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REVIEW PAPER

Hypereutectic Aluminum Alloys and Composites: A Review

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Abstract
Fast development of automotive industry increases demands in terms of fuel efficiency, reduction of weight and increased reliability of constructions. Nowadays major materials for production of pistons are cast iron, Aluminum–Silicon (Al-Si) alloys and some composites. Use of hypereutectic Al-Si alloys is increasing in automobile and aerospace industry. Application of hypereutectic Al-Si alloys with more than 12wt.% of Si is due to their properties like good thermal and electrical conductivity, high strength to weight ratio, good corrosion resistance and others. Higher Si content in the alloy can affect its properties; it increases size of primary Si and hardness but reduces machinability. In order to improve their properties and meet the high requirements of the industry, usually, grain refinement of these alloys is needed. Some of the ways to obtain grain refinement and potentially improve hypereutectic Al-Si alloys' properties are different manufacturing technologies, heat treatments and/or addition of grain refiners like Ni, Mg, Sr, Sn and many others. There is a large amount of manufacturing technologies used for hypereutectic Al-Si alloys, and in this paper will be considered most of them, as well as their influence on microstructure, mechanical and tribological properties of hypereutectic Al-Si alloys and composites. Also, the effect of higher Si content in the hypereutectic Al-Si alloy on its properties will be considered, as well as addition of modificator/refiner or reinforcement. Liquid state processes are usually used for hypereutectic Al-Si alloys, but some newer (semi-solid and solid processes) have emerged that give better microstructure, mechanical and tribological properties, and those are tixocasting, rheocasting and selective laser melting. Based on available investigations tixocasting gives promising results, the only drawback is the price and in the future, investigations should be oriented to finding ways for its reduction.

Keywords Hypereutectic Al-Si alloy · Hypereutectic Al-Si composite · Fabrication process · Microstructure · Wear rate · Coefficient of friction

1 Introduction

Use of lightweighting technology is expanding in automotive industry due to its economic and environmental factors. Lightweight materials used in automotive industry are mainly aluminum, its alloys and composites [1, 2]. Next to the automotive industry, aluminum and its alloys are used in aerospace and electronic industry as well, because of low density, high electrical and thermal conductivity, good specific strength, high corrosion resistance, good casting properties and good weldability. However, in addition to all these good qualities, the shortcomings of aluminum alloys are reflected in low strength and wear resistance and high thermal expansion coefficient. In automotive industry aluminum and its alloys are used for car's power train, car body, suspension and chasis [3, 4]. This research will consider Aluminum–Silicon (Al-Si) alloys. There are three

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types of Al-Si alloys and they are: hypoeutectic, eutectic and hypereutectic alloys. Difference between these alloys is in the percentage of Si in the alloy. Hypoeutectic alloys have up to 12wt.% of Si, eutectic alloys have around 12wt.% of Si and hypereutectic have more than 12wt.% of Si in the alloy [5]. Aluminum alloys used in power trains for pistons are hypereutectic Al-Si alloys. These alloys have low thermal expansion coefficient, good casting performance, good weldability, high wear resistance and high temperature strength [4, 6–11]. The mentioned properties are due to the presence of primary Si in the microstructure of the Al base [4, 6, 10, 11]. It is known that microstructure of materials determines their properties; in the microstructure of hypereutectic Al-Si alloy prepared by conventional casting methods there are coarse primary silicon phase, usually irregulary shaped, plate-like, or block-like, and long needle-like eutectic silicon [4, 5, 11–15]. More of the Si content in the alloy results in bigger size of primary Si particles which is the cause of poor machinability and ductility of hypereutectic Al-Si alloys [16, 17]. In order to obtain good properties of hypereutectic Al-Si alloys, it is of great importance to obtain good distribution of particles and fine primary Si phases, which is possible in three ways: by developing a suitable fabrication method [4, 8, 12–19], applying heat treatments [12, 20] and/or addition of grain refiner/modificator [4, 5, 11, 15, 18, 21]. Fabrication method for hypereutectic Al-Si alloys is mostly casting, especially conventional casting but, without modifications, it gives not so favorable microstructure of material with bigger size of primary Si particles. Fabrication methods can affect on the microstructure of the material, for example centrifugal, stir casting, squeeze casting and others give higher hardness, better distribution of particles and lower size of primary Si then conventionally casted hypereutectic Al-Si alloys. Reduction of size of primary Si due to fabrication method was high and in some cases even more then 50% [16, 22]. More about the impact of the fabrication methods will be given in the paper.

Heat treatment, usually T6 is used for obtaining better microstructure of hypereutectic Al-Si alloys and composites. This treatment consists of: solution treatment, quenching and artificial aging, and gives higher hardness and improved microstructure [12, 23].

Although the hypereutectic Al-Si alloy itself has satisfactory properties, reinforcements are added in order to further improve their properties, thereby forming a composite. In recent years composites with base of hypereutectic aluminum alloy are being investigated in order to reinforce pistons especially their head [20]. In the following text when referred to amount of Si, or other elements in the alloy, it is given in wt.% unless otherwise stated.

Next to the manufacturing technology, heat treatment and Si content in the hypereutectic Al-Si alloy, the addition of elements like Ni, Mn, P, Sr, Sn, Mg, Er, Co, Fe, sillimanite, ilmenite, etc., in the alloy is also important [4, 5, 11, 12, 14, 15, 18, 21, 24–28]. There are investigations on how addition of some elements to hypereutectic Al-Si alloys influences microstructure, mechanical and tribological properties of hypereutectic alloy. Elements are added in order to obtain homogeneous distribution and refinement of primary Si particles and/or eutectic Si particles, and improve mechanical and tribological properties. Some of these elements form compound intermetalic phases during casting and heat treatment. Modification processes are complex and are more described in [12, 15, 18, 20, 21, 24–28]. If there is iron in hypereutectic Al-SI alloy it acts like an impurity, increases wear rate and morphology is needle-like. With addition of Mn the effect of iron is mitigated, morphology is star-like and wear resistance is increased [29]. In investigation [30] to hypereutectic alloys Al-19Si and Al18-Si were added 0.795 and 5.901Fe without significant change in other elements. Investigation showed that higher addition of Fe in the hypereutectic Al-Si alloy improved microhardness, but lowered Ultimate Tensile Strenght (UTS) and elongation, which is due to the formation of iron rich intermetalics. With addition of Cu ang Mg to hypereutectic alloy hardness increases [31] and just a small addition of modifier like Sr (0.06) can have significant effect on tensile strength and hardness [32].

In the last years, there has been intensive research of hypereutectic aluminum alloys and their composites in order to investigate the effects of different elements and manufacturing processes on mechanical and tribological properties. In this paper, a brief overview of the production techniques of hypereutectic Al-Si alloys and composites was made with reference to their microstructure and mechanical properties. A more detailed review was made for the tribological properties, the values of which are greatly influenced by a huge number of factors that are tabulated.

2 Manufacturing Technologies, Microstructures and Mechanical Properties

There are many fabrication methods for hypereutectic Al-Si alloys and composites. Most common methods are liquid state processes like: gravity, conventional and die casting. During the years, a lot of other fabrication methods emerged, such as stir casting, squeeze casting, centrifugal casting, as well as some semi-solid state processes: rheocasting, tixocasting; and solid state processes: selective laser melting and other powder metallurgy techniques. Among all mentioned fabrication methods most advantages has centrifugal casting because of low cost, easy operation and flexibility of this process in order to obtain alloys of different properties [8, 16, 17, 19, 20, 33–39].

