Chapter 1

Light Alloys — From Traditional to Innovative Technologies

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Additional information is available at the end of the chapter

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Abstract

Selection of materials with the expected, application-dependent characteristics constitutes a very important point in any industrial application. In the automotive and aeronautical industries, the current tendency is to use light metals and their alloys for production of various components. For example, some of the problems related to fuel consumption and weight reduction could be partially solved by using such alloys as an alternative to traditional iron-based alloy components. Due to their very attractive properties, the most commonly employed light materials for producing high-stressed components are aluminium, magnesium and their alloys. Al-based alloys have a high strength/weight ratio, good formability, excellent combination of castability and mechanical properties which together with an excellent corrosion resistance make them very appropriate for a large variety of applications. There are two important families of aluminium alloys: (i) wrought alloys, firstly cast as ingots and/or billets and then mechanically hot- and/or cold-worked into the preferred shape, and (ii) cast alloys, directly cast into their final form through different traditional or innovative processes.

At the same time, there is continuing interest in Mg alloys for engineering proposals because of their lowest density directly connected to a weight saving of about 40% compared to steel and cast iron and 20% compared to aluminium for the same component performance. Their high specific strength, good castability and machinability, high thermal conductivity, high dimensional stability, good electromagnetic shielding property, high damping characteristics and full recyclability place them in a particular position for production of different types of components. High-pressure die casting is the most widely used technique and represents about 50% of all light alloy casting production. The tendency to use low-pressure die casting is increasing (it accounts for about 20% of all production). Gravity die casting, a small but growing contribution derived from a vacuum die casting and squeeze casting process, represents the remaining share of manufacturing processes. Generally, during solidification in a traditional manufacturing process, volume contraction is observed. This is due to the wrong feeding system and/or gas development, which in turn generate some voids or cavities within a casting, which are in turn responsible for the presence of defects in the casting components. For these reasons, the research community and manufacturing industries are giving a high level of attention to the development of innovative production procedures. In this context, semi-solid metal processing is able to attain at least the same level of properties and performances as those obtained by conventional techniques. Progresses in materials development represent a valid support for enhancing the life of an engineering component and its reliability.

In this chapter, a general overview of the actual scenario concerning the production and use of light alloys will be presented, including a short history and description of state-of-the-art techniques integrated with some results of the current research in this field carried out by the authors.

Keywords: Al alloys, Mg alloys, High-pressure die casting, Low-pressure die casting, modified squeeze casting, semi-solid metal processing, innovative rheocasting process, self-hardening Al alloy, microstructure, mechanical performance

1. Introduction

1.1. Overview on light metal alloys

Currently, a great variety of materials are available with their own features, values, applications and obviously their restrictions. Ferrous and non-ferrous metals and their alloys, ceramics, composites, plastics and various other materials with unique properties are employed today in manufacturing, either separately or in combination. Selection of the materials with the expected application-dependent characteristics constitutes a very important aspect in any industrial application. After material selection, the manufacturing processes to be used based on the targeted application also become very important. As concerns materials, the general tendency is to better control the alloys' compositions and the presence of defects due to impurities, inclusions and faults. Progresses in materials development represent a valid support for enhancing the life of an engineering component and its reliability. As regards manufacturing procedures, the efficient management of the productivity is very important, minimizing the cost and maintaining the high quality of the product.

In this chapter, a general overview of the present scenario concerning the production and use of light alloys will be presented. It is based on the data available in the literature integrated with some results currently obtained during the research carried out by the authors. Although

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the widespread production of light alloys considers traditionally developed processes and commonly employed alloys, there is a general tendency to provide and develop innovative production procedures and new alloy compositions able to guarantee excellent performances, in a more cost-effective and/or timely manner. These aspects are directly correlated to mass reduction and to fuel economy and they constitute a central aspect for many industrial applications. In automotive and aeronautical fields, the current tendency is to use light metals and their alloys to produce different components: the most frequently employed Al alloys belong to the AlSi7Mg, AlSi7Cu3Mg and AlSi7Cu3Mg systems. As regards Mg alloys in the automotive industry, the preferred selection is related to Zr-free alloys. The commercially available alloys are Mg-Al, Mg-Al-Zn, Mg-Al-Si, while the alloys belonging to the Mg-Al-Rare Earths, Mg-Al-(Alkaline Earths) systems are semi-commercial or being developed [1].

Al alloys reveal a high strength /weight ratio, good formability, excellent combination of castability and mechanical properties, which associated to an excellent corrosion resistance, make them very suitable for a large variety of applications. Al alloys are basically classified in two ways: on one hand, as (i) heat-treatable and (ii) non-heat-treatable alloys and, on the other hand, according to the process by which they get their properties: (a) wrought alloys, firstly cast as ingots and/or billets and then mechanically hot- and/or cold-worked into the preferred form, and (b) cast alloys, directly cast into their final form through a variety of traditional or innovative processes. Al alloys have a particular position concerning its use as a structural material in automotive applications for producing cylinder heads, brake rotors, engine blocks, for manufacturing aircraft components or marine engines [2-10]. To produce components of complex shapes, casting or forging are the most convenient processes [2, 3, 6, 10]: forged parts have better quality and mechanical properties and castings are cheaper and the foundry route is generally preferred.

Currently, the interest in Mg alloys for engineering proposals continues because of their lower density directly connected to a weight saving of about 40% compared to steel and cast iron and 20% compared to aluminium for the same component performance. Their high specific strength, good castability and machinability, high thermal conductivity, high dimensional stability, good electromagnetic shielding property, high damping characteristics and full recyclability place them in a particular position for different types of component production. Some drawbacks, i.e. their high tendency to galvanic corrosion when they are in contact with dissimilar metals or electrolyte, the difficulty to deform them by cold-working and last but not least their high cost seems to be limiting their spread. Most Mg alloy components are produced by a high-pressure die casting process, which is one of the most efficient and growing methods for Mg production of complex shape components, but defects, i.e. shrinkage and gas porosity, are often observed in the cast parts. These defects deteriorate the mechanical properties of the casting components, limiting the application of Mg alloys [1, 11-17].

1.1.1. Heat-treatable and non-heat-treatable Al alloys

Generally, the mechanical properties of Al alloys with a specific composition can vary drastically depending on their thermo-mechanical processing, applied either during production or as a post-production step. The non-heat-treatable alloys have their strength through different levels of cold-working or strain hardening applied to them that can be performed by rolling, drawing through dies, stretching or similar operations where area reduction is obtained. Regulating the amount of total reduction in area of the material controls its final properties. In the case of heat-treatable or precipitation hardening alloys, achievement of their strength and other properties occurs after applying different heat treatments.

For the non-heat-treatable alloys, the highest mechanical properties are achieved by hot- or cold-working mechanisms during their production. The initial strength of these alloys depends on the hardening effect of some elements, i.e. manganese, silicon, iron and magnesium, individually or in various combinations. Strength can further be improved by a cold-working process, as the aluminium has got a high ductility, and consequently can be easily deformed. For example, alloys containing appreciable amount of magnesium are usually given a final elevated-temperature treatment called stabilizing to ensure the stability of their properties.

Heat-treatable alloys are those whose characteristics depend on heat treatments and age hardening. In this case, significant strengthening can be achieved by heating and cooling. The initial strength of these alloys is also influenced by the addition of alloying elements to the pure aluminium. The series that belong to this group are copper, magnesium, silicon alloys and zinc alloys.

The presence of these elements determines higher solid solubility as the temperature increases, producing further important reinforcement by solution heat treatment (quenching, age hardening, artificial or natural aging) [18-20].

1.1.2. Casting and wrought Al alloys

Casting aluminium alloys were already very popular, and they are still finding new applications in many industrial fields. About 80% of all aluminium casting products are derived from aluminium scrap, a fraction that is significantly higher than for wrought products. In the past 10 years, casting technologies have been considerably developed and at present a high product quality is achieved. There are several requirements for casting aluminium alloys:

a. good corrosion resistance;

b. high level of mechanical properties, i.e. yield strength, tensile strength and elongation;

c. good castability, which is correlated to excellent fluidity in liquid state, and low shrinkage porosity.

The last condition is particularly important, and porosity is still the most critical problem. There are two principal ways to approach it, using on the manufacturing route (1) or alloy composition (2):

1. enhancement of the available casting processes and generation of innovative production technologies which provide a guarantee for excellent castings with low castability;

2. elaboration of a new alloy composition employing conventional production processes.

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Due to the high temperature used in the casting process, the solubility of these alloys is higher than that of wrought alloys.

Wrought aluminium alloys represent about 85% of aluminium alloy applications. They are initially cast as ingots or billets and then hot- and/or cold-worked mechanically into the desired shape. Their crystal structure gives them good cold formability. The addition of alloying elements improves most of their mechanical properties. Although they contain relatively small amount of alloying elements, the structure of wrought alloys offers better mechanical properties than cast alloys. Adopting plastic deformation techniques, a high level of grain refinement and homogenized microstructure has been obtained. There are four main processes applied to wrought alloys to obtain different final products:

1. rolled plates, fat sheets, coiled sheets, and foils;
2. extruded rods, solid and hollow shapes, profiles, or tubes;
3. forming products: rolled or extruded products are formed to achieve complex shapes;
4. forged products: they have complex shapes with superior mechanical properties.

1.1.3. Casting and wrought Mg alloys

The development of Mg alloys started shortly after the first industrial production of this light metal, but unlike Al wrought alloys their development was not constant. Similar to Al alloys, it can be differentiated between cast or wrought Mg alloys. From a technological point of view, the capability of plastic deformation is of vital importance with wrought alloys, while casting alloys should exhibit good mould-filling features. On one hand, Mg has excellent casting properties, but its deformation at room temperature is reduced due to the hexagonal crystal lattice structure. Mg alloys can be deformed by classic deformation processes (rolling, extruding, forging), depending on the alloy composition, above 200°C. More casting alloys than wrought alloys are available. On the other hand, wrought Mg alloys have specific advantages because they are not porous and excellent mechanical properties can be achieved by special thermos-mechanical treatment. This leads to some differences in alloy content, but they are not as significant as in the case of Al alloys [10, 21-28].

