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Influence of various trace metallic additions and reinforcements on A319 and A356 alloys—a review

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Abstract: In this article, aspects related to A319 (AlSi5Cu3) and A356 (AlSi7Mg) alloy are covered owing to their prominent role in the automotive and aerospace industries. It is important to collect overall information related to these alloys and process them so that the material properties can be improved easily in the future by the addition of various trace metallic elements such as Mg, Sr, Sc, Cu, No, Ti, B, Mn, V, Zr and Ca. The addition of Mg (up to 0.45 wt.%) has been identified as the best way to improve tensile properties. It has also been identified that Sr addition modifies eutectic Si morphology and increases tensile properties. The presence of Cu causes the formation of Al12Cu which must be taken care of with proper treatments. Ni addition reduces the effect of Fe phases, and Sc addition improves the tensile properties. Various methods that can be used to produce the alloys mentioned above, related heat treatment processes, and parameters were briefly discussed. The influences of various reinforcements, modifiers, and grain refiners are presented. Solution heat treatment is implemented to dissolve intermetallic phases and the various parameters for aging treatment, cooling rate, and temperature to be used to improve the mechanical properties are also discussed. Among the

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Mr. D Srinivas (Research Scholar), Dr. M C Gowrishankar, Dr. Pavan Hiremath, Dr. Sathyashankara Sharma, Dr. Manjunath Shettar, and Dr. Jayashree P K are the faculty members in the Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India. The authors’ areas of interest are heat treatment of metals and alloys, metal matrix composites’ characterization, machining of MMCs, etc. This paper on influence of various trace metallic additions and reinforcements on A319/A356 alloys opened a wide area to explore. Hybrid composites, multistage heat treatments and aging treatments are some of them.

PUBLIC INTEREST STATEMENT

A319/A356 hypoeutectic alloys are widely used in automotive and aerospace industries. Many researchers have studied the behaviour of these alloys in detail by varying trace metallic additions and reinforcement inclusions. This paper will provide an overall knowledge on how each metallic and reinforcement inclusions to these alloys (A319/A356) effect the overall properties. Various methods used to prepare composites were discussed, stirring casting method is proven to be the best one. This paper also provides detailed information on how cooling rates, temperature and precipitation hardening effect the properties of alloy/composite. Optimum parameters like pouring temperature, stirring rate, solution heat treatment temperature were provided in conclusions. From literature it was concluded that A319 is displaying better properties and it is preferred over A356. Taking a cue from this paper researchers can do improvement studies on these alloys/composites and it is advised to concentrate on hybrid metal matrix composites.
various heat treatment processes, two-stage solutionizing treatment outperforms single and triple stage treatment processes in terms of improving the mechanical properties.

Subjects: Composites; Materials Processing; Metals & Alloys
Keywords: A319 (AlSi5Cu3) alloy; A356 (AlSi7Mg) alloy; metal matrix composites (MMCs); solution heat treatment (SHT); aging

1. Introduction
Al alloys are impressive in the automotive industry because of their low density, castability, specific strength, thermal conductivity, stiffness, and recyclability (Shi et al., 2021). Aluminum has an appreciable density of 2.7 g/cm³, which is very less compared to cast iron/steel, which is also one of the primary reasons for its wide application in the automotive industry (Lombardi et al., 2015). Most of the automobile industries use hypoeutectic Al-Si alloys (A319 and A356) owing to the added advantages of low weight and good thermal conductivity (Yadav & Chakrabarty, 2020). While using these alloys, it is mandatory to have sound knowledge on how alloys get solidified at different cross-sections of cast parts, changes that can be observed in mechanical properties, etc. This helps us to choose better alloys for various applications (Mohamed et al., 2012).

Al alloys with Si as their alloying element (Al-Si) are majorly used in producing kitchen utensils, aerospace, automobile components, and pumps because of their advantageous properties of easy weldability and machinability (Tzeng et al., 2014). Hypoeutectic Al-Si alloys are generally preferred over other aluminum alloys for various real-time applications, especially for casting thin sections. Like all other Al-Si alloys, their mechanical and electrical properties depend on the morphology of Si, which is naturally in coarse platelets form. These act as major sites for crack initiation because of the stress concentration effect resulting in inferior mechanical properties (Kumari et al., 2008). Al-Si binary phase diagram is shown in Figure 1. The mechanical properties of Al alloys are influenced by their composition, trace metallic elements, heat treatments, melt treatments, and solidification rates (Kori & Prabhudev, 2011).