2.1 Gravity, Conventional Casting, Die-casting

Conventional casting is the simplest form of casting; it includes melting of the material and pouring it into the mould that can be made of sand, metal or some other material [36]. Die casting is a form of casting where liquid metal fills mould under pressure. This type of casting gives elements high dimensional accuracy and less porosity [34, 36]. In the observed papers, when mentioning fabrication method, if it was said casting in the metal mould it was assumed it was conventional casting. Alloys Al-17Si and Al-25Si modified with Er were manufactured by conventional casting in metal mould [11]. After tribological tests, the lowest wear loss was observed for Al-17Si-0.3Er and Al-25Si-0.05Er and 0.3%Er. In the microstructure of unmodified Al-25Si primary Si average particle size was 95.62 µm. After the addition of 0.05 Er size of primary Si was 42.31 µm; and after 0.3%Er average size of these particles was 52.31 µm, which shows that primary Si particles were refined but not enough which resulted in not enough improvement of poor wear properties of Al-25Si. Unmodified Al-17Si had finer primary Si particles of size 35.61 µm and for the modified alloy Al-17.5Si-0.3Er size of primary Si was 28.34 µm. This only shows that appropriate amount of Er can refine primary Si particles. As for the shape of primary Si in unmodified hypereutectic Al-Si alloys primary silicon crystals were large polygonal, branched and platelet-like; after modification of Al-Si alloy platelet-like Si crystals have decreased in number, and polygonal crystals decreased in size. Refinement of primary Si particles leads to better mechanical properties of these alloys [11]. Sand casted mould for conventional casting was used for hypereutectic Al-17Si alloy [40]. After microstructural observation of obtained alloy in the aluminum–silicon base there are: irregular sharp-edged (polyedral-shaped) primary silicon particles, with size of 360 µm, and long needle-like eutectic silicon particles. Irregular sharp-edged (block-like) primary Si particles in the eutectic base are present in the microstructure of conventional casted hypereutectic alloy Al-20Si, which limits further improvement of its properties [41]. Both of the alloys, Al-17Si and Al-20Si were produced in order to compare their properties to rheocasted and spray-deposited alloys respectively [40, 41], which will be discussed later in this paper. Another conventional casted and heat treated alloys were Al-18Si alloy with 0.8%Fe [42] and Al-18Si with 0.95%Fe [23]. In the microstructure of as-casted Al-18Si-0.8Fe alloy there was primary Si non uniformly distributed, eutectic α-Al,eutectic Si and needle-like intermetalic Fe rich phases. Size of the primary Si particles in the as-casted state was approximately 37.5 µm, α-Al size was 95 µm, and intermetalic Fe rich phase length was 50 µm. After heat treatment cycles (1, 2, 3, 4) size od the primary Si was 35; 36.5; 37.5 and 50 µm, as for α-Al its size, after heat treatment, was 77,5; 78; 79.5 and 130 µm. Length of Fe rich intermetalics for first three cycles was similar and for the fourth it was 60 µm, but in the heat treated samples their shape was plate-like. Hardness of the heat treated samples slightly increased when compared to the as-casted sample from 56 to 64.5 HRB. In [23] microstructure of as-cast Al-18Si-0.95Fe alloy there was Fe-rich needle-like intermetalics, primary Si with size 70 µm eutectic Si and α-Al with size of 155 µm. After heat treatment (10–40 min) particles were more refined. The highest hardness was obtained for heating time of 25 min and its value was 72.5 HRB which is increase of 10.5 HRB when compared to the as-casted alloy. In order of examination if hypereutectic Al–13.5Si alloy is suitable for fabrication of pistons, research was conducted in [43]. In this research the microstructure properties, mechanical properties, fracture analysis and corrosion behaviors of hypereutectic Al–13.5Si alloy were observed. Hypereutectic Al–13.5Si alloy was obtained by conventional casting, pouring temperature was 740 °C and mould was not preheated. In microstructure of specimens the fine dendrites of α-Al phase, significantly dispersed eutectics and particles of intermetallic phases were noticed. In the central part of specimen extensive areas of eutectics and porosity are present; presence of porosity was probably result of quality of the melted material and pouring process. After cooling of the casted specimens tensile tests were performed in room temperature (25 °C), 250 °C and 300 °C. Specimens tested on room temperature show the highest tensile strength, and by increasing temperature tensile strength gradually decreases. After hardness tests it was observed that temperature changes didn't have any significant influence. Modification of hypereutectic alloy Al-30Si with different amounts of Al-3P and Al-10Sr was observed in [21]. Modified alloys were obtained with different treatment temperatures (770–850 °C). Unmodified sample had irregular distribution of coarse platelet and polygon primary Si with size of 203.8 µm and needle-like eutectic Si. The highest tensile strength and lowest size of primary Si (32.5 µm) was for alloy obtained by conventional method which means that modifiers were added as following: on temperature 770 °C was added 0.7%Al-10Sr, on temperatures 800 and 830 °C was added 0.5%Al-3P and on 850 °C was added 1%Al-3P. This combination of temperatures showed as appropriate for these modifiers because at low temperatures they don't react with each to form intermetalic compounds. In some investigations it wasn't stated what was the manufacturing technology like in [32] so it will be considered as conventional casting. Hypereutectic alloy Al-18Si was modified with 0.06%P or 0.12%Sb, and the samples were observed in room temperature and on elevated temperature at 250 °C. For both modifiers at room temperature hardness was approximately the same (≈111 HB), but tensile strength for alloy with addition of 0.06%P was higher (209 MPa). At elevated temperature alloy modified with 0.12%Sb showed better hardness (89.5 HB) and tensile strength (166 MPa) than the alloy with modification of 0.06%P (81.9 HB and 153 MPa). For both modified alloys dense distribution of primary Si particles with size no higher than 70 µm and needle like eutectic phase were present in the Al base [32]. Increase in size of primary Si is possible with higher content of Ca in the hypereutectic alloy. In the alloy Al-18.7Si increase of Ca content from 0.0016–0.019%Ca, resulted in increase of primary Si size, while tensile strength and elongation decreased. Particles of primary Si were more refined and better distributed for lower content of Ca in the hypereutectic Al-Si alloy [44]. Observation of the influence of Nd on the Al-20Si alloy on size of primary Si and wear was done in [45]. Addition of 0.3%Nd reduced size of primary Si from 80–120 µm to 20–50 µm when compared to the unmodified sample. Unmodified sample had irregular morphology and star-shaped primary Si, while modified sample had regular morphology with fine polyhedral-shaped Si. Due to changes in morphology wear resistance is improved after addition of Nd.

Conventionally casted samples of Al-16Si alloys, their microstructure and hardness were investigated in [46]. The alloys were in the as-casted state and modified by the addition of CeO_2. Later in text this results will be compared to the same alloy modified by electromagnetic stirring (EMS) and/or CeO_2. Casted alloy Al-16Si had primary silicon particles of a large size (152 µm), β-intermetalic Al–Fe–Si (314 µm) and some intermetalic Co–Ni in Al base. The large size of present particles affects alloys' strength and ductility, which is the reason of the 0.2%CeO_2 addition. With the addition of CeO_2 particles were more refined and the primary Si particles had average size of 98 µm and β-intermetalics Al–Fe–Si average size was 221 µm. Hardness, UTS, tensile yield strength and elongation have all increased with the addition of 0.2%CeO_2 which can be attributed to better refinement of particles and lower porosity. Samples prepared by conventional casting of hypereutectic Al-18Si had in their microstrurcture sharp-edged primary Si, intermetalic compouds (β-Al4.5FeSi and Al2Cu) and needle-like eutectic Si, which were irregularly dispersed in aluminum base in [47]. The properties (microstructural studies, tensile, hardness and wear tests) of obtained samples were compared to the samples undergone to compression in the converging die with reduction ratios of 1.5 and 2.0 at temperatures of 300, 400 and 500 °C. After compression primary Si and eutectic Si got fractured and better distributed in the Al base. For both reduction ratios, refinement of particles increased with increase of temperature for 300–400 °C, but increase in temperature from 400–500 °C led to rough formation of primary Si particles. The obtained results show that temperature of processing has high influence on properties of hypereutectic Al-Si alloys. Compressed alloys when compared to as-casted samples show better properties especially at 400 °C and at reduction ratio 2.0, those are the lowest size of primary Si (7.5 µm) and eutectic Si particles (6.7 µm), UTS (240 MPa), hardness (125 HV) and wear rate ($1.4–1.6 \times 10^{-3} mm^3/m$).

Die casting process where liquid metal fills the mold with high speed is called high pressure die casting (HPDC) [48]. Three hypereutectic Al-Si alloys (denoted as A, X and C) obtained by HPDC were studied in [49]. Alloy A was Al-17.3Si-4.20Cu alloy, X was Al-17.26Si-2.37Cu alloy and alloy C was Al-20.01Si-2.58Cu alloy. Processing parameters for obeserved alloys were: melting temperature (730, 750, 780 °C), initial mould temperature (120 °C), slow shot speed (0.2, 0.2, 0.1 m/s), fast shot speed (2.75 m/s), mould holding time (8 s). Microstructure shows low density of primary Si particles on the surface that was facing die walls and higher density of primary silicone particles and pores in the center of the casted alloys. Alloy A had the highest volume fraction of porosity and alloy X had the lowest volume fraction of porosity. Eutectic Si and intermetallic Cu-rich phases were present in the observed alloys as well. Formation of pores was due to Cu-rich phases which affected the growth of Al dendrite arms. HPDC alloys Al–20Si and Al-17Si were investigated in [50] and [51] respectively. Alloys Al–20Si were prepared with different cooling rates (4.9 to 82.9 °C/s), and it was observed that with increase in cooling rate size of particles decreased significantly, and their distribution was more uniform. For cooling rate of 4.9 °C/s average diameter of primary silicon particles was 89.7 µm and average size of secondary dendrite arm spacing (SDAS) was 22.1 µm. The smallest particle size was for cooling rate of 82.9 °C/s and primary silicon average diameter was 17.3 µm while average size of SDAS was 5.1 µm [50]. Alloy Al-17Si was, also, prepared by high pressure die casting, and in its microstructure were present primary Si with size of 20–30 µm and irregular rough shape, eutectic Si which was less in size and more regular strip shaped, around primary silicon particles were α-Al dendrites and around eutectic Si were Cu-rich phases. As for porosity it was present in the primary silicon particles, around boundaries of primary silicon or in the α-Al dendrites [51].

When the preforms of the casted parts are made of a type of foam then this type of casting is called lost foam casting. Lost foam casting uses sand moulds and preforms evaporate when the molten metal is poured. With this type of casting a parts of complex shape can be casted [52]. Microstructure after lost foam casting of Al-16Si is finer with reduced primary Si particle size from 121 to 25 µm when compared to conventionally casted sample and hardness after T6 treatment is higher [53].