1.2. Traditional manufacturing processes for light metal alloys

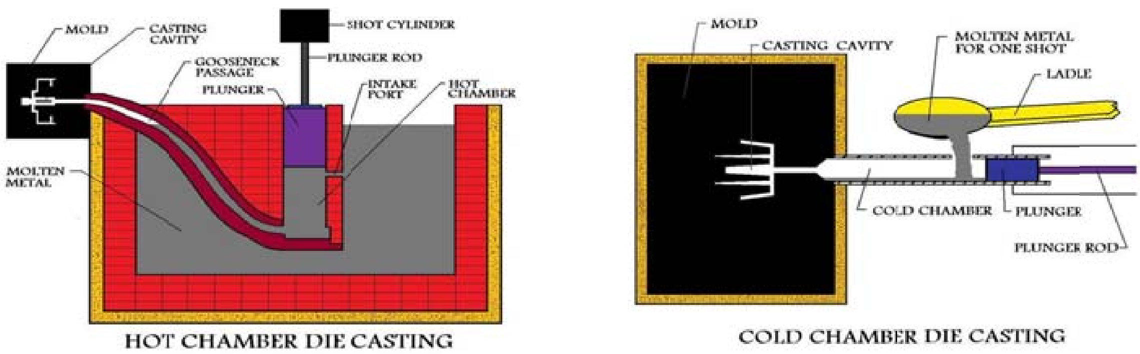
There are several types of die casting processes. Various processes are now in use to achieve both economically and technologically viable Al castings production. The variety of methods results from the different ways in which gas can be eliminated from the cavity, how the injection system works or how much heat is lost during the process. Die casting is a metal casting process characterized by forcing the molten metal under pressure into a mould. The mould cavity is created using two hardened tool steel dies. A die casting die is a complex tool usually made up of two halves called a cover and an ejector die: the cover die is fixed to the motionless part of the injection machine, while the ejector die is secured to a moveable ejector plate. The die cavity in which the castings are formed is made of cavity inserts fixed to each of the two die halves, fixed or moveable cores, as well as other moveable parts.

At the end of the casting process, the die opens and the ejector pins extract the part from the die; furthermore, a die can be constructed as a simple die in order to produce a single casting for each shot or as a multiple-cavity die to produce multiple castings of identical shape per each shot [24-26, 29].

Non-ferrous metals, like Al, Zn, Cu, Mg, are the most processed materials using this technique, because of their relatively low melting temperature that steel can withstand. Depending on the casted metal, there are two kinds of available processes:

1. hot-chamber pressure die casting (Figure 1a): in this case, the pressure chamber is joined to the die cavity and is permanently dipped in the liquid metal. The inlet port of the pressurizing cylinder is uncovered as the plunger moves to the open, unpressurized, position, consenting the filling of the die cavity with fresh melt. This process is used for metals with a low melting point and high fluidity such as Sn, Zn and Pb.

2. cold-chamber pressure die casting (Figure 1b) : the liquid metal is placed into the cold chamber before each shot and is suitable for Al and its alloys, Cu and its alloys where combination with Fe at high temperature occurs with no difficulty [30-34].



a b

Figure 1. Scheme of the hot-chamber and cold-chamber die casting machine

1.2.1. Cold and hot die casting: Differences and similarities

Compared to the hot die casting process, the cold die casting process requires the application of higher pressure; in fact, the pressure at which the molten metal is forced into the die cavity and fills it properly is an order of magnitude higher in cold die casting than in hot die casting. The cold-chamber die casting production process involves a pressure (20-350 MPa) which leads to a product with thin walls and good mechanical properties. From an economical point of view, in this case a substantial initial investment is required. The key dissimilarities of the two methods belong to the mode in which the liquid metal is introduced into the tool.

The selection of material for die casting is principally centered on material characteristics, i.e. the density, the melting point, the strength and the corrosion resistance of the alloy. The hot-chamber process is used for metals of low melting point and high fluidity (i.e. Sn, Zn or Pb),

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but not for Al, Mg or steel. Cold-chamber die casting makes it possible to increase the temperature of liquid metal and a wide range of metals with different sizes can be manufactured by this process.

Preheating the die to 100-200°C is fundamental in order to reduce the thermal shock when liquid metal comes in contact with the tool steel. Two operative parts in particular are in motion during the casting cycle: a metal shot chamber (cold chamber) located at the entrance of the mold, and a piston connected to a power cylinder injects a fixed quantity of liquid metal.

The application of pressure, which is released just at the beginning of the solidification process, causes the liquid metal to fill all the sections of the die that evenly guarantees great surface detail. The mold is then opened and the casting can be removed by the action of the ejector pins. The mold is closed after spraying its internal walls with lubricant and the piston is retreated in the shot chamber for the next cycle of production [29]. The type of tool depends on the casted metal properties.

In hot-chamber die casting, the supply of molten metal is close to the die casting machine and it is part of it. The shot cylinder provides the power for the injection of the stroke, situated above the liquid metal. The plunger rod moves down to the plunger, which interacts with the liquid material. Initially, the plunger is situated at the upper part of the hot chamber and die filling takes place when the port opens. When the phase initiates, the power cylinder forces the plunger down, cutting off the flow of liquid metal to the hot chamber.

At this moment the correct amount of molten material should be in the chamber for the 'shot' that will be used to fill the mold and produce the casting: the plunger travels further downward forcing the molten metal into the die. The pressure exerted on the liquid metal to fill the die in hot-chamber die casting manufacture usually varies from about 5-35 MPa. The pressure is held long enough for the casting to solidify while the plunger travels upward to the hot chamber exposing the intake ports again and allowing the chamber to refill with molten material. Hot-chamber die casting has the advantage of being a very productive manufacturing process although it has some drawbacks, because the setup requires critical parts of the mechanical apparatus to be continuously submersed in molten material. Continuous submersion at a high enough temperature will cause thermal-related damage to these components with a risk of breaks.

However, at industrial level, the disadvantages of the hot-chamber process usually make it the most suitable choice for lower melting point alloys. In the cold-chamber die casting process, the material has to be carried in for every shot or cycle of production and this slows down the production rate.

Aluminium casting alloys were first produced using processes that were historically used to cast other metals. It is generally believed that the art of metal casting was first practiced more than 5500 years ago. Pressure die casting began in the 1820s to deal with the high demand for casting parts. Initially, the high pressure of the injection was achieved manually, but it was later replaced by pneumatic and hydraulic systems. The improvements aimed not only to reduce production time but also to improve products to make them last longer. In 1870, the process was considerably automated [31, 35, 36].

Magnesium alloy components are usually produced by various casting processes. The most appropriate methods are high-pressure die casting and gravity casting, particularly sand and permanent mold casting. Other important production technologies are squeeze casting, thixocasting and thixomolding [32, 11, 15]. The use of die-casting Mg alloys in automotive components continues to grow and in terms of long-term potential growth high-pressure die casting continues to remain the best choice [16, 17, 34].

Die casting process are in continuous development to improve production efficiency and to find new applications. Engineers are able to optimize current designs and use aluminium in place of other heavier materials.

1.2.2. Low-pressure die casting process

Among the most interesting techniques, low-pressure die casting constitutes an excellent compromise between quality, costs, productivity and geometrical feasibility. The first patent, concerning casting of Pb alloys, was deposited in England at the beginning of the 19th century, and its industrial application started 30 years ago [36]. Nowadays, it is also adopted for casting Al and Mg alloys. Low-pressure die casting is especially suitable for the production of components characterized by a symmetry with respect to an axis of rotation (body of revolution). In the automotive field and in many other fields there are several applications; however, this process is frequently wrongly associated only with the development of wheels. The initial economic investment is generally situated between the gravity casting and the high-pressure die casting processes. The tendency to use low-pressure die casting is increasing: it accounts for about 20% of the whole production. This technique is considered as a competitive casting method in cases of relatively small production mass and/or when heat treatment is needed after casting to increase the mechanical properties. The tolerances and the surface finishing properties are about the same as those obtained by gravity die casting. Thanks to the absence of feeders, the reduction of machining costs is significant. However, the initial machine cost is slightly higher than that requested for sand casting. The principle of low-pressure die casting is relatively simple, but the design of the die, control of the cooling circuits and of the solidification step need to be accurately designed and controlled. A schematic outline of the instrument is reported in Figure 3. In this process, the permanent die and the filling system are placed over the furnace containing the liquid alloy and the cavity is filled by forcing the liquid metal into a ceramic tube (stalk), which connects the die to the furnace. The forcing is done using a pressurized gas, typically ranging from 0.3 to 1.5 bars. Once the die cavity is filled, the overpressure in the furnace is taken out and the casting is finally removed. The low injection rate and the relatively high cycle time lead to good control of the fluid-dynamics of the process, avoiding the defects caused by turbulence phenomena [36-40].

Low-pressure die casting has been well established for aluminium casting with some commercially available casting machines. Producing Mg alloy components using low-pressure die casting has the potential benefits of low porosity and the possibility of semi-automatic production, offering superior casting quality and high productivity. Even if many casting processes can potentially be used for structural cast Mg component production with many advantages, the low-pressure casting process is not widely adopted as yet and its use for mass production has still to be consolidated [41-44].

1.2.3. High-pressure die casting process

High-pressure die casting is the most widely used technique and represents about 50% of all light alloy casting production. Due to its flexibility, it is the widest used method for casting metals: almost all possible sizes and shapes can be produced, from the smallest electronic components, which require precise engineering and weigh less than one gram, to the largest automotive components requiring durability and high mechanical strength. This technique is characterized by the introduction of the alloy at high pressure into a metal mold. A schematic outline of the instrument is reported in Figure 4.

Production is faster with this compared to other methods, making total costs per casting lower. In addition, the high integrity of the components and their external surfaces help to reduce finishing operations and so lower production costs. On the other hand, both the device and its dies are very expensive, so it is only cost-effective for high production volumes. Special attention has to be paid in order to reduce the presence of the porosity in the castings: the component produced by this process suffers from porosity and cannot be submitted to heat treatment, because blistering occurs. A vacuum pump decreases the pressure inside the die and the difference in pressure promotes entrance of the liquid metal in the die: not only air is removed but also the metal flow is less turbulent producing a more limited presence of gas inclusions. A metal mold is a good heat conductor and dissipates the heat more quickly and is also resistant enough to absorb the high levels of pressure caused by the injection of aluminium into the cavity. In addition, it facilitates the removal of the product once it is solidified. These products have already good surface finishing properties, avoiding the need for further machining operations. With shapes which have complex geometry, a reduction of the assembling step has been obtained. The benefits achieved by this technique make it one of the most reliable processes: it is dimensionally consistent, economical, environmentally acceptable, versatile and clean. This process is ideal for high-volume thin-walled castings production because of the fast cycle times. The development of gas due to the extremely turbulent liquid metal flow constitutes the main weakness of this method. The presence of gas porosity in the central part of the casting inhibits any heat treatments damaging the features of the overall casting product.

