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# A review of hypereutectic aluminum piston materials

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**Abstract.** Demands of today's automotive industry are increasing; there is a constant tendency of weight reduction and higher reliability of constructions. Pistons and piston liners for vehicles are mostly manufactured from aluminum-silicon alloys. With different manufacturing methods and/or the addition of some chemical elements, base alloy properties can be modified. Methods for hypereutectic aluminum alloys and composites manufacturing and their influence on material properties will be given in this paper. The influence of Si percentage in base alloy and how an addition of some chemical elements affects the properties of these materials will be observed as well.

## 1. Introduction

Expansion of automobile industry and industry in general, has created a need to use light weight materials, especially metals. Mostly used light weight metals in vehicles are steel, aluminum, magnesium, plastics and different types of composites. Use of light weight materials in vehicles has a great importance due to their influence on environment and economy. The most widely used lightweight materials in vehicles are aluminum and its alloys. Some useful properties of aluminum are good heat and electrical conductivity, light weight (only one third of the density of steel), corrosion and wear resistance, high recyclability, good castability and weldability [1].

Usage of aluminum and its alloys is increasing every year. In 2006 there was estimation, in [2], of how much the consumption of aluminum is going to increase globally. In figure 1 is represented aluminium percentual usage for every sector in year 2020, where can be observed that aluminum was mostly used for construction, followed by automotive and transportation, foil and packaging, etc.

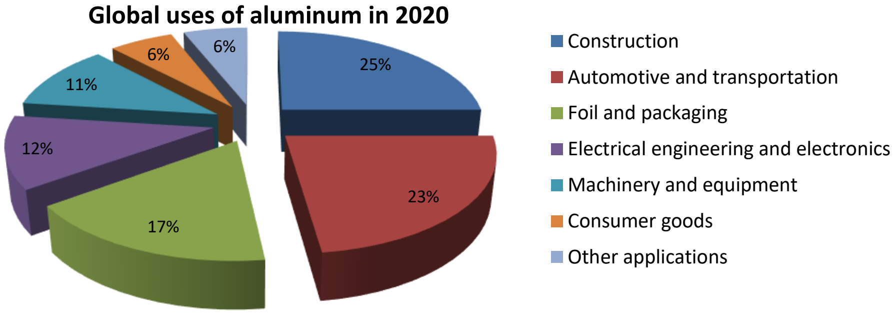

**Figure 1.** Major global use for different sectors in year 2020. [3]

Aluminum and its alloy in vehicles are used for: powertrain, chassis and suspension and car body. In power trains aluminum is used for engine parts (pistons, engine blocks, cylinder heads), fuel system and liquid lines; in chassis aluminum is used for cradle, axis wheels and suspension components; and in car body is used for hoods, bumper, interiors, doors, etc. [4, 5]. On figure 2 are illustrated car parts made of aluminum and its alloys.