Gravity casting is permanent mold casting and one of the most common types of hypereutectic Al-Si alloy casting. This type of casting consists of melting the metal and filling the mold only with the help of gravity force [34, 36]. Strength, hardness and tribology test were done for hypereutectic Al-21.6Si manufactured by gravity casting [35]. The average hardness was 70 HV, UTS was 175 MPa, for dry wear test conditions and contact geometry ball-on-disc specific wear rate was measured, there was no report of microstructure for this material. Hypereutectic Al-Si alloy with 15–22%Si in its microstructure, had coarse (sharp-edged) primary Si phase, plate-like eutectic Si phase in the Al base [16]. Properties of alloys obtained by gravity casting [16] were compared to the squeeze casted samples which will be discussed later in this paper.

Microstructure of conventional casted, gravity casted and die casted materials shows that there isn't uniform distribution of particles, as well as presence of coarse, block-like or polygonal-like primary Si particles of big size and needle-like eutectic Si, which is the reason for addition of modifiers/refinemers and application of some other manufacturing process.

2.2 Centrifugal Casting

Cetrifugal casting is a type of casting where a molten metal (slurry) is poured into a preheated rotating mould, the reinforcement is added in case of composites, and the mould continues rotating until the solidification. This process uses the centrifugal force to distribute the molten material [54]. When producing the composite, due to the influence of centrifugal force, two zones of particles are formed: enriched and depleted zone; and they depend of the melt temperature, metal viscosity, cooling rate, density and size of particles, and centrifugal acceleration and its magnitude. Particles of the higher density form a particle enriched zone on the outer periphery of the cast while particles with lower density migrate and form particle enriched zone on the inner periphery. With increase of pouring temperature and speed of rotation the thickness of particle enriched zones decreases. Centrifugal casting can be divided into two groups, first one is based on the axis of rotation of the mould and the second one is based on the temperature of the slurry. The first group consists of two main types vertical and horizontal centrifugal casting and others are variation of this main two such as, vertical-inclined and horizontal-inclined centrifugal casting, and others. In the second group based on the temperature, there are in-situ and ex-situ processes. For in-situ process the temperature is higher than the base material liquidus temperature and reinforcement are formed in the base material melt during the process of solidification. Ex-situ centrifugal casting is casting where prefabricated solid reinforcement is added to the base material by infiltration, vortex or casting methods [54, 55]. Based on literature, liquidus temperature for Al-18Si is from 640–690 °C and solidus around 575.5 °C, but it depends of percentage of Si in the alloy [23, 42].

Investigation of alloy Al-18Si obtained with centrifuge casting was done in [56]. This process uses modified centrifugal casting set-up. It is based on centrifuge, and the set-up consists of motor, which is connected via shaft to an arm, on one end of arm is fixed mould while on the other end is counter weight for balance. Alloy was fabricated with slurry temperatures of: 750 °C and 850 °C, and mould rotational speed of 200 rpm. Microstructure analysis showed that for both temperatures silicon percentage is increasing from bottom to the top due to action of centrifugal force. Primary Si particles were more refined and better distributed for 850 °C slurry temperature. t Results obtained with tensile and hardness testing show that with the increasement of slurry temperature UTS and hardnesss are increased, andit was concluded that Al-18Si alloy obtained with slurry temperature of 850 °C has better properties in terms of microstructure, ultimate tensile strength, hardness and wear rate [55].

The effect of horizontal centrifugal casting on microstructure and properties of hypereutectic Al-18Si in-situ composite for cylinder liner was investigated in [57]. For in-situ composites reinforcement of Si particles is forming during the process of solidification. Rotation speed of the mould was varied: 1100 rpm, 1300 rpm and 1600 rpm, temperature of slurry was 800 °C. Hardness of materials obtained by centrifugal casting was tested for each layer in three points and calculated the average, and then these materials were heat treated by T6 heat treatment.. In the T6 heat treatment solid solution temperature and solution time were 515 ± 5 °C and 7 h, while artificial aging temperature and aging time were 185 ± 5 °C and 11 h respectively. Hardness is influenced by the location on the specimen, as already said there were observed three layers on the specimens: outer, middle and inner layer. With increasement of rotation speed in centrifugal casting primary Si gradually shifts from outer layer to the inner layer of the alloy. For rotational speed of 1100 rpm in all layers there are dendritic α-Alphase, flocculent eutectic (α + Si) phase and bulk primary silicon phase present. In the outer layer of specimen obtained with rotational speed of 1300 rpm there is α (Al) base and a large number of eutectic silicon and a small amount of primary silicon present. Middle layer shows aggregated part of primary silicon, while in the inner layer is more of primary silicon present. Specimen obtained by rotational speed of 1600 rpm in the outer layer shows: clear stratification, almost no primary silicon, large number of flocculent eutectic silicon and α (Al) base. In the middle layer, there is small part of the primary silicon gathered together, and in the inner layer large number of bulk primary silicon is enriched. Hardness of casted Al-18Si alloy depends on the quantity of primary Si particles; in this case hardness had the highest values for the highest rotation speed in centrifugal casting (1600 rpm), because there was the highest quantity of primary Si particles. When heat treatment by T6 was conducted, hardness of alloy slightly increased in all layers [57].

Mechanical and microstructural properties of the Al-17Si in-situ composite cylinder liner obtained by horizontal centrifugal casting were investigated in [55]. Microstructure of the hollow cylinder liner shows that in the most distant zones of cylinder there are eutectic microstructures, and towards the inner area there is increased Si content i.e. hypereutectic microstructure is present. Near the inner periphery there is presence of gas and shrinkage porosities. Microstructure of these in situ hollow cylinders leads to better hardness, improved wear resistance and durability [44]. For hollow cylinder obtained from Al-Si in situ composite there is presence of primary Si particles towards the inner periphery, and the same is observed in [57].

In [20] composite pistons with base of Al-18vol.%Si alloy were obtained by vertical centrifugal casting, reinforced locally at the head with SiC particles (15–30 μm), and heat treated. Centrifugal casting parameters were: slurry temperatures of 850 and 800 °C, mould temperature of 600 and 500 °C and rotation speed of the mould 800 rpm. On the bottom of the piston skirt there were a large number of pores, small amount of irregularly shaped primary silicon particles and SiC particles present. Going towards the head of the pistons the amount of SiC particles and α-Al increases and in piston head SiC particles are uniformly distributed in the base and some SiC particles are embedded in primary silicon. For combination of temperatures of 800/500 °C SiC particles, primary silicon particles and pores are present. Because the temperatures of the slurry and the mould are low in this processing, the viscosity of the molten metal becomes so great that the SiC particles, primary silicon particles and pores cannot be effectively separated from each other. Hardness values increase from skirt to piston head, which means that the peak values of hardness occurred at the SiC segregation zone of piston heads. By comparing results of hardness testing for pistons fabricated by centrifugal casting it was observed that hardness value in piston head was increased with higher pouring temperature and rotating speed of the mould. It was observed that with increasement of temperature hardness increased significantly and for head of piston obtained with combination of temperatures of 850/600 °C it was 93.9 HRB. Investigation of hypereutectic Al-17Si alloy in terms of microstructure and hardness was conducted in [58]. Cast tubes from observed material were fabricated by vertical centrifugal casting with different mould speeds of: 600 rpm, 800 rpm, 1000 rpm and 1200 rpm. Regular cast tube was obtained only at 1000 rpm, and this speed is considered to be optimal speed. In the microstructure of cast tube obtained with rotational speed of 600 rpm irregularly shaped primary silicon particles are present. Cast tube obtained with speed of 800 rpm had smaller, uniformly distributed Si particles. For speed of 1000 rpm where regular cast tube was obtained refined Si grains are formed (fine structure), while for speed of 1200 rpm there was, again, primary silicon. As for the hardness tests, they have shown that the highest hardness values are for optimal rotational speed. When rotational speed was 1000 rpm hardness was 104 HV and 103 HV for inner and outer layer respectively. It can be concluded that, in this case, rotational speed of mould has big influence on hardness and grain size of Al-17Si alloys. Higher values for hardness were obtained in [8] where Al-18Si alloy was investigated. The alloy was obtained by vertical centrifugal casting and heat treatment (mould temperature 100 °C, rotational speed of mould 450 rpm), hardness was measured in 3 different distances from surface of ingot and mean value for hardness was 109.33 ± 2.83 HV.

For centrifugal casting, with the different manufacturing parameters like mould rotating speeds, slurry and mould temperatures it can be influenced on microstructure and by that on the properties of hypereutectic Al-Si alloys. Higher slurry temperature, appropriate mould rotational speed and higher mould temperature can give well refined structure, with primary Si on the top of piston head or in the inner part of cylinder liner depending if its horizontal or vertical casting.

2.3 Stir Casting

After centrifugal casting, mostly used process for manufacturing of hypereutectic alloys and composites is stir casting. IPrinciple of stir casting is reflected in melting the metal, and adding the reinforcement (for composites), while mechanically stirring the mixture. Reinforcement can be directly introduced into molten base with the help of inert gas or by vortex method. This method is very cost effective and simple, it can be applied for a large variety of materials, but, there are some disadvantages in terms of poor wettability, difficulty to obtain a homogeneous distribution of particles, porosity and chemical reactions between base material and reinforcement [59, 60].