The final product quality depends not only on the process but other aspects have to be considered, i.e. the composition of the Al alloy that will be cast, the impurities or gas that can be retained in the metal and its temperature. Most Mg castings are made by high-pressure die casting [45-51].

1.2.4. Vacuum die casting and modified vacuum process

For parts which have to be submitted to further heat treatments, vacuum die casting proves to be of interest and constitutes an ideal method to produce high-quality structural automotive Al alloy components because it represents a solution for most of the problems associated with porosity. Through vacuum die casting, it is possible to produce high-quality thin-walled parts with expected and repeatable mechanical properties, with or without heat treatment or welding. Vacuum die casting was first used in Japan and it extended rapidly around the world. Vacuum die casting has some important advantages: the vacuum systems remove the air from the cavity reducing gas porosity. In addition, very thin sections can be casted easily; good surface finishing properties and appearance can be obtained with no need for further machining. Using this technique, casting defects are low and the rejection of the component is reduced. The general principle is the same as in low-pressure die casting. Depending on the alloy used, the required properties can be achieved in vacuum die casting even without additional heat treatment; but whenever such treatment is required, it will produce superficial defects in the presence of even minor gas porosity, which are usually not tolerated on the final product.

The ranges of application that have components manufactured by the vacuum process are almost the same as those produced by the conventional die casting process, but with enhanced quality. In addition, the components obtained by this method can be subjected to further heat treatments and welding processes without the appearance of new problems of porosity, as usually occurs with high-pressure die casting. This system improves overall component quality by reducing or eliminating the presence of porosity due to gases; but in the case of shrinkage, porosity it is not an effective solution, and other measures should be considered and adapted [37, 52-56].

For high-pressure die casting of Al alloys, two types of vacuum systems have been developed: (i) a complete vacuum system where the complete die casting system are fully enclosed and evacuated during casting and (ii) a vacuum assistance system where a vacuum valve is incorporated into a die to evacuate the air entrapped in the cavity. The system is relatively simple, cheap and stand-alone, but needs a complex set-up of the complete vacuum system [54, 57, 58] and requires fast, accurate control of the vacuum and precise timing of its cut-off.

The latest improvements on vacuum die casting are related to a modified vacuum process to produce components with structural applications, i.e. automobile chassis with very high quality. The ultra-high vacuum casting process involves lowering the pressure with respect to the ordinary vacuum system. In this process, air and gas content will be 5 to 20 cm^3 per 100 g of Al [54].

1.2.5. Squeeze casting process

The concept of squeeze casting was originally introduced in 1819 [59] and the first scientific experiment was scientifically carried out in Germany on Al-Si alloy [60]. This process can be considered among the best to be produced casting components, and it is based on the principle of pressurized solidification in which the final product can be produced in a single step from the molten metal to a final component using a re-usable die. A significant advantage of this process is the lack of a runner system, leading to high yield and a cost benefit. In the squeeze casting process the injection of the metal takes place vertically and at a slow speed, producing a high cooling rate due to the instantaneous contact between the molten alloy and the cavity. As in the high-pressure die casting process, the molten metal solidifies under pressure inside the cavity giving rise to cast components with finer microstructure and therefore better

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mechanical properties approaching those of a wrought product. The components manufactured by this technique have wide range of applications because they meet higher requirements. This process is suitable to produce structural aluminium components to reduce vehicle weight and improve efficiency.

Squeeze casting has been widely used to produce non-ferrous components, i.e. Al, Mg and Cu components, besides some ferrous components with a relatively simple geometry. Squeeze casting is used for producing components with high mechanical properties and it is also suitable to produce structural Al components of relatively low weight, which are becoming more in demand in the automotive industry to reduce fuel consumption and improve vehicle efficiency. However, the quality of the parts depends on the same variables as the more traditional methods, i.e. alloy composition, design of gates and runners, the pressure and temperature of the metal when it fills the cavity, solidification time and lubricants. Pumps, steering column components, suspension links, transmissions components are just a few of the range of components casted by this method. The process is characterized by a low injection speed, with minimum turbulence and a high pressure maintained during cooling to produce heat-treatable, high-integrity components. In this process, the molten metal solidifies under pressure inside a cavity which is vertically positioned. Die halves are also closed by hydraulic presses that are pre-heated before the metal reaches the die to reduce thermal shock. The metal flows slowly into the die, providing instant contact between the die surface and itself and pressure is applied during the whole solidification. This produces a rapid heat transfer and results in a pore-free fine-grain casting with mechanical properties approaching those of a wrought product.

The squeeze casting process eliminates both types of porosities: shrinkage porosity is eliminated by using a relatively large gating area, while the other form of gas entrapment derived from dissolved hydrogen is reduced using a conventional degassing technique. Air entrapment is avoided by using a relatively slow in-gate velocity, maintaining a planar front filling of the die. The squeeze casting process provides a net shape with minimum porosity which allows secondary porosity sensitive processes, i.e. solution heat treating and welding. The most important advantage of a squeeze casting process is its ability to produce high-integrity castings with negligible porosity, by minimizing turbulence during the filling of the cavities, and by guaranteeing directional solidification to the gates.

1.2.5.1. Types of squeeze casting process

Two alternatives of this special process have been developed based on different approaches of metal movement, namely direct and indirect squeeze casting. In the direct process the pressure is applied by the mold itself as it closes, while in the indirect squeeze casting the mold is totally close before applying the pressure [61-64].

- Direct squeeze casting: during direct squeeze casting, also known as liquid metal forging, metal is poured into a pre-heated and lubricated die contained within a hydraulic press. It is then covered by the other die half which applies pressure gradually as it is placed over the lower half. The load is applied just after the metal starts to freeze, in order to prevent the beginning of solidification prior to pressurization, and it is maintained until solidification has been completed.

- Indirect squeeze casting: this is more similar to high-pressure casting: the metal is not poured directly into the mold, but into a cold chamber. As in the conventional method, the metal is then injected in the cavity and pressure is applied through the shot system throughout solidification. However, in this case the injection velocity is relatively lower and the cold chamber is vertical. As the metal is poured through the sidewall of the cold chamber with a vertical movement, it is tilted back before filling the die, thus turbulence and consequently also porosity are minimized. The slow velocity of about 0.5 m/s of the metal flow during the injection does not enhance waves or swirls, so entrapped air almost disappears. To reduce the production cycle, pouring is done while the die is being sprayed. The shot system applies pressure since it starts to force the metal into the die until the solidification phase is finished. Pressure is continuously maintained to reduce shrinkage porosity and enhance heat transfer to achieve a small grain size.

In squeeze casting, there are several parameters that must be carefully controlled to guarantee the quality of the casted components, i.e. volume of metal, the temperature of the metal and die, the time delay between the pouring of the molten metal and the instant in which pressurization starts, pressure - depending on the size and geometry of the component and on the required mechanical properties, lubrication - to guarantee the ejection of the cast once it has solidified.

1.3. Commonly used alloys for die casting

A wide variety of non-ferrous die casting alloys is available for a wide range of applications on the basis of the physical and mechanical properties requested. Generally, Al and Zn alloys, followed by Mg, Zn-Al (ZA) alloys, Cu alloys, Sn and Pb alloys are the materials most frequently used. On the basis of the melting temperature, these alloys can be classified as low melting point metals (less than 385°C); ZA alloys have a slightly higher melting range of 430-480°C. While Al and Mg alloys are considered to be moderate melting point alloys, casted in the range of 620-700°C, Cu alloys are considered to be high melting point alloys, with a casting temperature of over 900°C. In addition, low melting point alloys and high melting point alloys can be differentiated by the casting method used in order to process them: low melting range alloys are casted in hot-chamber machines while the higher ones are casted in cold-chamber machines. Aluminium die casting alloys are lightweight, offer good corrosion resistance, no difficulty as regards casting, good mechanical properties and good dimensional stability. Moreover, a variety of aluminium alloys can be die-casted from primary or recycled metal. Actually, at industrial level the most commonly used Al alloys are:

- A356 and A357 alloys (belonging to the AlSi7Mg system) and the A319 alloy (belonging to AlSi7Cu3Mg), usually processed by low-pressure die casting and gravity semi-permanent mold technology; they are employed to produce for cylinder heads, knuckle components, engine blocks, pistons;

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- A360 alloys show higher corrosion resistance, superior strength at high temperatures, and slightly better ductility, but reveals some difficulties during casting;
- A380, A383 andA384 alloys offers the best combination of properties and production cost; they offer superior die filling but with a significant loss in mechanical properties, i.e. toughness;
- A390 alloys are used for special applications where high strength, fluidity and wear-resistance properties are required. They are employed for cylinder head and piston production;
- A413 is used for its maximum pressure tightness and fluidity [65].

The chemical compositions of the alloys mentioned earlier are reported in Table 1:

Chemical composition (wt%)										
Type of alloys	**Elements**									
	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Ni**	**Zn**	**Sn**	**Ti**	**Al**
A356	6.5-7.5	0.2	0.2	0.1	0.25-0.45	-	0.1	-	0.1	bal.
A357	6.5-7.5	0.2	0.2	0.1	0.4-0.7	-	0.1	-	0.04-0.2	bal
A360	9-10	1.3	0.6	0.35	0.4-0.6	0.5	0.5	0.15	-	bal
A380	7.5-9.5	1.3	3-4	0.5	0.1	0.5	3.0	0.35	-	bal
A383	9.5-11.5	1.3	2-3	0.5	0.1	0.3	3.0	0.15	-	bal
A384	10.5-12	1.3	3-4.5	0.5	0.1	0.5	3.0	0.35	-	bal
A390	16-18	1.3	4-5	0.5	0.45-0.65	0.1	1.5	0.20	0.2	bal
A319	6.5-8	0.8	2.8-3.5	0.5	0.25-0.5	-	-	-	0.25	bal
A413	11-13	1.3	1.0	0.35	0.1	0.5	0.5	0.15	-	bal

Table 1. Composition of the main alloys used in aluminium die casting

1.4. Innovative manufacturing processes for light metal alloys - Semi-solid metal processing

Generally, during solidification, in traditional manufacturing process, volume contraction is observed. This is due to an inappropriate feeding system and/or gas development, as also illustrated previously, which in turn generates voids or cavities within a casting, which are then responsible for the presence of defects in the casting components. Commonly, defects such as interdendritic shrinkage pores, inclusions, enlarged secondary dendrite arm spacing are considered the most important reasons for crack growth. Independent of the loading conditions, they reduce the alloy’s mechanical resistance and during severe stress conditions lead to the failure of the alloy.

