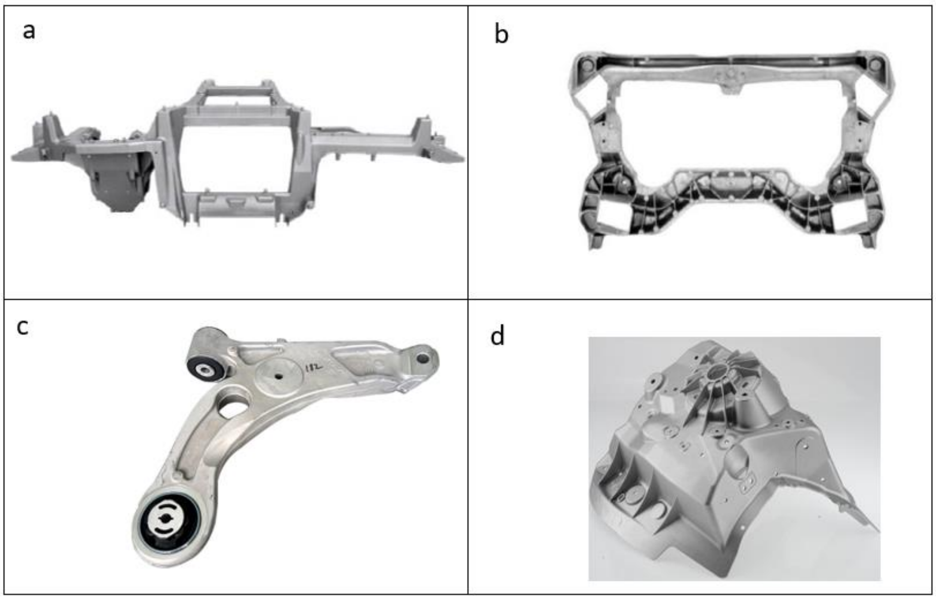

Figure 4. Examples for Al casting structural parts; cross car beam (a), engine cradle (b), control arm (c) , shock tower (d) (Hirsch et al, 2011, Baser, 2012, Hartlieb, 2013).

Aluminium has been the fastest growing material in light vehicles now for more than 50 years. The first wave of aluminum growth was mainly for casting in powertrain, chassis and wheels. Automotive aluminum content continues to steadily grow within multiple product forms and vehicle applications. Figure 5 shows the long term aluminum growth by product forms (Ducker Frontier, 2020).

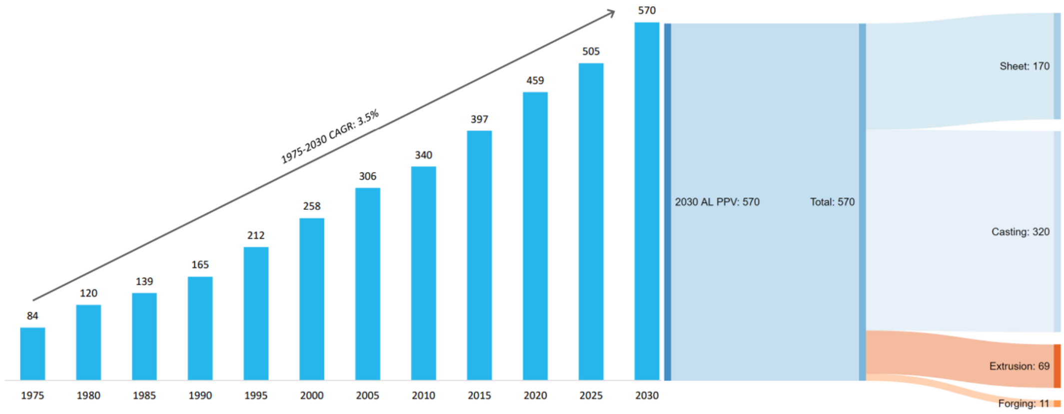

Figure 5. The long term aluminum growth by product forms (Ducker Frontier, 2020).