Microstructure and machining properties of hypereutectic Al-Si alloys were investigated in [61]. Fabrication process wasn't stated but from schematic diagram of the process it was concluded that it was stir casting. Hypereutectic Al-Si alloy had in their content 16–24%Si and they were observed in the as-cast state and heat treated. As-cast alloy Al-16Si had a small amount of sharp-edged primary silicon particles, α-Al and eutectic Si, but after heat treatment morphology was changed and primary Si particles had rounded edges and eutectic Si had almost spherical-shaped. For Al-20Si microstructure showed large amount of sharp-edged primary Si, α-Al and eutectic Si, and after heat treatment primary Si size was smaller and egdes were more rounded; eutectic Si had spherical shape. A large amount of massive and polygonaly-shaped primary Si was present in microstructure of Al-24Si as well as α-Al and eutectic Si. It was observed that with increase of Si in the alloy hardness and particle size of primary Si increases, eutectic Si particles become progressively coarser which all affect machinability After the heat treatment hardness and size of primary Si decreased. Influence of 1–1.5%Mn addition on microstructure and wear rate of Al-14Si was investigated in [62]. Best results of tribological tests were obtained for Al-14Si-1.5Mn for load of 40 N and rotational speed of 500 rpm. As for microstructure, base alloy had sharp-edged irregular polygonal primary Si around which were α-Al dendrites and eutectic Si. Addition of Mn resulted with better distribution, refinement and finer edges of primary Si and globular eutectic Si particles, and presence of intermetalic Mn phases. Addition of small amounts of Ti (0.05%), Sr (0.05%) and graphene (5%) on mechanical properties of stir casted hypereutectic Al-16Si alloy was investigated in [63], Base alloy without modification had in its microstructure sharp-edged block-like primary Si, needle-like eutectic silicon and coarse columnar α-Al dendrites in aluminum base. Ti addition in the base alloy enabled denser α-Al dendrite distribution and fine equal-axed grains of eutectic silicon in the Al base. Addition of Sr to the base alloy, also, leads to denser α-Al dendrite distribution, refinement of block-like primary Si and thinner globular eutectic Si in the Al base. When combining grain refiner and grain modifier in the Al16Si alloy the distribution of particles is more homogenous and particle size decreased. With graphene addition there is finer and dense distribution of α-Al dendrites, globular eutectic Si and dispersed graphene particles in the Al base. With addition of grain refiner and/or grain modifier and graphene mechanical properties were better, and the best were for Al16Si-0.05Ti-0.05Sr-5graphene. Composite of Al-17.4Si base reinforced with sillimanite and/or Sn and/or Gr prepared by stir casting process was observed in [64]. Sillimanite composition was Al_2O_3 (58.60%), SiO_3 (38.54%), ZrO_3 (2.20%), TiO_2 (0.26%) and Fe_2O_3 (0.40%). In the microstructure of base alloy were present inhomogeneous primary Si particles of large size and rough block-like shape and needle-shaped eutectic silicon, which reduced wear rate. Addition of sillimanite refined structure of base alloy (primary Si size ≈72 µm), globular eutectic Si was present and sillimanite particles were uniformly distributed in the Al base. Addition of Sn or Gr to silliminate composite for lubrication results in further refinement of primary Si, the best refinement of particles gave combination of Al17.74Si with 10%silliminate and 1%Sn (49 µm). With the addition of 0.5%Sn and 0.5%Gr to silliminate composite, also, primary Si had fine size (50 µm), the highest hardness of 189 BHN, lowest CoF and wear rate. Another composite with sillimanite, Sn and Gr but with the addition of ilmenite with composition: TiO_2 (55.3%), Al_2O_3 (0.8%), Cr_2O_5 (0.1%), FeO (20.5%), SiO_2 (1.6%), MgO (1.0%), Fe_2O_3 (19.9%), V_2O_5 (0.2%) was observed in the [15]. Tribological properties, microstructure and hardness of the compostes were observed, and the highest hardness and lowest wear rate were for composite with Al17.74Si base and addition of 5%sillimanite, 5%ilimenite, 0.5%Sn and 0.5%Gr. In the microstructure of base alloy there was present primary Si of a large size and cube-shaped, star-like and poligonaly-like shape. When added sillimanite and ilmenite to the base alloy uniform distribution of reinforcement particles as well as refinement of primary Si particles was achieved. Adition of Sn and Gr to composite, also, resulted in refinement of primary and needle-like eutectic Si. Refining elements like Sr and Sb were added to stir casted Al-17.74Si alloy in [65]. In unmodified sample size of primary Si was 67 µm, with addition of Sr it reduced to 12 µm and with addition of Sb to 24 µm. Refinement with addition of P in hypereutectic Al-Si alloys with 24%Si and 18%Si was considered in [25] and [66] respectively. Into the Al-24Si were added three different master alloys: Si-3P, Si-25Mn-10P and Al-10Si-2Fe-3P. Base alloys microstructure show coarse star-shape primary Si particles with size of 200 µm. For all alloys the lowest size of primary Si was for holding time of 30 min, and when holding time increased size of primary Si increased as well. The lowest size of primary Si (18 µm) was obtained for 0.35%Si-25Mn-10P and holding time of 30 min, and primary Si had block equal-axed shape. Alloy Al-18Si was stirred and refined with addition of Al-3P forming Al-18Si; Al-18Si-0.02P and Al-18Si-0.04P [66]. With addition of 0.02%P and 0.04%P density of particles increased and size of primary decreased from 160 µm unmodified to 83 µm and 28 µm respectively. It can be concluded that even low amount of P in hypereutectic Al-Si alloy can lead to a good refinement of primary Si particles.

Hypereutectic Al-Si material for piston fabrication by stir casting (vortex method) was investigated in [67]. In this research was observed friction and wear behavior of graphite and/or short carbon fibers (cf) reinforced Al-17Si alloy hybrid composites. As reinforcement were used copper coated graphite particles of 10–30 µm size and copper coated carbon fibers. Copper coating was applied using electroless deposition method. From microstructure observations by SEM (scanning electron microscope) uniform distribution of the reinforcement in the composite base was noticed. The highest values of UTS and hardness are obtained for hypereutectic Al-Si-2Gr-2cf hybrid composite due to the uniform distribution of Gr and cf reinforcement in the base of hybrid composite.

Alloy used in diesel engine pistons was investigated in [22], more precisely stirring and graphene nanosheet addition effect on the microstructure and mechanical properties of 393 hypereutectic Al-Si alloy (Al-22Si). First sample was conventionally casted and the second sample was only depending on stirring the Al-Si alloy for 12 min at speed of 400 rpm. The third and fourth sample were obtained by stirring of the Al-Si alloy for 2 min, then adding the graphene nanosheets into the alloy and continuing the stirring for 10 min at speed 50 rpm slowly increasing to 400 rpm. In microstructure of conventionally casted specimen mostly observed were primary Si, eutectic Si and eutectic α. With mechanical stirring microstructure was well refined, the Si primary particles were more globular and finer, but these particles were not homogenously distributed especially in the center of the specimen. Addition of low amount of graphene nanosheets into the Al base was resulting with further refinement of primary Si particles, while with the addition of 1% of graphene nanosheets resulted in better distribution of primary Si particles, on the edge and center of specimen, as well as their finer and more globular shape. Average size of primary Si particles for edge and center of stir casted specimen was 65 and 69 µm respectively. Addition of 0.25% of graphene in stir casted specimen doesn't affect in big measure size of primary Si particles, for this specimen average size for edge and center of specimen was 67 and 69 µm. Specimen with the addition of 1% of graphene has the lowest size of primary Si particles, on its edge and center, of 49 and 52 µm respectively. Stir casting and addition of graphene obtain the higher hardness of specimens, formation of finer and globular primary Si particles and their better distribution. Influence of the addition of 2%Al_2O_3 and 3%Al_2O_3 nanoparticles on hypereutectic alloy Al-16Si fabricated by stir casting process with three different pouring temperatures (720–820 °C) was observed in [68, 69]. Wear, hardness and microstructure were investigated in both papers. Addition of 2%Al_2O_3 and 3%Al_2O_3 increased hardness of the composite, as well as increase in pouring temperature from 720 to 770 °C, with more increase in pouring temperature hardness decreased. Increase of pouring temperature from 770 to 820 °C hardness decreases, which is result of grain coarsening and accumulation. Wear rate was the lowest for composites obtained with pouring temperature of 770 °C, due to uniform distribution of particles [68, 69].

Modification by EMS of conventionaly casted Al-16Si and Al-16Si-0.2CeO_2 during the process of solidification was done in [46]. After melting of the alloy it was placed in electromagnetic field (22.5kWh) and it was stirred for 2 min in mushy zone (under 625-645ºC). EMS of unmodified alloy showed better properties than conventionally casted sample. Size of primary Si particles was lower (120 µm) and β-intermetalic Al–Fe-Si had lower length as well (234 µm). Addition of 0.2%CeO_2 resulted in better refinement and distribution of particles, and the highest hardness, UTS, tensile yield strength, elongation and the lowest particle size and porosity from all observed samples [46].