For these reasons, the research community and manufacturing industries are giving a high level of attention to the development of innovative production procedures.

In this context, semi-solid metal processing is able to attain at least the same level of properties and performances as those obtained by conventional techniques. Despite half a century of evolution, there is still a serious need for additional and more detailed rheological data for the successful use of components developed through these methods. The real and important advantages of semi-solid metal processing are prevalently related to faster production times at lower cost. When fully developed, it is expected to represent a viable solution compared to conventional methods. The group of innovative manufacturing techniques, based on the thixotropic characteristic of the alloys in a non-dendritic structure in the semi-solid state, approaches its fourth decade, its starting point being the scientific studies of Spencer et al. (1972) [66]. The most important characteristic of semi-solid metal processing, known as slurry, which makes it superior to conventional casting processes, is the non-turbulent (or thixotropic flow) behaviour which occurs at the two-phase field of solid and liquid. In such conditions, materials have to be managed in a way analogous to solids, but flowing as liquids when a shear stress is applied and the viscosity decreases dramatically so that the alloy can be cut and spread like butter. The laminar flow and thixotropy of the semi-solid metal are directly connected to its microstructure: the semi-solid state consists of spheroids of solid phase enclosed in a liquid phase. Semi-solid metal processes produce the metal slurry at a semi-solid casting temperature with globular microstructure. Rheocasting and thixocasting processes belong to this approach. In the ‘Rheo’, one-step process, the alloy is introduced into a die with no transitional stage. As starting alloy, it is a regular and completely liquid alloy which is cooled to arrive at the chosen solid fraction and then casted. For the ‘thixo’, two-step process, the starting alloy is prepared externally and then the billet is cut to length, re-heated to arrive at the proper solid fraction and then casted [67-71].

Semi-solid casting is one of the most reliable technologies to cast metal components of complex shapes. To produce aluminium cast components, this latest patented technology is based on keeping the metal in the semi-solid phase between solid and liquid. Two main types of processes have been developed to cast aluminium components: thixocasting and rheocasting. The difference between these methods is the process to make the slurry. In thixocasting a cast billet, which has a dendritic microstructure, is heated to the liquidus temperature, and then injected into a mold cavity. Rheocasting consists of cooling the molten metal to the liquidus temperature and then injecting it into the sleeve of a conventional die casting machine. This is a considerable advantage over thixocasting because it results in less-expensive row material. Semi-solid processed components are heat-treatable, weldable and show superior mechanical properties. In addition, the wear of the die-casting machines is low due to the low injection speed. These processes also reduce traditional die casting process costs due to the elimination of the secondary process, the increase of productivity and the reduction of die maintenance [72-76].

The semi-solid concept fits very well with Mg alloys too; in fact, the use of Mg alloys produced in this way during the past decades comes rapidly of age as a reliable alternative to high-pressure die casting. In the case of Mg alloys, Thixomolding® process is preferred, adopted from the injection moulding of polymers. As a result of this process, there are a number of possible advantages, including high process control, dimensional constancy in produced parts, low porosity, capacity to mould parts with complex geometries, good surface finishing properties, and production of near-net-shape parts. Because of lower and predictable shrinkages, the component produced has good dimensional tolerances. The thixoformed parts are able to meet stringent dimensional tolerances [72, 77-83].

1.5. Advantages and disadvantages of traditional and innovative methods

Different processes have been used to produce lightweight components, including conventional and new technologies. Forging is evidently always the best way, but also the most expensive one. Casting technologies are more competitive from the economical point of view, while forging is able to guarantee the best performances, thanks to the high level of soundness. Castings are generally affected by defects. The new trend is to use a new manufacturing route to obtain a similar performance compared to the product obtained by traditional processes. Semi-solid processes can reduce the existing gap between casting and forging; and during such a process, better control of the defect level can be attained. The components manufactured by the semi-solid process acquire a very low content of defects (shrinkage or gas porosities, segregations, surface defects). Semi-solid processed components are heat-treatable, weldable and reveal superior mechanical properties. Productivity can be improved with a using semi-solid process because of the shorter production cycle time. Semi-solid slurries normally contain about 50% solid fraction before they come into the die cavity, so only about 50% of the latent heat is released within the die during the solidification stage. The lower heat content of semi-solid slurries reduces thermal shocks on the die, improving the life of the die. In addition, wear of the die-casting machines is lower than during the traditional manufacturing route due to the low injection speed connected to the reduction of die maintenance. The casting surfaces of the heat-treated components are free from formation of blisters. Another important advantage of the semi-solid process is related to its weight-saving capacity: all the metal introduced at the beginning of the process evolves to the development of the final component and risers are absent. Due to the excellent surface quality all finishing operations are reduced, saving additional time and cost.

2. Experimental study results

2.1. Influence of the Al-based alloy composition on the performance of the product manufactured by modified squeeze casting process: Real case study

2.1.1. Modified squeeze casting process - General approach

This technique combines the advantages of low-pressure die casting, one of the most efficient casting method, and of forging, till now the most efficient technique to obtain superior mechanical characteristics. The modified squeeze casting process produces near-net-shape components in a single step, obtaining materials with high quality and good mechanical properties. A schematic illustration of the modified squeeze casting process is given in Figure 5 [84]. In this process the liquid metal is injected bottom up from the furnace into the closed mould at very low velocity; once filling is complete, a high pressure is applied to the liquid material thus 'forging' the component. The high pressure is maintained throughout the component solidification producing a final component with very fine microstructure and no defects. This way a very interesting process was built for automotive industry safety and high-performance components such as suspension and engine components. Moreover, this process can use wrought alloys, high-performance alloys that until now could only be processed by forging. Modified squeeze casting technology is different from already established casting technologies, since the cavity of the die is filled due to the application of low pressure (about 0.5 bar); during the solidification phase the pressure rises to 120 MPa, due to an applied force of 1,100 tons on a large diameter cylinder, approximately 0.1 m^2, to realize the 'forging'. The working cycle is varied between 60 and 70 s (similar to the high-pressure die casting process), but all the finishing operations are reduced, due to the absence of risers and scraps from the feeding system. In this method no contact between liquid metal and the environment occurs and, if necessary, can be used protective gas, especially interesting for the production of Mg-based components. Compact and fine microstructure is obtained, due to the pressure applied on the liquid metal during the solidification phase. It is possible to obtain components with inserts or sand cores, quite isotropic components, with similar microstructural and mechanical properties in all directions.

A pre-quantified liquid metal, at 700-730°C inserted at very low pressure inside a pre-heated die (at about 200°C) die (Figure 2a) and then the power system is closed (Figure 2b). About 90 MPa pressure is applied (Figure 2c) on the metal, and it is applied until total solidification of the metal. The die is opened (Figure 2d) and the final shape is removed (Figure 2e). The continuous application of pressure during solidification generates a defect-free part.

Applying pressure during solidification develops a fine crystalline structure with a minimum of defects. The size of grains is considerably smaller than those obtained by other casting techniques and the developed microstructure is uniform. The presence of gas or shrinkage porosity is radically reduced (or even absent) resulting in superior mechanical properties. Although porosity is minimal, this process promotes grain boundary segregation and sometimes a non-uniform macrostructure can develop.

Despite these benefits, the process also has several drawbacks. One of them is related to productivity: at present the process does not reach the typical productivity of die casting process and its production capacity can be considered to be between high-pressure die casting and classic processes of sand casting. The complex tooling involves higher initial costs and complex shapes cannot be produced by this process. To compensate for the initial investment, a high production volume is needed to make this process a cost-effective technique.

Compared to conventional high-pressure die casting, in the modified advanced squeeze casting process, components are gated in a different casting position. In modified squeeze casting the gate is settled at the bottom of the side wall, while the plunger is guided horizontally in conventional high-pressure die casting machines, and in this way it fills the die at a high velocity; while in the modified squeeze casting there is no plunger to inject the metal in the cavity. The metal fills the die due to the pressure difference created by vacuum pumps. The holding furnace is placed at the bottom of the machine, right under the dies. The furnace and the cavity are connected by the filling channel through which the metal fills the dies. This happens rather slowly and with a vertical movement, hence the die is filled without significant gas inclusions.

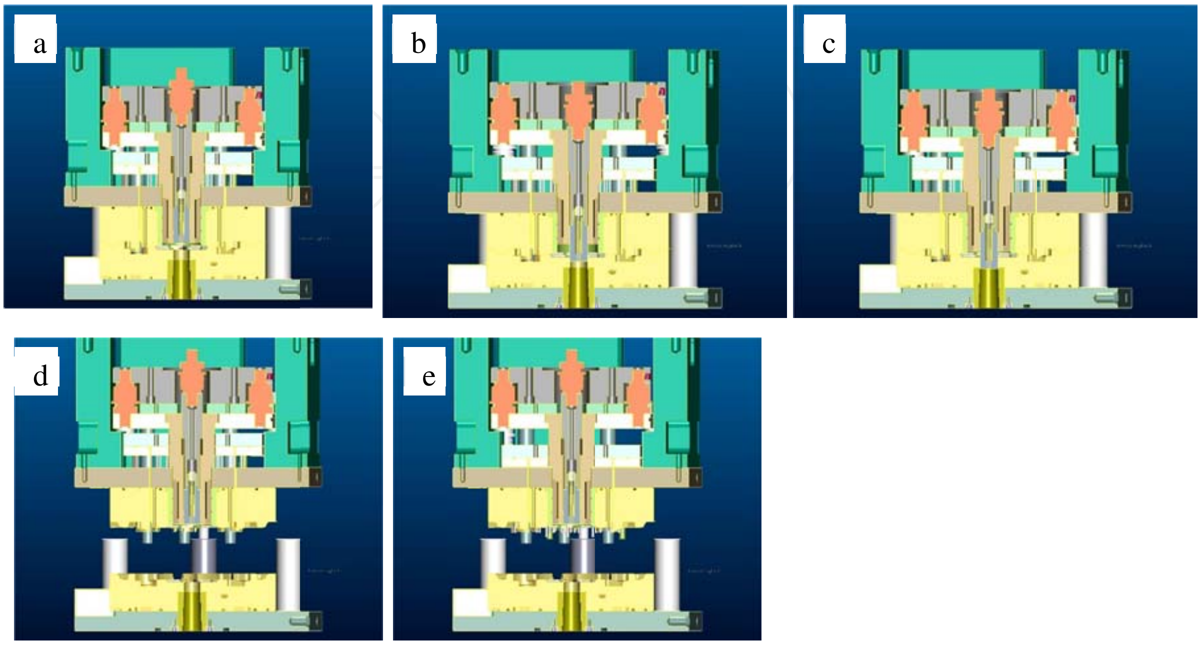

Figure 2. Modified squeeze casting cycles: a) low-pressure feeding, b) closure of the feeding gate, c) application of the pressure, d) opening of the die, e) rejection of the components