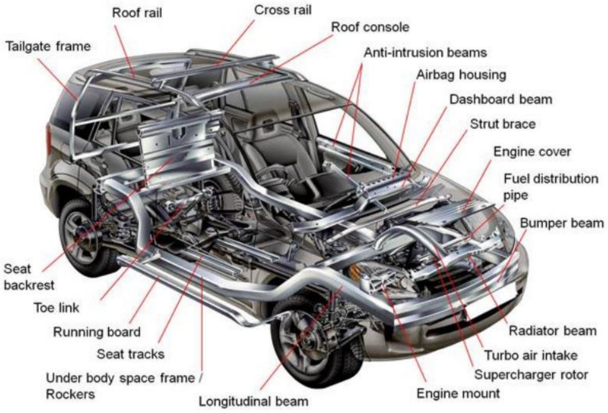

**Figure 2.** Car body parts made of aluminum and its alloys [6]

One of aluminum alloys that is used mostly for engine parts, especially pistons, due to their high wear and corrosion resistance, good thermal conductivity and low thermal expansion and small specific gravity [5,7, 8] are hypereutectic aluminum alloys. The mentioned properties depend on the microstructure of hypereutectic aluminum alloys, dendrite cell size, morphology and distribution of primary and eutectic silicon particles. Primary silicon morphology depends of conditions during solidification, alloying elements and chemical composition, and it can induce lower wear resistance, and also negatively affect the machinability and mechanical properties of these alloys. Some of the techniques by which this can be mitigated i.e. which can refine primary and eutectic silicon particles in hypereutectic aluminum alloys are given in [9]. The application of electric current on the cast microstructure of Al-13wt%Si (Al13Si) and Al-20wt%Si (Al20Si) was investigated. It was observed that after electric current application during solidification of Al13Si and Al20Si, for all cases except for bottom of Al20Si, there was reduction of the average dendrite cell size. Size of largest primary silicon particles wasn't changed but there was an increase in amount of primary silicon particles of a smaller size in the Al20Si. The electric current didn't cause any changes in Al13Si. Properties of hypereutectic aluminum alloys can be changed by addition of modifiers like Phosphorus, Erbium, Cobalt, Magnesium, Strontium, etc, and/or refiners like Al-1Ti-3B. Modifiers are added to the alloy in purpose of refinement of Si particles (primary and eutectic) as well as better and more homogenous distribution of particles. In case that there is iron present in the alloy it acts like impurity reducing wear rate, but with addition of Manganese it is possible to null the effect of iron on the alloy and increase wear rate [10-14]. As a modifier in hypereutectic alloys was even used Calcium in [15]. Addition of Calcium resulted in refinement of primary silicon particles and enhancement of mechanical properties especially elongation. In further enhancement of hypereutectic aluminum alloys, it is possible to add reinforcement to them and by it creating composite. As reinforcements for composites with aluminum base are most commonly used alumina, silicon carbide, basalt, glass fibre, carbon fibre and even biomaterials such as bamboo fibres [16]. There aren't a large number of investigations of hypereutectic aluminum composites, because these materials are new, but in recent years there have been some investigations.

In this paper the manufacturing methods and mechanical characteristics of hypereutectic aluminum alloys and composites will be reviewed.

## 2. Methods for manufacturing of hypereutectic aluminum alloys

Aluminum alloys and composites, in general, can be manufactured by liquid state processing, semi-solid processing and solid state processes. Liquid state processing are different types of casting such as gravity casting, stir casting, squeeze casting, ultrasonic assisted casting and others. Semi-solid process is newer manufacturing method which includes rheocasting and tixocasting, while solid process includes powder metallurgy processing, friction stir processing, diffusion bonding and sintering [17,18].

Hypereutectic alloys and composites are, usually, manufactured by gravity casting. Nowadays most of these materials are manufactured by centrifugal casting. Next to the gravity casting and centrifugal casting manufacturing methods for hypereutectic aluminum alloys are: stir casting, pressure die casting, tixocasting, rheocasting and some very new methods like selective laser melting, electron beam melting and spray-deposition.

### *2.1Gravity casting*

Gravity casting or just conventional casting, is one of the oldest processes which includes melting of the material and if needed (depending of the material which is being manufactured) addition of refinement/modifier/reinforcement, and pouring the melt into the mould. The name is given because the pouring into the mould is done with the influence of gravity without any pressure. In [15] was investigated influence of calcium addition on B390 alloy with the chemical composition Al–18.7Si-4.0Cu–0.56Mg–0.68Zn–0.13Mn–1.0Fe (wt%) produced by gravity casting. The alloy was melt and held at 750°C and treated with Titanium chloride (Ti2Cl6) for modification, and after 30 min the melt was poured into mould. Al4.5wt%Ca and AlCuP were added to the base alloy as well, and after observing mechanical properties, it can be seen that with decrease in Calcium content, the tensile strength increases as well as elongation, while the size of primary silicon increases. Minimum size of primary Si was 20.3µm. In [11] Al–30Si alloys were melted and degassed with $C_2Cl_6$ for 15 min, and the modification treatment was carried out with the addition of Al–3P and Al–10Sr master alloys at different temperatures (770 °C, 1000°C and 1300°C). It was concluded that with addition of P and Sr there was refinement of Si particles and tensile strength was increased. In [19] the mechanical properties of hypereutectic Al17.5Si (Al–17.5Si–4.5Cu–1Zn–0.7Mg–0.5Ni) alloy were investigated. Specimens of hypereutectic alloy were hot deformed and aged for 4–16h at temperatures of 120, 150 and 180°C. For specimen aged at 120°C there was no significant difference in ultimate tensile strength when aging time increased from 4 to 16h. When aging time at temperature at 180°C increased the ultimate tensile strength decreased. The best results gave the specimen aged at 150°C, where with the increase of aging time ultimate tensile strength increased and was highest for aging time of 16h (396 MPa).