2.4 Other Manufacturing Processes

Next to the already mentioned types of casting there are other, less used, manufacturing processes that are mentioned in the text below.

Squeeze casting is also known as liquid forging, it includes melting of the material, pouring it into the lower half of the mould, lowering the upper half of the mould and applying pressure until solidification [34, 70]. In [16] the effects of squeeze casting on mechanical properties and microstructure of three Al-Si alloys (15, 17, 22%Si) are described. For investigation of these alloys, specimens were prepared with squeeze casting and gravity casting. Unlike gravity casted samples the microstructure of samples fabricated by squeeze casting showed refined eutectic structure and there were α-Al dendrites in the structure as well, while primary Si size and quantity reduced. With increase of Si content in the alloys, amount of primary Si phases increased and amount of primary α-Al dendrites reduced gradually. After comparison of hardness of both, gravity casting and squeeze casting specimens it was concluded that alloys obtained by squeeze casting had improved hardness and that with the increase of Si content hardness increases.

Another fabrication method for hypereutectic Al-Si alloy is electric pulse modification (EPM). This fabrication method consists of melting the material, degassing the molten metal, inserting graphite electrodes into the crucible and applying EPM. Influence of electric pulse modification on Ni-rich Al-13Si piston alloy was investigated in [71]. Four samples were fabricated (denoted from A to D) with four different pulse voltages: 0 V, 300 V, 500 V and 700 V respectively at fixed pulse frequency of 3 Hz. After fabrication microstructure observations revealed following phases: α-Al, primary Si, eutectic Si, and Ni-rich phases. In the microstructure of alloy A distribution of primary Si phases in the base was uneven, while there was a random distribution of large eutectic Si phases in the base. There was a large amount of α-Al dendrites, along which, in the divergent way, the coarse floccules of Ni-rich phases grow. In samples B, C and D, which are obtained by EPM, size of primary Si phases is smaller and decreases with a higher voltage, and in addition α-Al dendrites disappear in these samples. There is a well distribution of Ni-rich phases for samples B, C and D. Micro-hardness test have shown that for sample D value of the hardness was the highest 144.56 HV, which is higher than micro-hardness of the sample A (132.12 HV) [71].

Most common semi-solid state processes for material fabrication are tixocasting and rheocasting. Rheocasting is a process that includes melting the material and carefully cooling it, while stirring it to obtain globular microstructure. When cooled properly the semi-solid melt is transferred to be casted. Tixocasting process consists of preparing casted billets that have globular microstructure, reheating the billets to semi-solid temperature and then casting the prepared material [72].

Rheocasting process for obtaining hypereutectic Al-Si alloy was applied in [73, 74]. Hypereutectic Al-17Si with different Mg content 60–10%Mg was observed conventionally casted and rheocasted. Significant segregation of primary phases and two layers could be detected in the microstructure of these alloys which is the result of rheocasting fabrication method. In outer layer the most of primary phase particles were concentrated and in the inner layer there were no primary phase particles but the globular α-Al grains [73]. With increase of Mg from 6 to 10% in rheocasted samples primary Si particle size decrease and the morphology is finer. In order to improve mechanical properties rheo-diecasting was assisted with ultrasonic vibration process (USV) in fabrication of hypereutectic Al–17Si alloy with 2%Fe [38]. Hardness of the sample treated by USV in the temperature range of 665–645 °C is the best (141 HB). Microstructure of USV treated samples compared to the untreated samples has shown that δ-Al4 (Fe, Mn) Si_2 phase was refined into small particles for temperature range 665–645 °C [38]. Rheo-squeeze casted Al-17Si and Al-20Si alloys reinforced with 0–6%TiB_{2p} were investigated in [74] and [75] repectively. In microstructure of Al-17Si base alloy in α-Al base were present primary silicon particles with diameter size of 50.2 µm and needle-shaped eutectic Si with length 20–50 µm. With addition of 1, 3 and 6%TiB_2 to the alloy diameter of primary Si was 40.4; 39 and 24.5 µm respectively. After addition of TiB_2 to the base alloy needle-shaped eutectic Si fine grains of 5 to 15 µm size were formed and diameter of fine α-Al particles was 10–20 µm. With higher Si content in the base alloy [75] diameter of primary Si particles was similar (50 µm) to that of the base alloy Al-17Si. With addition of 1–6%TiB_2 microstructure and the average size of particles is the same as that of the composites investigated in [74] and at the highest amount of TiB_2 diameter of primary Si was 26 µm. For base Al-17Si and composites UTS increased from 173.4 MPa to 283.3 MPa and for composites with Al-20Si base for the same reinforcements UTS increased from 110 MPa to 215.7 MPa. TiB_{2p} (≤ 2 µm) exists in the primary Si and eutectic structures of the Al-17Si-6TiB_2 [74, 75].

Tixocasting of an automotive part-brake drum from hypereutectic Al-15Si alloy and 0.4-4Ni was observed in [76]. Brake drums were in the tixocasted and T6 treated state, and their hardness, weight and cost were investigated. In tixoforming primary Si is not remelted and its homogeneity depends of the already prepared billets, and in low percentage of tixocasting. After tixocasting was in range of 67–76 HRB and after T6 treatment it increased to 83–84 HRB. The weight of tixocasted samples was the lowest for specimens with the addition of 1-4Ni, but their cost was high. Microstructure investigation showed that the polyedral-shaped primary Si was homogeneously distributed in material with size of 30 µm. Al globules had size of 60–100 µm, and there was present eutectic Si and intermetallic phases between globules. Also, it was observed that high Ni addition (4Ni) has deteriorating effect at spheriodicity of the microstructure, which is very important in tixocasting [76]. Tixocasted hypereutectic Al-17Si pistons were fabricated by magnetohydrodynamical (MHD) stirring and casting followed by extrusion [77]. The investigations were done for different ram temperatures, die temperatures and load during the fabrication process.

Next to the liquid state and semi-solid processes there are solid state processes. Fabrication of hypereutectic Al-Si alloys by powder metallurgy technique-selective laser melting (SLM) was investigated in [78, 79]. Selective laser melting is a process where in the laser chamber material is fabricated layer by layer by melting the powder mixture of material [19]. Investigated materials were Al-18Si and Al-50Si, and after microstructure observation on uniformly distributed pores of both alloys were detected. Al-18Si alloy had pores of smaller size, and even pores with crescent shape because of partially melted particles. Mixed structure porosity was detected in Al-50Si alloy with less pores but size of those pores was bigger. Investigated samples have shown ultra fine microstructure when compared with conventional casted hypereutectic Al-Si alloys. Microstructure of Al-18Si and Al-50Si both consists of mixed microstructure of particle eutectic (P-eutectic) and fine primary silicon phase, and with the increase of silicon amount (from Al-18Si to Al-50Si) primary silicon increases proportionally. Also, tribological tests (ball-on-disk contact geometry) were done, and results show that Al-50Si has slightly lower wear resistance than Al-18Si [78]. The highest microhardness was obtained for laser power of 320 W and it was 188HV [80]. For Al-50Si sample at laser power of 260 W primary Si was 3.12 µm, and with further increase in laser power size of primary Si increases [78, 79].

In Table 1 are given manufacturing methods, base alloys, type and amount of reinforcement/modifier/refiner, hardness, elongation and size of particles. It should be noted that most of data displayed in the table are average or approximate values since most of researchers presented them in form of diagrams. Hardness wasn't given in all investigation in HV so it needs to be taken into an account that there might be some conversion errors.

In Table 1 are given manufacturing methods, base alloys, type and amount of reinforcement/modifier/refiner, hardness, elongation and size of particles.

As already mentioned, fabrication methods can have a great influence on properties of hypereutectic Al-Si alloys and composites. In cases where size of Si particles was higher hardness was higher as well. Where refiners and

Table 1 Mechanical properties of Al-Si alloys and composites with influencing factors