2.1.2. Modified squeeze casting process - Experimental results

In this section some results will be presented based on the study carried out on two components, using A356 and A380 (with the chemical compositions reported in Table 1) Al alloys, manufactured by advanced squeeze casting [85]. The components were T6 heat-treated (510°C for 6 h, water quenched to room temperature and aged at 200°C for 8 h) and their properties were evaluated to study how the alloy composition and the process parameters influence the performance of the final component. In addition, the feasibility and the efficiency of the modified squeeze casting process in a real industrial frame was evaluated. On one hand, the pressure applied (i.e. uniform distribution of the pressure on the whole pieces) and the period of the pressure applied can be considered the most important key process parameters analysing and comparing two types of samples, from two different sites (Figure 3). Sample A was extracted from the area where pressure was directly applied on the piece, while Sample B received lower pressure during production. The effect of the alloy composition was estimated, comparing the properties of Sample A and of Sample C (A380 Al alloy).

2.1.3. Microstructural analysis

Figure 4 reports the microstructures related to the composition of Samples A and B. Dendritic microstructures with comparable features were obtained, made of primary α-Al solid solution

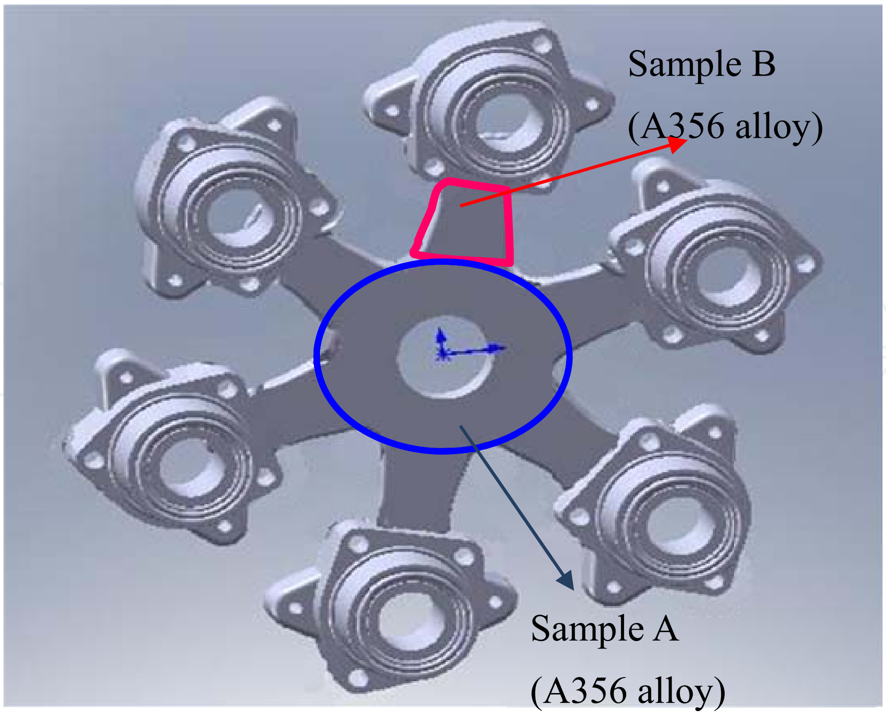

Figure 3. Scheme of the investigated component, in A356 and A380 alloy showing the initial position of samples before analysis

phase enclosed within the eutectic mixture of Al and Si. The size of the primary α-Al particles increased (Sample A, 30-50 μm) as a sign of a lower solidification rate (Sample B, 50-70 μm). Coarse-grained morphology developed in the case of the A380 (Figure 4). Figure 5 reports the microstructure of the A380 alloy sample. Apart from α-Al grain the presence of some other phases can be detected: one of these was chemically constituted by Al, Fe (about 14% wt), Mn and Si while the other consisted in block-like Al_2Cu particles (about 15 % wt of Cu). The presence of Chinese script intermetallic compounds are more accentuated in the case of the A380 composition controlling matrix stiffness and contributing to the brittleness of the material.

2.1.4. Mechanical property evaluation and fracture surface analysis

Evolution of hardness was evaluated, starting from the border of samples A, B and C and going toward the core along a direction normal to their edges. The results are reported in Table 2. Higher hardness values were achieved for the samples subjected to higher pressure, caused by the growth of hardening phases. Tensile properties of both alloys were determined at room temperature, according to the UNI EN 10002 standard and the results are reported in Table 2. Actually, the samples did not show an outstanding mechanical performance, but an indication of the positive effect of pressure during solidification can be deduced.

Figure 6 reveals some characteristics of the fractured surfaces: for both alloy compositions and for both regions generally ductile fractures occurred as illustrated in Figure 6. A380 alloy revealed the occasional presence of some shrinkage porosities (Figure 6c), and due to the higher

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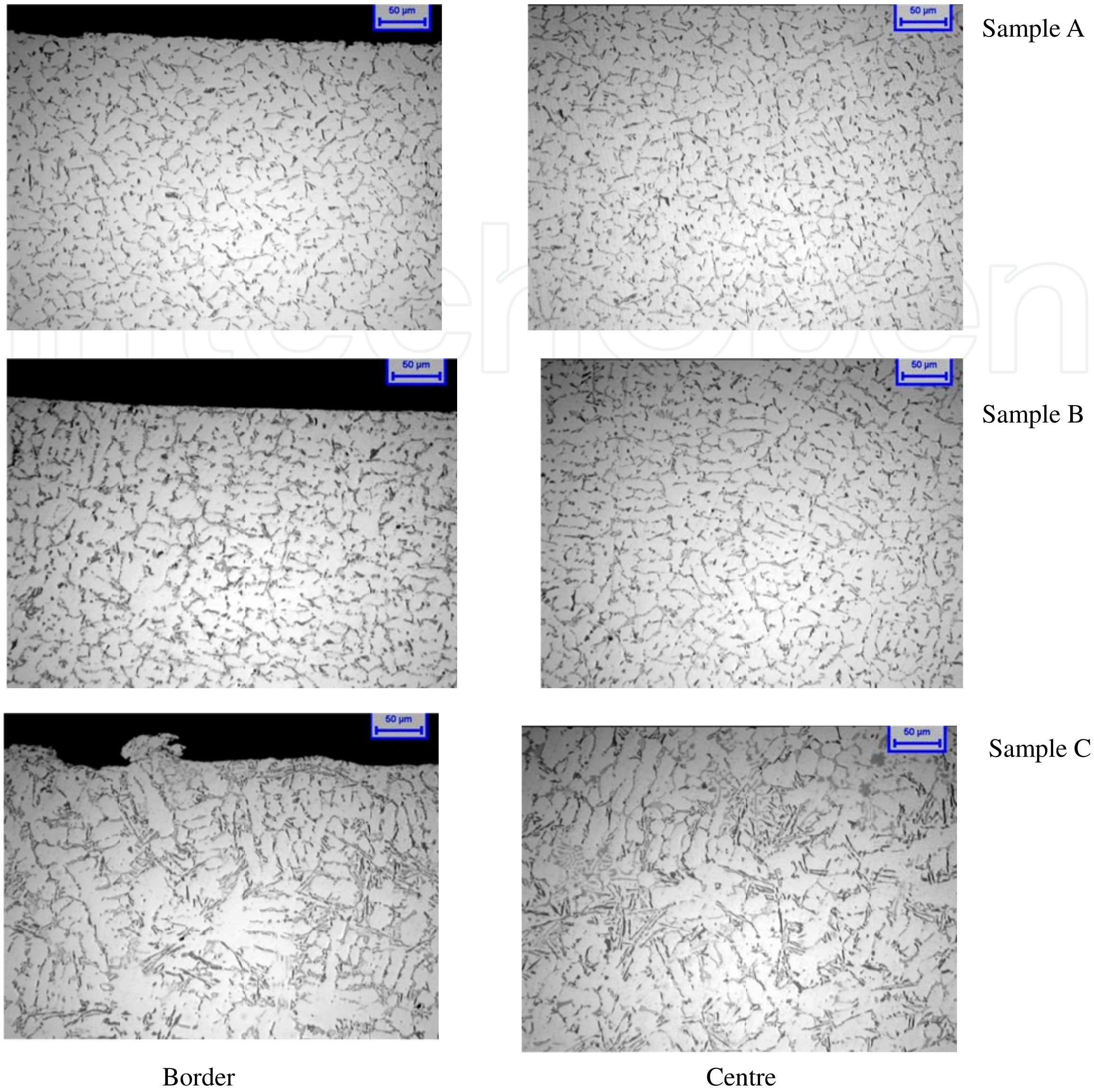

Figure 4. Microstructure of the samples obtained by optical microscopy, showing the differences between the samples and between the edge and the central part of the samples

presence of some intermetallic fragile phases some crack development was observed (Figure 6d).