### *2.2Stir casting*

Stir casting is a process where melt is stirred continuously and then pouring into the mould. In the production of composites there is also degassing and the reinforcement addition during the stirring of the melt. Degassing is applied due to oxidation during the stirring which adversely affects properties of base material [20]. In [21] Al17Si hypereutectic aluminum alloy was reinforced with 2wt% graphite and/or 2 wt% carbon fibers and produced as-cast (only matrix alloy) and stir casted by vortex method. [22] Vortex method includes stirring of the melt at high speed to form vortex and then adding reinforcement at the side of the vortex. Highest ultimate tensile strength and hardness are observed for the hybrid composite [21]. Another hypereutectic AlSi composite, with base of Al22Si alloy, reinforced with graphene (0.25 and 1%), is manufactured by stir casting by vortex method in [23]. Hardness of specimens was measured at edge and center of the casted cylinders. The highest hardness was for composite with 0.25% of grapheme nanosheets, followed by composite with 1% of grapheme nanosheets and stir casted base alloy. Characteristics of stir casted A390 alloy (Al17Si) with the addition of Mg were compared before and after T6 treatment in [24]. Amount of Mg in the alloy was 0.5-10%. Hardness of untreated samples increased with the addition of Mg gradually, but was lower than hardness of samples that were T6 treated. For T6 treated samples highest hardness was for alloy with 0.5%Mg, and the lowest for alloy with 5%Mg, which means that even if hardness increases with Mg for untreated samples after T6 that is not the case.

### *2.3Centrifugal casting*

Centrifugal casting of materials is casting where the mould cavities are filled with the influence of centrifugal force that pushes molten metal to the walls of the mould. This type of casting is usually used for rings, hollow cylinders and other hollow parts [25]. Centrifugally casted hypereutectic alloys Al18Si reinforced at the piston head with SiC were investigated in [26]. During the material manufacturing two different slurry and mould temperatures (850, 800°C and 600, 500°C respectively) were applied at the constant rotational speed of the mould of 800rpm. All the results were compared to Mahle piston (17-19wt%Si). The highest hardness value had the piston obtained with combination of slurry/mould temperatures 850/600°C respectively at the piston head. A variation of centrifugal casting is centrifuge casting which means that there is rotating arm centrally mounted on motor shaft, and on one side of rotating arm is mould and on the other is counterweight. Manufacturing of Al18Si alloy by centrifuge casting was done in [27], and during the manufacturing pouring temperatures were varied (750 and 850°C) while arm rotational speed was constantly 200 rpm. With increase of pouring temperature the microstructure is better and due to centrifugal force there is higher primary silicon content at top region of specimen, providing better mechanical characteristics.

### *2.4Other manufacturing processes*

Squeeze casting is a form of liquid state processing that includes application of pressure during solidification of casted material in the mould [28]. Squeeze casted Al 15-22Si alloys were compared to the gravity casted ones and the squeezed casted samples had higher hardness and ultimate tensile strength, and even better elongation. The casted alloy Al22Si had the highest hardness (≈76HV) and Al17.5Si had the highest ultimate tensile strength (153MPa) [29].

As already said, next to the liquid state processes there are semi solid state processes. First ever semi solid process that was commercialized was tixocasting. Tixocasting is a type of process where billets that are pre casted are reheated to the semi-solid casting temperature, and then the material is casted again [18]. Advantage of tixocasting is better quality of the product due to uniform globular microstructure, while some disadvantages are higher cost and the fact that scraps from production cannot be recycled [30].Tixocasted and T6 treated aluminum alloys with 15.3%Si and 15.7%Si were investigated in [31], and results were compared to casted alloy Al15.9Si. Hardness before T6 treatment was the highest for Al15.7Si (77HRB≈145.41HV), while after T6 treatment the casted alloy Al15.9Si had the highest hardness of 91HRB which was ≈197.5HV. T6 treatment didn't have a great impact on wear of the alloys. Same three alloys were compared with Al16.11Si produced by lost foam technology, Al16.2Si and Al19.85Si produced by squeeze casting and T6 treated [32]. For all alloys except casted Al15.9Si Phosphorus was used as primary Si refiner. Before T6 treatment, like in [31], hardness was the highest for Al15.7Si alloy, but after T6 treatment, hardness was the highest for alloy Al16.11Si (93HRB≈207.5HV). Observation of hardness and microstructure of A390 (Al16.83Si) alloy fabricated by cooling slope (CS) casting and tixocasting was done in [33]. CS casting is type of casting where ingot of material is melted and then cooled to the temperature slightly above liquid temperature, but in [33] this temperature was slightly under liquidus temperature. Melted alloy was then poured on the inclined steel plate leading to the mould. These ingots were used for tixocasting, and some tixocasted specimens were treated with T5 and T6 heat treatment. Even without heat treatments, tixocasted specimens had higher hardness than specimens fabricated by CS casting.