Average aluminum alloy content per vehicle is expected to 20 kg increase by 2025. Aluminum casting is expected to remain the predominant forming process. In 2025, the use average aluminium content per vehicle considering product forms such as cast, sheet, extrusion and forged forms will be 118 kg, 43 kg, 26 kg and 10 kg, respectively (Ducker Frontier, 2019). North American Light Vehicle Aluminum Content report currently reveals that aluminum usage has already experienced significant increases in last ten years. In 2010, the average aluminum content per vehicle was at 154 kg. At that time, the applications for aluminum were rather limited, with only small amounts of body sheet was used. Since 2010, additional aluminum usage in automotive applications was demonstrated more than 50 kg per vehicle, with 210 kg of average aluminum content per vehicle expected in 2030. According to reports (Ducker Frontier, 2020), more than 30 platforms in 2025 will have more than 230 kg of aluminum content in vehicles. Within next years, aluminum is expected to see another burst of growth, with average aluminum content to exceed 250 per vehicle, a 12% increase from the current numbers.

Advanced manufacturing technologies are needed to adapt new materials as well as production strategies. Figure 6 shows emerging manufacturing processes in the automotive applications (Center for Automotive Research, 2019). Among those emerging manufacturing processes, high-pressure thin-walled aluminum die casting was also underlined. It was expected that application of high pressure aluminium die casting will be increased towards to 2040. High-pressure die-casting (HPDC) is a technology that is proper for high production rates. Nowadays, about 50% of the world production of light metal castings is obtained through this technology.

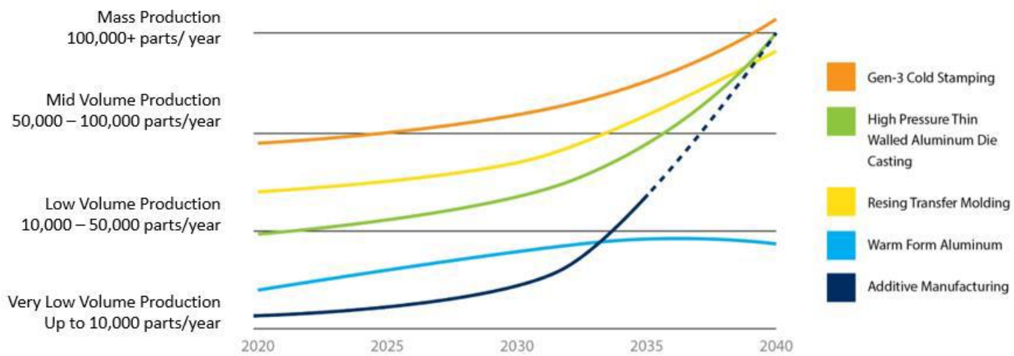

Figure 6. Emerging manufacturing processes in the automotive applications (Center for Automotive Research, 2019).

Aluminum cast parts for automobile manufacturing also include oil pumps, water pump housings, connectors, transmission parts, and a wide variety of brackets. The durability and reliability of aluminum cast parts has made them an essential part in auto design improvements and innovations (Hartlieb, 2013). Aluminum casting still account for the largest amount of aluminum content at 65% with about 135 kg per vehicle in 2025 through 2030, aluminum castings per vehicle is expected to grow to 145 kg. However, this will take up a smaller amount of the overall aluminum content at 61%. In general, the amount of aluminum powertrain castings has been decreasing, in part due to the downsizing of engine blocks and the number of cylinders. Instead, there is a new trend towards structural castings, especially for BEVs (battery electric vehicle) and plug-in hybrids. For example, Tesla is adopting a large structural casting for the rear of its electric SUV (Sports Utility Vehicle). The massive casting is said to replace over 70 extrusions and stamped sheet components, combining them into a single piece. However, Volvo has just announced its desire to build body-in-white architectures using giant aluminum castings which is called mega-giga casting technology (Duckers, 2022). The Swedish automobile producers invests more than a billion euros for future EV's (electric vehicle). They also consider to meet several objectives with mega-casting in order to get weight reduction in vehicles. In additional it was also aimed to improve the use of interior space, and to be able to develop several vehicles capable of using the same modules based on the same body-in-white elements (mega castings). Volkswagen also revealed recently that their “Project Trinity” will likely use Tesla-like manufacturing processes in order to speed up production including potential mega-casting solutions (Duckers, 2022).