	Sample A	Sample B	Sample C
YS [MPa]	240 ± 20	170 ± 20	182 ± 20
UTS [MPa]	418 ± 20	386 ± 20	374 ± 20
HV	71 ± 1	67 ± 0.5	96 ± 1.5

Table 2. Average mechanical properties of samples

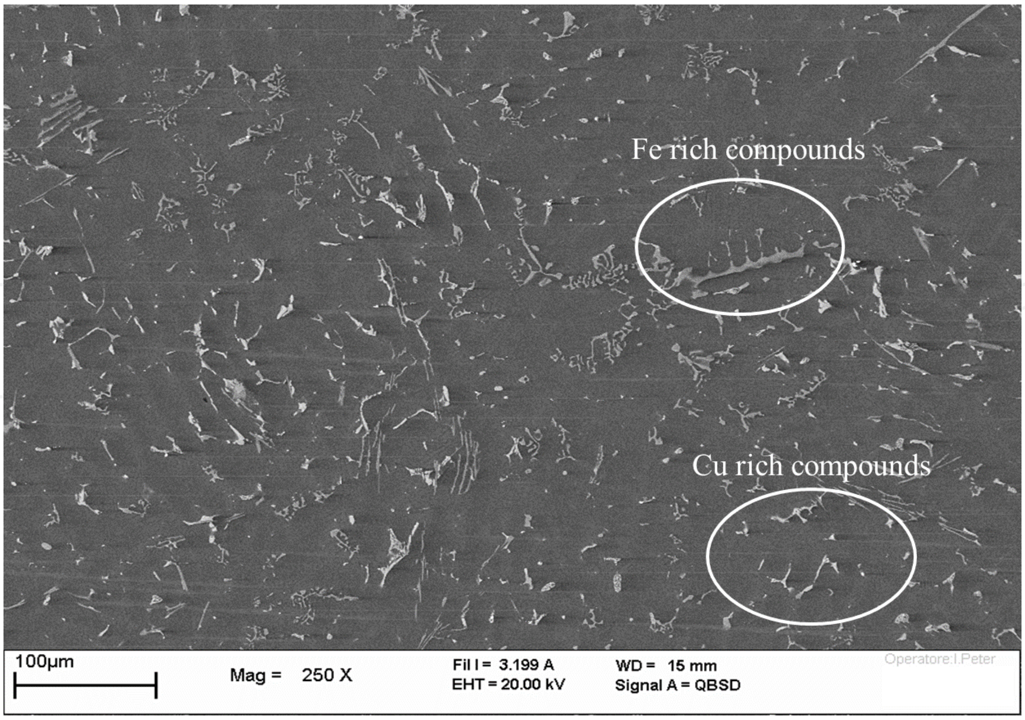

Figure 5. Microstructure of the A380 alloy obtained by scanning electron microscopy

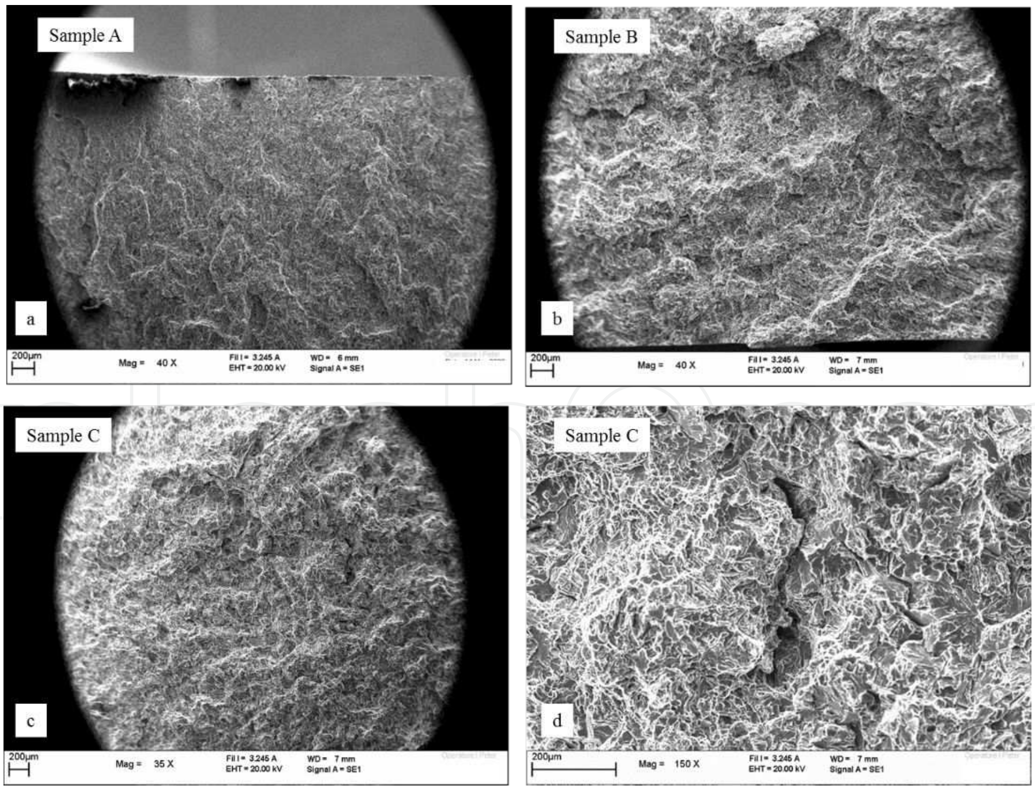

Figure 6. Fracture surface analysis: scanning electron microscopy images showing the nature of the fracture and some details on the fractured samples

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In accordance with the data in literature, the experimental analysis presented demonstrates that the modified squeeze casting process is suitable for the production of automotive components using A356 and A380 aluminium alloys. The positive effect of the pressure applied during solidification was observed on both the microstructure and on the mechanical properties of the modified squeeze casted components. Among the two considered compositions, the A356 alloy appears to be more appropriate for the production of automotive components, in particular suspension lever arms, through modified squeeze casting process.

2.2. Feasibility of a new rheocasting process - Weldability of T6 heat-treated Al alloy parts manufactured by new rheocasting process - Real case study

2.2.1. New rheocasting process - General approach

To confirm why automotive component designers consider the semi-solid state forming process as an alternative to traditionally employed processes, some highly stressed parts (flanges for truss) for structural applications and automotive space frame component were produced by innovative rheocasting process at ATS Company (Lugo Ravenna, Italy):

1. The structural part is characterized by a relatively heterogeneous geometry. Microstrucral analysis and mechanical characterization was performed. Because of the particular shape of the rib arms, it was not possible to obtain samples for tensile tests, so the most suitable opportunity was to machine bars, with a cross-section of 10 × 5 mm and about 7 mm long to perform three point bending tests.

2. The automotive component characterized by quite an intricate shape with 2 mm maximum thickness and a length in the range of 300 mm was considered. Two different aluminium alloys were investigated B356.2 and B357.2, and in combination two different kinds of heat treatment, in particular T5 and T6 on B356.2 and T5 only on 357.2 parts. From these parts two different series of dog-bone-shaped flat samples for tensile tests were obtained, the first one obtained directly as an appendix of the casting, with a transverse section of about 6 × 22 mm and a total length of about 200 mm; henceforth, these samples will be identified with the bold letter A: appendix. The second series was machined from the parts using three different zones where it was possible to extract dog-bone-shaped samples with a rectangular section of about 2 × 5 or 10 mm dimension and 100 mm total length: hereafter, these samples will be identified by the bold letter T: thin section.

An important aspect related to this process is the possibility of obtaining quite a wide range of thicknesses, starting from 2.5 mm.

Two types of heat treatments (HT) were used after production: T5 HT (by water quenching out of die followed by ageing at 165°C for 6 h) and T6 HT (520°C for 6 h and then ageing at 165°C for 6 h); and following the encouraging results obtained in the case of the T6 HT structural parts, their weldability has demonstrated. In this section, only the results on the welded parts are presented and more details on the microstructural and mechanical behaviour concerning the un-welded samples can be found in references [86, 87]. Welding was done with the tungsten inert gas (TIG) procedure with Peraluman Al alloy (Table 3) as filler material.

For innovative rheocasting process a TCS vertical hydraulic press Rotorone 400 tons model was employed. The press has an injection piston of 180 mm diameter; the closure power is 400 tons with an injection power of 320 tons. Under the lower level of the press, a turning table moves with the containers set up at 120°: the first contains the slurry to be injected after rotation; the second one has the evacuation of the biscuit; the third is lubricated ready to inject a new quantity of slurry from the ladle. The two upper and lower half dies are heat-controlled by oleodynamic panel controls. When the right injection temperature is reached (between 577 and 590°C, depending on the employed alloy), the piston pushes the slurry very slowly through the in-gate until the filling of the cavity is complete. After a very short time, just to maintain the pressure so that the cycle can finish, the piston comes down carrying the biscuit cuts off the in-gate pieces. The press opens and the upper part goes up allowing the piece to come out, helped by the ejector. This part is immediately quenched into water when T5 heat treatment is requested. The cycle is ready to continue after die lubrication [86, 87].

Elem.	Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Impurity	Al
Wt (%)	0.4	0.4	0.1	0.4-1	4-4.9	0.25	0.15	0.05	0.05	Balance

Table 3. Chemical composition (%wt) of the filler metal

2.2.2. New rheocasting process - Welded component characterization and mechanical behaviour of the automotive component

The welded component for structural applications and the automotive space frame component are shown in Figure 7a and 7c, respectively. The shape of automotive component produced had quite a complex shape with 2 mm maximum thickness and a length of about 300 mm. Figure 6a reports the photo of the welded element. Following some mechanical stresses, failure of the component occurred, but the failure only affected the area external to the welding zone (Figure 7b), showing that the welding was successful and the fracture of the sample was independent from the welding.

Figure 7. Photograph of the massive welded element: (a) position of the fracture, (b) automotive components, (c) produced by an innovative rheocasting process [86]

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Figure 8 shows the microstructure of the welded samples prior and post T6 heat treatment, with the evidence of some porosity. The base metal without T6 heat treatment contained α-Al particles and Al-Si eutectic phases with a coarse microstructure (on the right-side bottom Figure 8). After T6 thermal treatment the microstructure became slightly finer. The weld fusion zone resulted in a finer dendrite structure due to the high cooling velocity during the solidification phase. A heat-affected zone was developed into a combined structure with non-uniform grain size, as a sign of the influence of heat from the welding.