Electric pulse modification (EPM) can be applied in order to control solidification of alloys. In [34] this technology is applied during the solidification of Al13Si alloy rich with Ni. EPM was applied to the melted alloy for 30s at pulse frequency of 3Hz at different pulse voltages (0-700V). Samples without EPM had coarse primary Si and large eutectic Si unevenly distributed and a high amount of α-Al dendrites around which Ni-rich phases formed. With application of EPM to the melted Al13Si alloy with the increase in voltage the hardness increased.

Another modification of hypereutectic AlSi alloys is possible by electron beam melting of their surface. In [35] EBM is applied on A390 hypereutectic (16-18%Si) AlSi alloy. More about this process can be found in the mentioned literature. It's basically use of plasma and magnetic field to help form an electron beam that was used for surface remelting. Voltages used for EBM are from 0-36kV. With the increase in voltage the hardness increased and was the highest for AlSi alloy treated with EBM at 36kV. Solid state process-powder metalurgy fabricated Al17Si alloy and forged was investigated in [36] in the as-forged condition (AF) and after direct quenching (DQ). After DQ in water hardness of hypereutectic AlSi alloy was slightly increased.

## 3. Microstructure

Microstructure of manufactured alloys and composites influences their mechanical and tribological characteristics.

Gravity casted materials.Microstructure of gravity casted B390 alloy was noted in [15] and it consisted of: primary Si particles, eutectic Si, α dendrite, eutectic α, $Al_8Fe_2Si$ compound and $Al_5FeSi$ intermetallic compound. With the addition of Calcium of 16ppm primary Si particles were refined and well distributed in the alloy. But higher amount of Calcium leads to increase of size of primary Si particles and it affects their distribution. Gravity casted alloy Al30Si in its microstructure had coarse irregularly shaped primary Si particles (platelets and polygon of average size 203.8μm), while eutectic Si was needle shaped. With the addition of Sr the primary Si particles size decreased and eutectic Si had granular structure. With the addition of P primary Si can be refined even to 32.8μm, and Sr addition mostly modifies eutectic Si [11].In [19] microstructure of as-cast (Al17.5Si)alloy shows fine primary Si particles, α-aluminum dendrites, eutectic Si and complex intermetallic phases, and the microstructure was much finer than that of the commercial Al-Si alloy. After T6 treatment and aging at 150°C for 16h the α-aluminum dendritic structure was eliminated. In samples aged for 16h at 120°C no precipitates were observed, only some spheroidal particles were dissipated in the matrix. In samples aged at 150°C for 16h two major precipitates were observed: the rod-shaped precipitates (of size of 20 and 3nm) and lath-shaped precipitates (rectangular or circular cross section ≈2-3nm) dispersed in the matrix. With increasement of the aging time in samples aged at 180°C can be seen that with increase of aging time density of the plate-shaped precipitate decreases while their size increases.

Stir casted materials. In [22] SEM metalography showed uniform distribution of reinforcements (graphite and/or carbon fibers) in hypereutectic Al-Si base. Metalographic examination of samples obtained in [24] for as-cast material contains mainly of primary Si, eutectic Si and eutectic α. Stir casted samples with or without graphene show that stirring can affect Si particle size, shape and distribution. In samples obtained by stirring of base material the Si particles are globular and finer but not very well distributed. The better distribution and refinement of Si particles was achieved with addition of low graphene content (0.25-1wt%) which resulted in better mechanical characteristics.