Reference	[11]	[11]	[40]	[46]	[46]	[22]	[53]
Fabrication method	Conventional casting	Conventional casting	Conventional casting	Conventional casting	Conventional + covering die	Conventional casting	Conventional casting, tixocast. and T6
Base material	Al-17Si	Al-25Si	Al-17SI	Al-18Si-2.5Cu-0.6Fe	Al-18Si-2.5Cu-0.6Fe	Al-22Si	Al-15.3–15.9Si
Alloying/reinforcing element	Er	Er	-	-	-	-	-
Amount of addition [wt.%]	0–1%	0–1%	-	-	-	-	-
Primary Si size before refinement [µm]	35.61	95.62	360	21.2	13.4	101.5	121
Primary Si size after refinement [µm]	Al17Si + 0.3Er 28.34	Al25Si + 0.05Er 42.31 Al25Si + 0.3Er 52.31	-	-	7.5	-	11.6–11.8
Hardness [HV]	-	-	130	78	85–125	94.38–98.57	as-cast 120.67–145.41 T6 treated 163.45–192.5
Tensile strength/ UTS [MPa]	-	-		114	165–240	-	-
Elongation [%]	-	-	-		-	-	-
Reference	[53]	[53]	[37]	[44]	[46]	[46]	[21]
Fabrication method	Conventional casting, lost foam and T6	Conventional casting, squeeze casting and T6	Conventional casting, tixo and T6	Conventional casting	Conventional casting	Conventional casting + ems	Conventional casting
Base material	Al-15.9–16.1Si	Al-15.9–19.85Si	Al-15.3–15.9Si	Al-18.7Si	Al-16Si	Al-16Si	Al-30Si
Alloying/reinforcing element	-	-	-	Ca	CeO_2	CeO_2	Al-3P; Al-10Sr
Amount of addition [wt.%]	-	-	-	4.5%	0.2%	0.2%	0–1.5%; 0.7–2%
Primary Si size before refinement [µm]	121	121	-	24.5	152	120	203.8
Primary Si size after refinement [µm]	29.1	15.1	-	20.3–54.7	98	76	32.5–58.7
Hardness [HV]	as-cast 91–120.67 T6 treated 192.5–207.5	as-cast 91.25–120.67 T6 treated 142.7–192.5	as-cast 120.67–145.41 T6 treated 179.52–197.5	-	104.17–126	124–129	
Tensile strength/ UTS [MPa]	-	-	-	127–162.5	107–128	119–139	45–130
Elongation [%]	-	-	-	0.75–3.4	2.2–3.4	2.4–4.5	

Table 1 (continued)

Reference	[16]	[81]	[57]	[20]	[55]	[64]	[15]
Fabrication method	Gravity casting	Cooling slope casting and tixoforming	Centrifugal casting and T6	Centrifugal casting and HT	Centrifugal casting	Stir casting	Stir casting
Base material	Al17.5Si	Al16.83Si	Al-18Si	Al-18Si	Al-17Si	Al-17.4Si	Al-17.4Si
Alloying/reinforcing element	-	-	-	SiC	-	Sillimanite and/or (Sn and/or Gr	Sillimanite, ilmenite and/or Sn and/or Gr
Amount of addition [wt.%]	-	-	-	17.2vol.%	-	10; 0.5–1; 0.5–1	5; 5; 0.5–1; 0.5–1
Primary Si size before refinement [µm]	Ø25.88	-	-	-	-	104	-
Primary Si size after refinement [µm]	-		-	-	-	49.72	-
Hardness [HV]	60	as-cast 68–92 tixocasted 86–147	as-cast 101.15–124.3 T6 treated 106.25–130.38	Al18Si 129–227	150–260	172–200	95–202.5
Tensile strength/ UTS [MPa]	115.67		-	-	-	-	-
Elongation [%]	1.96	-	-	-	-	-	-
Reference	[65]	[25]	[61]	[61]	[61]	[63]	[21]
Fabrication method	Stir casting	Stir casting	Stir casting and HT	Stir casting and HT	Stir casting and HT	Stir casting	Stir casting
Base material	Al-17.4Si	Al-24Si	Al-16Si	Al-20Si	Al-24Si	Al-16Si	Al-22Si
Alloying/reinforcing element	Sr or Sb	Si-3P, Si-25Mn-10P and Al-10Si-2Fe-3P	-	-	-	Ti and/or Sr and graphene	graphene
Amount of addition [wt.%]	-	1.2%; 0.35%	-	-	-	0.05%; 5%	0.25–1%
Primary Si size before refinement [µm]	67	200	18	26	39.5	-	67
Primary Si size after refinement [µm]	12 for Sr 24 for Sb	18–42	14.5	22.5	34.5	-	51–68
Hardness [HV]	-	-	51.5–72	58–76	61–80	99.253–111.91	67–75
Tensile strength/ UTS [MPa]	-	-	-	-	-	164–197	
Elongation [%]	-	-	-	-	-	1.6–3.4	
Reference	[67]	[82]	[83]	[66]	[74]	[75]	
Fabrication method	Stir casting vortex technique	Stir cast, and HT: T4, T6	Stir casting and T6	Stir casting	Rheo-squeeze cast	Rheo-squeeze cast	
Base material	Al-17Si	Al-17.74Si	Al-17Si	Al-18Si	Al-17Si	Al-20Si	
Alloying/reinforcing element	Copper coated Gr and short Carbon fibers (cf)	Ilmenite, Sn and Gr	Mg	Al-3P	TiB_2	TiB_2	

Table 1 (continued)

Amount of addition [wt.%]	2%; 2%	10; 0.5; 0.5	0.5–10%	0.02–0.04	0–6	0–6
Primary Si size before refinement [µm]	10-30 µm Gr and 1:1000 at a content of 2% short cf	-	0.5 Mg: Si 190.876	160	50	50.6
Primary Si size after refinement [µm]	-	-	6%Mg: Si 145.1 Mg_2Si 88.31 10%Mg: Mg2Si: 95.38	28–83	24.5–40.4	24.5
Hardness [HV]	base alloy 120 composite 122–139	base alloy 130 composites 170 Composite T4,T6 360–450	as-cast 116–131 heat treated 139–163	-	-	-
Tensile strength/ UTS [MPa]	base alloy 144 composite 149–169	-		-	173.4–283.3	110–215.7
Elongation [%]					0.97–1.62	2.3–4.2

modificators are present size of primary Si particles is decreased significantly, in this case the higher hardness might be due to fact that some of them form intermetalic compound which also affects properties of materials. Tensile strength also depends on Si content and size of particles, higher amount of Si and refined particles can increase tensile strength. Another important factor is heat treatment which can significantly increase hardness and reduce grain size of hypereutectic Al-Si alloys and composites.

From Table 1 it can be observed that the highest value of hardness was for composite with Al-17.74Si base and addition of 10%Ilmenite, 0.5%Sn and 0.5%Gr [82], which should be more investigated. HPDC obtained alloy had fine size of primary Si and eutectic Si and high hardness in hypereutectic Al-Si alloys [51]. Centrifugal casting and stir casting gave good distribution and refinement of particles in hypereutectic Al-SI alloys. Conventional casting processes like gravity casting, centrifugal casting and stir casting are mainly used for hypereutectic Al-Si alloy. Their high prevalence in manufacturing of the hypereutectic Al-Si alloys especially of conventional casting, stir and centrifugal casting is because of their low cost, flexibility of the process and material, and reusable moulds. Main disadvantages of gravity casting is that without grain refiners or heat treatment refinement of the primary Si is possible only with pouring temperatures, and there is no way to influence on distribution of particles of composites. In centrifugal and stir casting influence on refinement and distribution of particles can be done with changes in process parameters like pouring temperature, rotational speed of mould or stirrer respectively, but their disadvantages are reflected in poor wetability, porosity,reactions between base material and additions and difficulty to obtain homogenous structure. SLM process gives well refined Si particles, good wear resistance and hardness can be achieved. Main drawback of the SLM process is high reflectivity and oxidation sensitivity of the materials. Tixocasting can be used in mass production of hypereutectic Al-Si, and with its use the weight of parts is reduced, but for now this type of production has high cost (more than 2 times higher than that of a cast iron) [76].

3 Tribological Properties

Tribological properties are influenced by a great number of factors, from fabrication process, presence of reinforcement, amount and size of reinforcement to the testing conditions, which makes comparison of the reviewed studies a lot more difficult. In the Table 2 a review of tribological properties of the Al-Si alloys and composites is shown. A review in the Table 2 was done through fabrication method, base material, type of reinforcement as well as its size and amount, contact

Table 2 Tribological properties of hypereutectic Al-Si alloys and composites with influencing factors

Reference	[37]	[53]	[11]	[40]	[41]
Fabrication method	Conventional casting, tixo and T6	Conventional casting, lost foam, squeeze casting, tixocasting and T6	Conventional casting	Conventional and rheocasting	Spray-deposition and conventional casting
Base material	Al-15-16Si	Al-15.3–19.85Si	Al-17Si and Al-25Si	Al-17Si	Al-20Si
Reinforcement		P	Er	-	-
Amount of reinforcement/ refiner/ modifier		-	0–1%	-	-
Size of reinforcement			-	-	-
Contact geometry	Pin-on-disc	Pin-on-disc	Pin on disc MG-2000	Pin on flat reciprocating motion	Pin on disc
Counter body material			-	Stainless steel and cast iron	quenched and tempered T8 tool steel 64HRC
Testing conditions	Dry	Dry	-	Dry	Dry
Load [N]	46.51	46.51	10	10–40	8.9–35.6
Sliding speed [m/s]	0.089–0.356	0.089–0.356	-	-	0.48
Slid. distance or time	2000 m	2000 m	500 m	50 m, 30 min	1700 m
CoF	0.45	0.47	Al-17Si + Er 0.11–0.24 Al-25Si + Er 0.17–0.31	-	-
Wear [$\times 10^{-3}$mm^3/m]	as-cast 0.319–1.72 T6 treated 0.355–1.95	as-cast 0.266–1.7 T6 treated 0.412–1.95	Al-17Si 1.357–6.786 Al-25Si 0.814–1.493	as-cast 5.72–13.74 rheo 400 rpm 2.09–5.91 rheo cast 800 rpm 3.43–8.397	as-cast 1.679–3.741 spray-dep. alloy 1.07–3.244
Reference	[47]	[84]	[85]	[35]	[16]
Fabrication method	Conventional + coverging die casting	Conventional sand casting	Conventional casting	Gravity casting	Gravity and Squeeze Casting
Base material	Al-18Si-2.5Cu-0.6Fe	Al-18.5Si	Al-18Si	Al-21.6Si	Al-15-22Si
Type of reinforcement	-	-	Fe, Ni, Cr	-	-
Amount of reinforcement	-	-	5%; 0.6%; 1.2%	-	-
Size of reinforcement	-	-		-	-
Contact geometry	Pin-on-disc	Pin-on-disc	Pin-on-disc	Ball-on-disc	Pin-on-disc
Counter-body material	stainless steel 63HRC		-	-	45# steel ring
Lubrication	Dry	Lubricated SAE5W-30 oil	Dry	Dry	-
Load [N]	10–30	0.5	20	14	70
Sliding/rotating speed [m/s]	1.256	0.05 m/s	0.64		200 rpm (0.06 m)
Slid. distance or time	2260 m	6×10^5 cycles	200-4600 m	1000 m	1800s (30 min)
CoF	-	-	Al-18SI 0.28–0.38 Al-18SiFeNiCr 0.3–0.375	0.42	-