The tensile properties of the samples prior and after welding and T6 heat treatment are reported in Table 4. The first sign from these measurements confirms the expected results: (i) a slightly higher tensile property was obtained; (ii) an improvement of the ductility of the alloy was reached. This latter point is also confirmed by the fracture surface analysis. Additionally, the fracture of the welded and T6 heat-treated samples always takes place external to the welding area, an indication that there was adequate welding which amplified the whole component's mechanical resistance. Prior to T6 heat treatment, a heat-affected zone was directly involved in the alloys failure. The presence of some small-sized brittle particle had no influence on the mechanical failure of the alloy, demonstrating that the weldability of the A356 alloy was successful and the welded component present promising mechanical properties. This aspect is important at industrial level when joining of different parts produces the final component.

Figure 8. Weld profile of A356 Al alloy with microstructural details of the involved areas prior and after T6 heat treatment

Table 5 reports the tensile test results obtained for the automotive component: a slightly higher performance was obtained on the thin samples (T) with respect to the thick samples (A) obtained as an appendix of the castings. Probably, the difference is due to the different feeding system used: feeding of the appendix was carried out as a separate branch from the main feeding gate; in that branch the flow of the semi-solid slurry favoured a higher concentration

Samples	T6 A356 alloy	Welded T6 A356 alloy
YS [MPa]	200 ± 10	230 ± 10
UTS [MPa]	280 ± 10	300 ± 10
Elongation [%]	7 ± 1	12 ± 1

Table 4. Tensile properties of the samples considered in the A356 alloy

of oxides particles and impurities introduced during mechanical stirring to produce the slurry. In fact, although observation of the fracture morphology of the type A samples showed the typical ductile fracture with dimples areas that follows the microstructure details like silicon particles, inside some dimples the presence of very small hard particles can be detected. These very small particles probably originated during the mechanical stirring of the semi-solid slurry. As expected, the tensile strength and ductility of T6 heat-treated samples were better than in the T5 state; moreover, the B357.2 alloy confirmed its slightly superior level of resistance.

Sample	A: 356 (Thick)		T: 356 (Thin)		A: 357 (Thick)	T: 357 (Thin)
Heat treatment	**T5**	**T6**	**T5**	**T6**	**T5**	**T5**
$\sigma_{0.2}$ [MPa]	132	190	140	200	160	165
UTS [MPa]	220	260	240	280	225	260
Elongation %	3	6	4	7	2	4

Table 5. Tensile properties of samples obtained from automotive parts

Our research demonstrates that it is appropriate to use the innovative rheocasting casting process to produce structural components and automotive space frame components. The positive effect of T6 heat treatment on A356 Al alloys was verified. Additionally, the feasibility of the welding was demonstrated: an adequate welding strengthened the mechanical resistance of the final component.

2.3. Study of the development of an alternative solution to the heat-treatable A356/A357 Al alloy - Self-hardening Al alloys: real case study

Self-hardening aluminium alloys (Al-Zn-Si-Mg alloys) represent an innovative class of light aluminium alloys. They exhibit excellent mechanical properties, which make them suitable for many applications in different industrial fields, especially in the transport industry. The most important and relevant feature of these alloys is their good performance without the need of any heat treatment: they are subjected to a natural ageing phenomenon at room temperature after a storage period of about 7-10 days. The possibility to avoid heat treatment represents an important benefit, contributing to considerably reduce both the production cost of some components and the amount of energy involved in the manufacturing process. Furthermore, without heat treatment the risk of the deformation of some component during the production is eliminated [88].

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The goal of this study was to find an alternative solution to the T6 heat-treated A356/A357 alloys currently used for automotive component production. The feasibility of the development of a knuckle suspension component, starting from the modified self-hardening alloy with an increased Mg content, was studied and investigated [89]. Comparison of the alloy properties, also considering the solidification rate, was carried out with the aim to find an optimal composition and condition for good mechanical performance and good corrosion resistance achievements. The alloys were produced using the permanent mould casting technique by Teksid Aluminium Srl (Carmagnola, Torino, Italy) and then investigated.

Since the maximum solubility of Mg in Al is at 17.4% wt. under equilibrium conditions, the Mg content does not usually exceed 5% in wrought alloy and 10% in cast alloy, respectively. For these reasons, the Mg content is maintained in this range. The alloys produced, with an increasing Mg content, were labelled as AlZn10Si8Mg, AlZn10Si8Mg1 and AlZn10Si8Mg3, as reported in Table 5. To analyse the effect of the solidification rates on the microstructure of the casting, a special geometry, presented in Figure 9, was developed. The weight of the aluminium alloy casting without a runner system is about 0.5 kg.

Elements	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
AlZn10Si8Mg	7,5-9,5	0,30	0,10	0,15	0,2-0,5	9,0-10,5	0,15	bal.
AlZn10Si8Mg1	7,5-9,5	0,30	0,10	0,15	1,0	9,0-10,5	0,15	bal.
AlZn10Si8Mg3	7,5-9,5	0,30	0,10	0,15	3,0	9,0-10,5	0,15	bal.

Table 6. Chemical composition (wt. %) of the three alloys produced

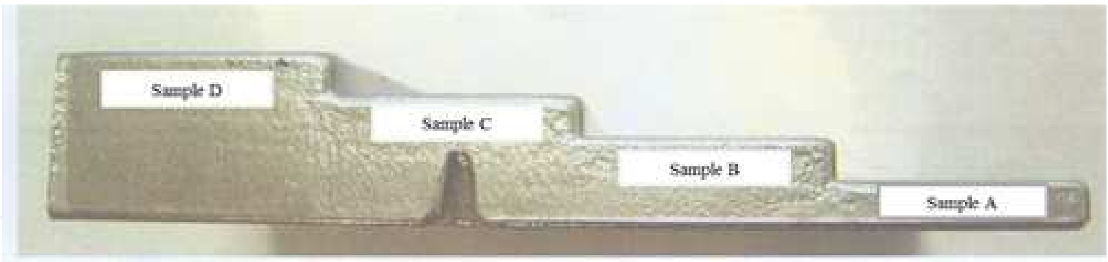

Figure 9. Step casting geometry

2.3.1. Microstructure analysis

Solidification is critical for the development of the microstructure in casting and can be considered as responsible for the development of mechanical properties. A typical casting microstructure made of α-Al dendrites and of Al-Si eutectic phase is reported in Figure 10. At comparable positions among the castings, no considerable variation was evidenced. As expected, higher values of cooling rate in all cases gave a finer microstructure. The precipitation of large Mg-based intermetallics, with a Chinese script morphology, is favoured by the high content of Mg as well as by high values of cooling rate. Mg_2Si hardening precipitates were developed as illustrated in Figure 11 and their level was directly associated to the Mg as

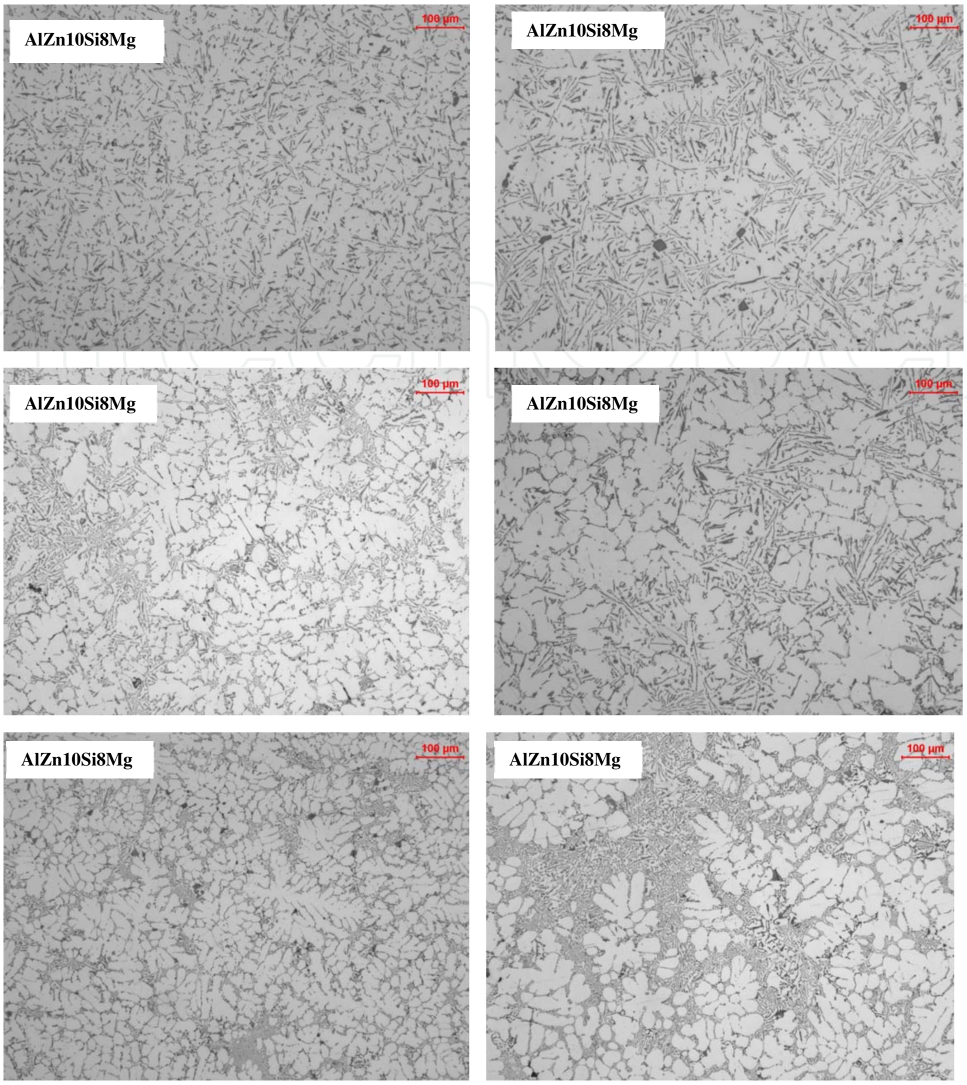

Figure 10. Microstructure of the alloys considered as function of Mg content and of solidification rate, left-side samples type A, right-side samples type D

reported in Figure 11a, b and c. Simultaneously, the solidification rate controlled the growth of the intermetallic particles: in the case of samples extracted from zone D with lower solidification rate, the largest precipitates were developed (in Figure 11 moving from d to f). A relatively equivalent condition was obtained with high Mg content (Figure 10c) and low solidification rate (Figure 11f).