Centrifugal casted materials. Microstructure of centrifugaly casted piston with hypereutectic AlSi base depends of the combination slurry/mould temperatures. In [26] in microstructure of piston obtained with slurry/mould temperature combination 800/500°C there were no zones observed. When temperatures increase there are three zones that can be distinguished: zone with a number of pores and oxides which is called the defects gathering zone, zone that doesn't contain SiC particles and impurities (mostly contains α-Al dendrite and eutectic Si) and is called the metal matrix zone and the zone where SiC particles are segregated (zone where SiC particles are well distributed in the base material and embedded in primary Si can be found SiC particles). In the last zone, the SiC segregation zone, is observed that with decrease in slurry and mould temperature there is decrease in number of SiC particles and some pores appear. Higher pouring temperature and centrifugal force influence that the distribution of Si particles is better and primary Si content is higher at the top region resulting in higher ultimate tensile strength and hardness at the top of specimen [27].

Squeeze casted materials. When compared to gravity casted samples in [29] squeeze casted samples had much finer structure, eutectic Si phase was fine, size and amount of primary Si particles was reduced and there were α-Al dendrites present in the microstructure. With increase of Si content in the alloy concentration of primary Si particles and their size were increasing while the concentration of primary α-Al dendrite decreased.

Tixocasted materials. When compared microstructure of casted alloy Al15.9Si and thixocasted alloys Al15.3Si and Al15.7Si; casted alloy Al15.9Si in its microstructure had a eutectic Al-Si phase which was very fine and some clusters of voluminous primary Si particles. Different from that the thixocasted alloys Al15.3Si and Al15.7Si had a uniform microstructure with globules of α aluminum, high amount of primary Si particles and small fraction of eutectic Si [31,32]. In [32] alloy Al15.9Si produced by ingot metallurgy had rough primary Si particles and not homogenous distribution in its microstructure. Al16.11Si produced by lost foam technology had a high amount of primary Si particles in its microstructure, and squeeze casted alloys Al16.2Si and Al19.85Si had fine microstructure. Influence of T6 treatment on observed materials resulted in some changes in their microstructure; eutectic Si was globular and tended to agglomerate, while the most intermetalic phases dissolved. Effect of microstructure like disposition of particles and their size on hardness is high. In this case hardness is affected by amount of primary Si particles and their size, as well as volumetric amount of $Al_2Cu$ particles in the alloys. Lower pouring temperature of CS casted specimens in [33] resulted in formation of primary Si particles of a small size, well dispersed and surrounded by α-Al rosettes. In the microstructure of CS casted specimens were some very small intermetalic particles present, and because of their small size they weren't identifiable. Tixoformed specimens had α-Al globules in its microstructure and between those globules were Si particles. After reheating CS casted specimens for tixocasting aluminum rosettes have started spheroidisation and coarsening. Primary Si particles have coarsened as well. Tixocasted sample had no porosity, while die casted sample had finer microstructure but porosity was present.

Casted material with applied EPM. Samples without EPM had coarse primary Si and large eutectic Si unevenly distributed and a high amount of α-Al dendrites around which Ni-rich phases formed. With the application of EPM the following changes to the microstructure of the alloy Al13Si occur: with increase of pulse voltage size of primary Si particles decreases, α-Al dendrite crystals disappear, and Ni-rich phases around α-Al are refined [34].

## 4. Mechanical properties of hypereutectic AlSi alloys and composites

There are many influential factors on mechanical properties of hypereutectic AlSi alloys and composites. In this paper was investigated how manufacturing process and composition of hypereutectic AlSi alloys and composites affects their mechanical properties and is shown in table 1.

**Table 1.** Review of mechanical properties of hypereutectic AlSi alloys and composites

| **Reference** | **[11]** | **[19]** | **[15]** | **[37]** | **[21]** |
|---|---|---|---|---|---|
| Manufacturing process | gravity casting | gravity casting, T6 and aged | gravity casting | gravity casting | stir casting |
| Base material (wt%Si) | Al30Si | Al17.5Si | B390 (Al18.7Si) | Al16.69Si | Al17Si |
| Type of reinforcement/ modificator | P and Sr | - | $Ti_2Cl_6$, Al –4.5 wt-%Ca followed by P addition of 30 ppm of the weight of the melt, using an AlCuP | - | Gr and short carbon fibers |
| Size of reinforcement | - | - | - | - | Gr: 10-30µm<br>carbon fibers: 1:1000 at 2wt% |
| Amount of reinforcement [wt%] | - | - | 0.6 | - | 2 |
| Hardness [HV] | - | - | - | 112.65 | 120-139 |
| Tensile strength/Ultimate tensile strength [MPa] | 50-135 | 282-396 | 125-162 | 250 | 144-169 |