Table 2 (continued)

Wear [× 10^{-3}mm^3/m]	as-cast 1.98–3 compressed at 300 °C 1.7–2.2 compressed at 400 °C 1.35–1.75 compressed at 500 °C 1.8–2.25	no measurable mass loss	Al-18SI 3.81 Al-18Si-5Fe 4.198 Al-18Si-5Fe-0.6Ni 8.38 Al-18Si-5Fe-0.6Ni-0.6Cr 4.96	0.0105-mild wear	grav.cast Al-15Si 27.34 Al-17.5Si 7.404 Al-22Si 5.725 squ.cast Al-15Si 7.139 Al-17Si 2.63 Al-22Si 2.485
Reference	[86]	[67]	[29]	[64]	[82]
Fabrication method	Centrifugal casting	Stir casting	Stir Casting	Stir casting	Stir casting, T4 and T6
Base material	A390	Al-17Si	Al-18Si Al-18Si + 1.2Fe Al-18SI + 1.2FeMn Al-18Si + 1.2FeMn-SM	Al-17.4Si	Al-17.74Si
Reinforcement	Mg	Copper coated Gr and short Carbon fibers	-	Sillimanite and/or Sn and/or Gr	Ilmenite, Sn and Gr
Amount of reinforcement [wt.%]	2-4vol.%	2%	-	10%; 0.5–1%; 0.5–1% respectively	0–10%; 0–0.5%; 0–0.5%
Size of reinforcement	-	10-30 μm Gr and 1:1000 at a content of 2% short cf[a]	-		
Contact geometry	Pin-on-disc	Pin-on-disc	Pin-on-disc	Pin-on-disc	Pin-on-disc
Counter body material	hardened EN 31 steel	Hardened steel disc of R_C60	Steel disc (62-65HRC)	EN31 steel disk 832 HV	EN31 die steel; 831 HV
Testing conditions	Dry	Dry	Dry	Dry	Dry
Load [N]	9.81–39.23	10–50	18, 51, 74,100	9.81–68.67	9.81–68.67
Sliding speed [m/s]	0.6 m/s	0.3–1.2	0.3	1.6	1.6
Slid. distance or time	500 m, ≈13 min	1800s	1000 m	3000 m	32 min/3000 m
CoF	-	Al-17Si 0.65–0.8 Al-17Si-2%Gr 0.5–0.7 Al-17Si-2%cf 0.45–0.65 Al-17Si-2%Gr-2%cf 0.4–0.5	-	base alloy 0.54–0.72 composites 0.26–0.66	as cast 0.54–0.61 composite 0.25–0.42
Wear [× 10^{-3}mm^3/m]	A390 0.8088–2.4265 A390 + 2%Mg 0.7406–1.8516 A390 + 4%Mg 0.5222–2.3874	Al-17Si alloy 1.7–10.5 Al-17Si-2%Gr 1.45–9.25 Al-17Si 2%cf 1.3–7.75 Al-17Si-2%Gr-2%cf 1.15–7.3	Al-18Si 1.8–5.5 Al-18Si + 1.2Fe 2–6.3 Al-18Si + 1.2FeMn 1.75–5.45 Al-18Si + 1.2FeMn-SM[a] 1.5–5	base alloy 4.5–13 composites 2–11.5	as cast 5–14 composite 4–12 as-cast T4,T6 4–13 composite T4,T6 2.5–9.5

Table 2 (continued)

[a]SM-Surface Melting
[b]short Carbon fibers

Reference	[27]	[87]	[45]	[88]	[15]
Fabrication method	Stir casting	Stir casting	Stir casting	Stir casting	stir casting
Base material	Al-15Si Modified/refined with 0.04Sr or/and 0.04P and/or Al-1Ti-3B and/or Al-5Ti-1B	Al-15Si Modified/refined with 0.04Sr or/and 0.04P and/or Al-1Ti-3B and/or Al-5Ti-1B	Al-20Si with 0.3wt.%Nd	Al-15.7Si	Al-17.4Si
Reinforcement	-	-	-	Mg	Sillimanite, Ilmenite and/or Sn and/or Gr
Amount of reinforcement [wt.%]	-	-	-	2.5–4.5%	5%; 5%; 0.5–1%; 0.5–1%
Size of reinforcement [µm]	-	-	-		37.25; 37,74
Contact geometry	Pin on disc	Pin on disc	Pin on disc	Pin on disc	Pin-on-disc
Counter body material	hardened steel disc	hardened steel disc EN-31	Stainless steel 192 HV		EN31 steel disk 832 HV
Testing conditions	Dry	Dry	Dry		Dry
Load [N]	20–100	40	10–30	4.9–19.6	9.81–68.67
Sliding speed[m/s]	1	1–3	0.8	2.5- 9	1.6
Slid.distance or time	1000 m	1000 m	500 m	10–40 min	3000 m
CoF	P1^a: 0.35–0.425 P2^b: 0.33–0.39 P3^c: 0.325–0.38 P4^d: 0.325–0.375 P5^e: 0.31–0.35 P6^f: 0.3–0.34	P1^a: 0.344–0.359 P2^b: 0.335–0.343 P3^c: 0.324–0.334 P4^d: 0.32–0.326 P5^e: 0.313–0.315 P6^f: 0.31–0.313	Al-20Si 0.28–0.43 Al-20Si-0.3Nd 0.19–0.32	-	
Wear [$\times 10^{-3}$mm^3/m]	P1^a: 2.6–12.5 P2$_b$: 2.4–10 P3$_c$: 2.3–9.25 P4^d: 2.1–8.25 P5^e: 1.3–6.25 P6^f: 1.63–7.5	P1^a: 4–4.95 P2^b: 2.5–3.8 P3^c: 2.4–3.5 P4^d: 2.2–3.1 P5^e: 1.4–2.35 P6^f: 1.6–2.6	Al-20Si 1.908–13.7 Al-20Si-0.3Nd 0.758–9.874	Al-18Si 2.78–7.04 Al-18Si-2.5 Mg 3.74–8.04 Al-18Si-3.5 Mg 6.0–9.01 Al-18Si-4.5 Mg 7.91–11.29	base alloy 4.2–13.2 composites 1.5–10

[a] P1 = Al15Si4Cu
[b] P2 = Al15Si4Cu0.04Sr
[c] P3 = Al15Si4Cu0.04P
[d] P4 = Al15Si4Cu0.04Sr0.04P
[e] P5 = Al15Si4Cu0.04Sr0.04P1M13; M13 = Al-1Ti-3B[f] P6 = Al15Si4Cu0.04Sr0.04P1M51; M51 = Al-5Ti1B

Reference	[83]	[62]	[78]	[79]	[19]	[7]
Fabrication method	Stir casting and T6	Stir casting	Selective laser melting	Selective laser melting	Selective laser melting	Electron beam melting
Base material	Al-16.7Si	Al-17Si	Al-18Si and Al-50Si	Al-18Si and Al-50Si	Al-18Si (16-22Si)	Al-16-18Si
Reinforcement	Mg	Mn	-	-	-	-
Amount of reinforcement [wt.%]	0.5–10%	0–1.5%	-	-	-	-
Size of reinforcement [µm]	-	-	-	-	-	-
Contact geometry	-	Pin-on-disc	Ball on disc	Ball on disc	Ball on disc	Ball on disc Reciprocating motion

Table 2 (continued)

Counter body material	-	-	Al_2O_3	Al_2O_3	Al_2O_3	52,100 steel ball
Testing conditions	Abrasive wear	Dry	Dry	Dry	Dry	Dry
Load [N]	130	40–60	-	5	2	5
Sliding speed [m/s]	300 rpm	0.628–1.047	-	0.02 m/s	0.03 m/s	-
Slid. distance or time	215.4 m	5 min	50 m	125 m 10,000 loops	≈80 m 5000 laps	6 m
CoF	-	-	Al-18Si 0.4 Al-50Si 0.4–0.5	Al-50Si 0.48–0.51	Al-18Si ≈0.46	Machined Al–Si 0.64 16.5–36 kV EBM-treated Al–Si 0.93
Wear [× 10^{-3}mm^3/m]	as-cast 0.278–0.344 T6 treated 0.259–0.301	as-cast 2–26.5 modified 1.7–19.5	Al-18Si 3.25 Al-50Si 4.05	Al-18Si 3.9 Al-50Si (275 W) 4.0 Al-50Si (320 W) 4.15 Al-50Si (350 W) 2.75	Al-18Si (160 W) 1.8 Al-18Si (195 W) 1.5 Al-18Si (210 W) 1.4 Al-18Si (225 W) 3.2	Machined Al–Si 14.5 16.5 kV EBM 13.75 30 kV EBM 5.25 36 kV EBM 7

geometry of the testing apparatus, counter body material, testing conditions and testing parameters.