The presence of Zn-based and the hexagonal α-AlFeMnSi intermetallic particles was detected by SEM observation and EDS analysis. They randomly interrupt the microstructure of the alloy for all compositions. The distribution of Zn-based compounds in the as-cast condition (Figure 12a) was a little bit different with respect to the situation after 20 days of natural ageing (Figure 12b), due to the diffusion of Zn within the Al-based matrix. After 20 days, no important differences were detected and stabilization of the microstructure was reached. A dense α-AlFeMnSi intermetallic particles were developed in the presence of a small amount of Fe which led to higher ductility and superior corrosion resistance. Higher Mg content favoured the development of $MgZn_2$ particles as reported in Figure 13. Usually, the growth of $MgZn_2$ intermetallics was close to the AlZn intermetallics. Migration of Zn occurred within the grain boundary and a diffusion of this element to produce $MgZn_2$ intermetallics was observed.

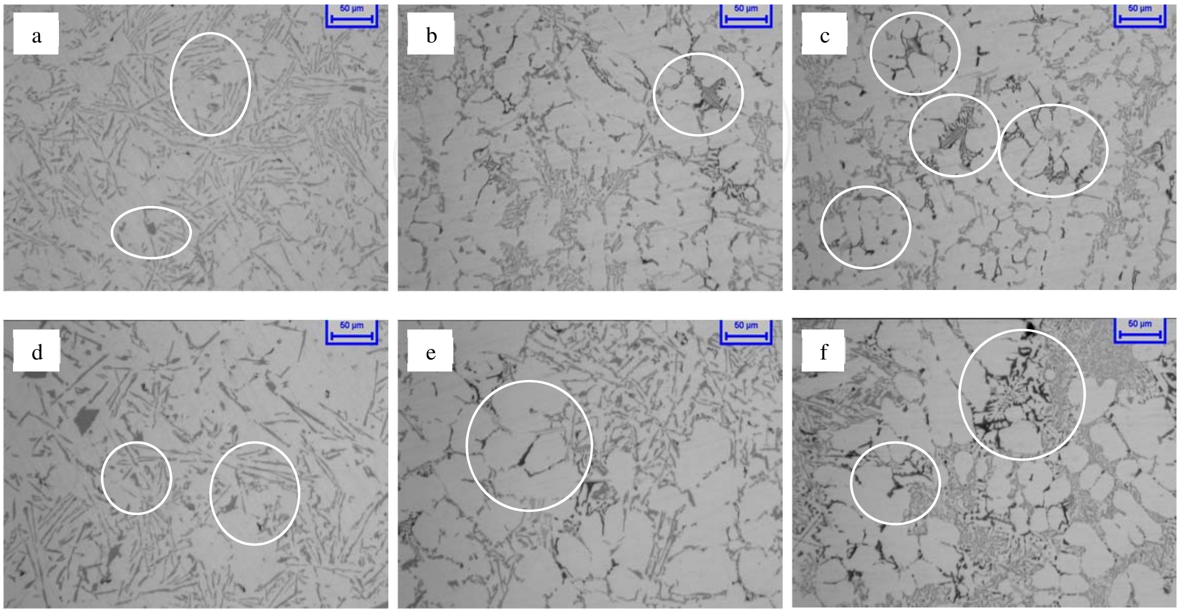

Figure 11. Microstructure of AlZn10Si8Mg alloy zone B (a) and zone D (d), AlZn10Si8Mg1 alloy zone B (b) and zone D (e), AlZn10Si8Mg3 zone B (c) and zone D (f).

The use of the modified self-hardening Al alloy avoided any heat treatment which in turn contributed to important energy saving during manufacturing, especially in terms of gas and electricity consumption, important features for the environment.

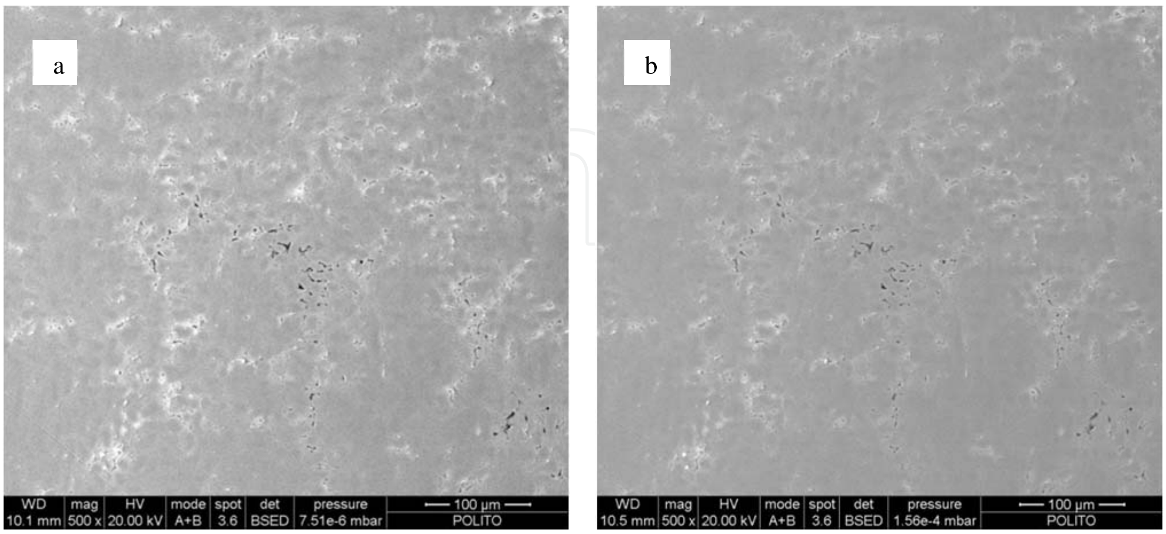

Figure 12. SEM microstructure showing the dispersion of the Zn-based intermetallics in as-cast sample (a) and after 20 days of natural ageing (b)

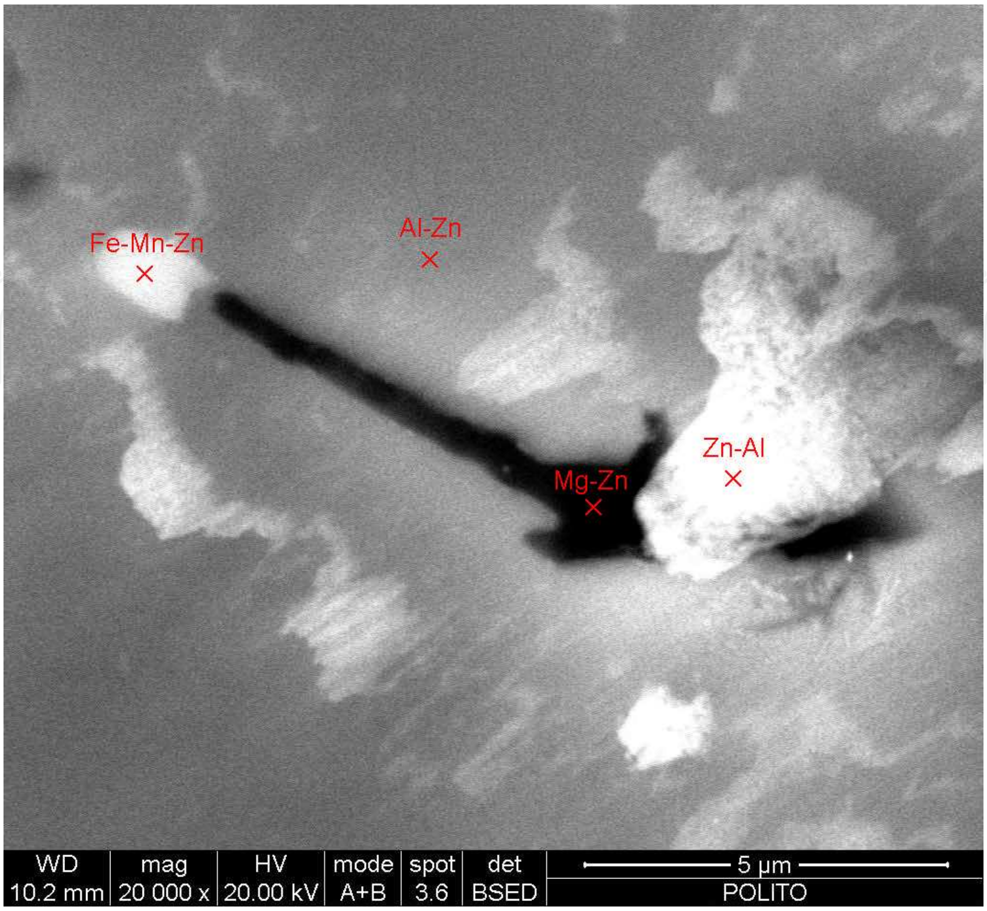

Figure 13. SEM microstructure showing the presence of the intermetallic particles in the as-cast sample

3. Conclusions

In this chapter, an overview of the actual state of the manufacture and use of light alloys has been presented. It includes a short history and description of state-of-the art techniques with special attention both to large-scale applications and to special use. The general description based on data available in the recent and past literature are integrated with some results of the current research carried out by the authors. It was pointed out that, in such critical areas of alloy development, detailed knowledge of the alloys' properties represents a key factor. Continuous interaction, data and know-how exchange between materials scientists, metallurgical engineers and industrial partners constitute a key-issue for the production of high-quality components based on innovative processes. The results presented within the research performed by the authors in collaboration with different foundries demonstrates the effectiveness of such strong interaction between industrial players and universities, e.g., the use of the developed modified self-hardening Al alloy can be considered an important energy-saving example, especially in terms of gas and electricity consumption. The increasing use of light alloys in different applications requires production of high integrity and improved perform-

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ance components, similar to those obtained by traditional processes, also taking into account the economical aspect of the production. In fact, commonly used production processes used in a conventional way by the industry can be enhanced by developing and making available innovative production procedures. In this context, the development of new industrial processes, namely modified squeeze casting and innovative rheocasting processes for light-weight alloy production represents a valid support to enhancing the life of engineering components and their reliability. Aluminium has proven to be the ideal light-weighting material allowing weight savings also in mass production within reasonable cost limits and without compromising safety. When considering various development methods, it may be helpful to consider the advantages and drawbacks of using a specific production process. Once the correct alloy for the production has been chosen, there are numerous factors to be considered, including the type of casting process to use and the intended purpose of the produced component.

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