**Table 1.**Review of mechanical properties of hypereutectic AlSi alloys and composites-continued

| **Reference** | **[23]** | **[24]** | **[26]** | **[27]** | **[31]** |
|---|---|---|---|---|---|
| Manufacturing process | stir casting | stir cast and T6 heat treatment | centrifugal casting | centrifuge casting | tixoforming and T6 |
| Base material (wt%Si) | Al22Si | A390 (Al–17Si–4.5Cu–0.5Mg) | Al18Si | Al-18Si | Al15Si |
| Type of reinforcement/ modificator | Grapheme nanosheets | Mg | SiC particles | - | - |
| Size of reinforcement | | - | 15 and 30 µm | - | - |
| Amount of reinforcement | 0.25-1% | 0.5, 6 and 10% | 17.2vol% | - | - |
| Hardness [HV] | 124-137 | as-cast<br>116-131<br>after T6<br>139-163HV | Al18Si<br>129-227<br>Mahle piston<br>115-160 | 750°C<br>81<br>850°C<br>34.5-38 83 | tixocasted<br>116.89-187.57<br>after T6<br>120.67- 197.5 |
| Tensile strength/Ultimate tensile strength | - | - | - | - | - |

**Table 1.** Review of mechanical properties of hypereutectic AlSi alloys and composites-continued

| **Reference** | **[32]** | **[33]** | **[30]** | **[35]** | **[34]** |
|---|---|---|---|---|---|
| Manufacturing process | ingot metallurgy-casting<br>lost-foam technology,<br>tixoforming<br>squeeze casting and T6 | coling slope casting and tixoforming,<br>and T5 and T6 treated tixoformed material | gravity casting<br>squeeze casting | EBM | casting with electric pulse solidification method |
| Base material (wt%Si) | Al15.3-19.85Si | Al16.83Si | Al 15-22Si | Al16-18Si | Al13Si |
| Type of reinforcement/ modificator/refiner | P | - | - | - | - |
| Size of reinforcement | - | - | - | - | - |
| Amount of reinforcement | - | - | - | - | - |
| Hardness [HV] | as-cast<br>85-142<br>after T6<br>140-199 | die cast<br>68-92<br>tixocasted<br>86-147 | gravity casting<br>52-62<br>squeeze casting<br>60-76 | as-cast<br>69.1-93.9<br>EBM<br>89.7-188.8 | 132.12-144.56 |
| Tensile strength/Ultimate tensile strength | - | - | gravity casting<br>92.33-115.67<br>squeeze casting<br>113.33-153 | - | 60-70 |

A lot of hypereutectic AlSi alloys and composites with different Si content are observed in table 1.
In some papers only tensile strength/ultimate tensile strength was observed and from those papers we can conclude that with aging time tensile strength increases. Higher Si content doesn't mean that tensile strength is higher, but it is hard to compare due to lack of investigations (not enough number of papers to make a proper comparison). When compared to gravity casting all other manufacturing methods give higher hardness. As for microstructure maybe the best ones are obtained for centrifugal, stir casted and tixocasted materials. After T6 treatment hardness increases in some cases significantely.

## 5. Conclusions

There are not many researches about neither mechanical characteristics of hypereutectic aluminum composites nor of their tribological characteristics. That is the reason this research was observing hypereutectic aluminum alloys as well. The conclusions that can be drawn from this research are following:

- There are many fabrication methods, and a lot more will be developed in future;
- All fabrication methods for hypereutectic AlSi alloys and composites have their advantages and disadvantages, the biggest disadvantage is cost of production and complexity of the process;
- Fabrication methods, heat treatments and Si content affect microstructure and mechanical properties of hypereutectic AlSi alloys;
- Due to cost and simplicity of the process, maybe, the best processes for fabrication of hypereutectic AlSi alloys and composites are centrifugal and stir casting.

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