Mega-castings provides reducing assembly time, length of the assembly line. Mega-casting involves molding a section of a vehicle with as many components built into the panel as possible, reducing complexity when it comes to main assembly. Tesla introduces Giga-casted parts for the front of the future Model 3. Production of Tesla Model 3 is revealed Tesla model Y by mega-giga casting technology, which provides 2 parts instead of combined 171 parts (Figure 7). Tesla has already been producing the Model Y with a single rear body piece that replaced 70 different parts in the vehicle (Duckers, 2022).

Figure 7. Production of Tesla Model 3 is revealed Tesla model Y by mega-giga casting technology (Duckers, 2022).

Recently, Volvo and its premium EV brand Polestar are joining in, with the adoption of the Giga Press named mega-giga castings is shown in Figure 8. Volvo plans to use the technology to create a single mega-cast aluminium floor pan. The mega-cast floor pans for Volvo’s next-generation EVs will have the mounting points for items like suspension arms and electric motors already built in, which negates the need for a rear subframe (Carney, 2022).

Figure 8. The megacasting replaces many stamped parts at the rear of this Volvo's chassis (Carney, 2022).

Two Chinese EV startups as Nio and Xpeng, have already followed Tesla's lead by ordering injection molding machines capable of 12,000 tons of force (Duckers, 2022). Compared to using methods such as welding multiple small parts in chassis production, the mega casting is expected to help enable the production of chassis parts in monolithic. In this way, it is aimed to eliminate many additional steps during assembling stage which provides cost reduction as well as energy efficient vehicles. The German automaker Mercedes-Benz aim to maximum cost and weight reduction (which megacasting makes possible) in order to provide management of energy consumption to increase EV range (Duckers, 2022).

Conclusion

Increasing global competition and the preservation of the ecological balance have pushed automobile manufacturers to new searches. It was aimed to produce vehicles keeping the the product costs at reasonable levels while maintaining efficiency in production, less fuel consumption, efficient material recycling as well as improve comfort without sacrificing safety. With the increase in the use of light metals, aluminum alloys became an indispensable material with its high engineering properties for the automotive industry. In recent years, aluminum die casting alloys have become one of the crucial alloy groups in many industrial applications. There have been many challenges in aluminum die casting to establish casting processes to produce high-integrity components from aluminum alloys. Advances in new casting technology mainly have been in pressure die casting; high-pressure die-casting is the most efficient process to reduce porosity, and hence can be used to produce both thinner and thicker parts. Most of engine parts such as fasteners, brake systems, engine system, pistons can be examples for aluminum die casting vehicle parts in automotive applications. Aluminum casting producers have been perfecting and improving their methods and techniques to streamline the production processes to increase output at a reasonable cost. Structural die casting are increasingly popular for the automotive industry. Besides, advanced emerging manufacturing processes are also needed to adapt new materials as well as production strategies. Among emerging manufacturing processes, high-pressure thin-walled aluminum die casting was underlined. It was expected that application of high pressure aluminium die casting will be increased towards to 2040. High-pressure die-casting is a technology that is proper for high production rates. Nowadays, about 50% of the world production of light metal castings is obtained through this technology. In general, the amount of aluminum powertrain castings has been decreasing, in part due to the downsizing of engine blocks and the number of cylinders. Instead, there is a new trend towards structural castings, especially for BEVs and plug-in hybrids. For example, Tesla is adopting a large structural casting for the rear of its electric SUV. The massive casting is said to replace over 70 extrusions and stamped sheet components, combining them into a single piece. However, Volvo has just announced its desire to build body-in-white architectures using giant aluminum castings which is called mega-giga casting technology.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to authors.

Acknowledgements or Notes

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