From the Table 2 it can be observed that there is no large amount of papers in which were investigated tribological properties of hypereutectic Al-Si composites,ost of reviewed papers from Table 2 are of hypereutectic Al-Si alloys. Tribological tests were, mostly, done in dry sliding conditions on the apparatus with pin-on-disc contact geometry (conformal contact), and then followed with ball on disc and pin on piston, some of the apparatuses were even self made. For most of the investigations, the environmental conditions, such as: humidity, temperature, etc., were not stated, it is assumed that investigations were done at room temperature with standard humidity.

3.1 Coefficient of Friction (CoF)

In studies of hypereutectic Al-Si alloys and composites mainly were investigated microstructure, mechanical properties and wear rate; very few of them investigated coefficient of friction. The lack of these investigations is the reason why tribological behavior of Al-Si hypereutectic alloys and composites can't be understood properly. What can be observed from Table 2 is that most of coefficients of friction in dry sliding conditions were in range 0.20–0.5, the lowest CoF, 0.11–0.15, was obtained for Al-17Si modified with 0.3%Er [11]. The highest CoF was obtained for specimens treated with electron beam melting (16.5–36 kV) [7] and it was in average 0.93, which was higher than in machined alloy. This phenomenon is due to adhesion of the aluminum to the steel ball, which resulted in higher friction energy and oxidation. During the testing, depending of the investigation, influence of different parameters was observed, such as sliding speed, distance and load. Increase of sliding speed leads to decrease and increase in CoF, for example in [87] CoF decreases for all samples from 1 m/s until the sliding speed of 1.5 m/s where it slightly rises until sliding speed 2 m/s, then it decreases again. Another example is in [67] were for all samples CoF increases from 0.25–0.5 m/s, then decreases from 0.5–0.9 m/s, and then increases again from 0.9–1.2 m/s and is in the area of ≈0.28–0.61. In Table 2 for [67] is shown only influence of load on CoF, and for all samples CoF decreases from 10–30 N and then from 30–50 N increases. Addition of 2%Gr in the base alloy lowered the CoF, and with the addition of 2% of carbon fibers the CoF was even lower, but the lowest CoF was obtained for addition of both 2%Gr and 2% of carbon fibers and it was in the range of ≈0.4–0.5. In [27] CoF increases slightly with the increase of load for all samples. Influence of microstructure on CoF is high, Addition of reinforcements, modifiers and grain refinement [11, 28, 59, 62, 76] to hypereutectic Al-Si alloys leads to fine and uniformly distributed silicon particles and additional increase in hardness. General observation is that increase in hardness results in lower CoF. For SLM treated specimens (Al-18Si and A50Si) microstructure had no important influence on CoF, because all specimens had fine microstructure, and for these specimens CoF ranges from 0.4–0.5 [34, 35]. CoF is, in most of the cases more or less constant, and in unlubricated conditions it didn't depend on load and sliding speed which is in correspondence with classical theory for metals in unlubricated sliding conditions.

3.2 Wear

In investigations of tribological properties of hypereutectic Al-Si alloys and composites were mainly investigated wear rate, wear loss, volumetric wear rate, etc. In general wear rate is influenced by hardness of the specimen, and with the increase of hardness wear rate is lower i.e. wear resistance is higher. Load and sliding speed also have influence on the wear rate, with the increase of load wear rate increases, and with the increase of sliding speed wear rate reduces. The most interesting paper is [84] where no measurable mass loss was detected, which is probably due to low load and lubricated testing conditions. The effect of slurry and mould temperature on wear rate for centrifugal casting of hypereutectic Al-Si alloy is notable [20]. The lowest average (piston head, skirt and piston end) wear rate was for 800/500 °C, but when observed hardness and wear rate at piston end and piston head the lowest wear rate was for 850/600 °C. In the area most influenced by centrifugal force, there is the highest concentration of uniformly distributed SiC particles resulting in higher hardness and wear resistance. T6 treatments of specimens result in increasement of hardness and decrease in wear rate. For centrifugally casted hypereutectic composites reinforced with SiC, Cu and Mg, the lowest wear rate was for A390 + 4vol.%Mg [86]. This is due to the fact that with the addition of Mg there is formation of Mg_2Si particles which leads to the higher hardness. From all of stir casted aluminum alloys and composites the lowest wear rate had aluminum composite with 2% of Gr and 2% of carbon fibers [67]. Microstructure, hardness and wear rate in squeeze casted alloys [16] were improved when compared to gravity casted alloys. Mechanical and tribological properties of conventionally casted alloys can be improved with the addditon of small amounts of Er. Addition of 0.05 and 0.3% of Er in Al-17Si and Al-25Si alloys results in refinement of Si particles for both alloys. Influence of Er addition on microstructure and wear rate of Al-17Si is higher than in Al-25Si, but due to high amount of Si in the alloy and refined Si particles Al-25Si-0.05Er has the lowest wear rate [11]. Lower wear rate was obtained for tixocasted and squeeze casted specimens, when compared to conventionally casted and gravity casted specimens, in [16, 37, 53]. From new fabrication methods SLM method gives good results in terms of microstructure, CoF and wear rate. Wear rate for specimens obtained with this process doesn't increase rapidly like in the case of conventionally casted hypereutectic Al-Si alloys. Addition of sillimanite, Ilmenite, Sn and Gr with combination of T6 heat treatment result in high hardness and low wear rate for load of 9.81 N ($\approx 1 \times 10^{-3}$ mm^3/m) [82].

4 Future Development

Hypereutectic Al-Si alloys and composites are new materials that are just making their way to the automotive industry. There are some hypereutectic Al-Si alloys already in use, but that is small amount [17]. The main problem with these alloys is that in most cases they can't be used without modifier/refiner, due to Si particles coarsening and agglomeration with higher Si amount. Liquid state metallurgy gives products of lower cost but they don't always have fine microstructure and good distribution of particles. Semi-solid and solid state processes are newer and they are receiving a lot of attention as alternatives for liquid state processes, due to the fact that uniform microstructure with finer, small sized Si particle can be obtained. The future development of piston alloys lies in semi-solid and solid state processes. The drawback is cost of production, but with their use the weight of parts and manufacturing time can be reduced and energy savings can be achieved. These processes need to be more investigated in terms of cost reduction and finding the best combination of manufacturing parameters, and after that software should be employed by which simulation of working conditions for the pistons and other automotive parts would be carried on. After numerical tests the pistons and other automotive parts of hypereutectic Al-Si alloys prototypes should be made for the real testing conditions, so it can be observed how materials would behave in the working environment. Another research direction should be of hypereutectic alloys and composites with 20–35%Si, due to lack of investigation of these alloys. Some automotive parts like pistons have reciprocal linear motion; the tribological behaviour under this type motion should be more investigated.

5 Conclusions

A brief overview of the production technologies of hypereutectic Al-Si alloys is given in this paper, and how it affects their microstructure, size of primary Si and tribological properties. There are many fabrication methods for hypereutectic Al-Si alloys and composites, and they all have their advantages and disadvantages. The biggest disadvantage that some fabrication method can have is complexity of the process and its price. Centrifugal and stir casting are, after gravity and conventional casting, mostly used fabrication methods for hypereutectic Al-Si alloys.

They are very easy and flexible method, and with different slurry temperatures, mould temperatures and mould/stirer rotation speed, materials of different properties can be obtained. What can be concluded is the following:

- higher amount of Si leads to increase in size of primary Si and increase of hardness for all fabrication methods,
- when compared to conventional casting stir casted and centrifugal casted samples gave better microstructure,
- tixocasted and rheocasted samples have even better refinement and shape of primary Si particles,
- laser melting had the lowest size of primary Si but the process is complex and very costly,
- heat treatments lead to decrease in size of primary Si, thus modification of the material
- addition of right amount of reinforcement/modifier/refiner can change material properties.
- with addition of reinforcement/modifier/refiner hardness increases resulting in lower CoF and wear rate.

When relating to the microstructure, mechanical and tribological properties, for different fabrication methods and testing parameters, presented in this paper, all fabrication methods give satisfactory results depending of the purpose of the fabricated material. However, in terms of cost effectiveness and flexibility of process it is still better to choose stir casting or centrifugal casting.

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Data Availability Not applicable.

Declarations

Consent to Participate All authors have agreed to participate in this manuscript.

Consent for Publication All authors have agreed with the content and gave consent to submit this paper, including the names and order of authors.

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