Figure 1. Binary phase diagram of Al-Si alloy.
In casting alloys Al3XX series, silicon is present in the range of 6–9 wt.%, leading to the formation of intermetallic phases (AlFeSi and alpha-AlFeSi) to its low solubility in aluminum. Iron forms Fe-rich intermetallic phases, which affects the material's ductility. This effect is even more severe in the presence of Si (Otani et al., 2019). Precipitation hardening can be used as a strengthening mechanism in aluminum alloys containing Cu and Mg elements. Further, better mechanical properties can be obtained by Cu/Mg-rich precipitates at low temperatures while artificial aging (Shi et al., 2021). To reduce the formation of alpha and beta Al intermetallic phases in the microstructure, the following two ways may be used: (i) Increasing the cooling rate during solidification (ii) Increasing the Mn content (Otani et al., 2019). A319 is widely used in various applications because of its castability, good corrosion resistance, and few other properties that make it the first preference for its applications (García-García et al., 2007; Shi et al., 2021). Mechanical properties of A319 alloy depend on SDAS (secondary dendrite arm spacing), Si particles, porosity, inclusions, and some other alloying elements present in it (Kori & Prabhudev, 2011; Mohamed et al., 2012). MMC's properties and performances depend on the selection of matrix material, reinforcements, processing parameters, and processing techniques (Karbalaei Akbari et al., 2015).

Among many alloy preparation techniques, spray forming is treated as a potential and advanced technique to increase ductility. Otani et al. (2019) observed that spray-formed deposits performed by hot swaging resulted in high ductility and hence offer possibilities for various applications. Robles Hernández and Sokolowski (2009) used the electromagnetic treatment on A319 alloy by varying the range of magnetic field (alternating current). They found that Cu phase, dendritic size, and grain size are sensitive for this stirring modification. Positive changes were observed by using this technique, but no significant modification was seen in Al-Si eutectic. Billet casting is also used as one of the techniques to produce matrix alloys (Lombardi et al., 2015). Semi-solid metal processing is gaining importance because it can produce near net-shaped products with better properties compared to conventional methods. Thixoforming is a semi-solid metal processing method where two steps are to be performed viz., preparing a feedstock material and heating to forming temperature (Alhawari et al., 2017). Thixoforming helps in enhancing corrosion properties and getting coarser microstructure of Al alloys (L. Wang et al., 2016).

The effect of heat treatment on thixoformed A356 and A319 alloys was studied by Cavaliere et al. (Cavaliere et al., 2005). The parameters included reheating temperatures of 583°C and 578°C for A356 and 319 alloys respectively with reheating time of 15 minutes each. The solid fraction
| S. No | Alloy        | Type of casting            | Pouring temperature in °C | Type of semi-solid metal process | Semi-solid heat treatment parameters | Reference             |
|-------|-------------|----------------------------|---------------------------|----------------------------------|-------------------------------------|-----------------------|
| 1     | A356 & A319 | Electromagnetic stir casting | NA                        | Thixoforming                     | 583 & 578                           | (Cavaliere et al., 2005) |
| 2     | A319        | Cooling slope casting       | 620–640                   | Thixoforming                     | 570                                 | (Alhavari et al., 2015)  |
| 3     | A319        | Cooling slope casting       | 630                       | Thixoforming                     | 564, 568, 571                       | (Salleh et al., 2016)   |
| 4     | LM4         | Cooling slope casting       | 620, 640, 660             | Thixoforming                     | 580                                 | (Salleh et al., 2020)   |
| 5     | A319        | Cooling slope casting       | 620, 630, 640             | Thixoforming                     | 571                                 | (Salleh et al., 2014)   |
| 6     | Al-5Si-Cu   | Cooling slope casting       | 640, 650, 660             | Thixoforming                     | 570, 572, 578                       | (Salleh et al., 2015)   |
| 7     | A319        | Cooling slope casting       | 630                       | Thixoforming                     | 574                                 | (Aziz et al., 2020)     |
maintained was 50%. From the results, they concluded that both the alloys displayed better properties than conventionally casted alloys. A319 showed higher yield strength (YS) and ultimate tensile strength (UTS) than A356 in thixoformed conditions.

Alhawari et al. (2015) studied the microstructure of thixoformed A319 alloy. Differential scanning calorimetry (DSC) curve showed liquidus and solidus temperatures as 610°C and 519°C, respectively. Taking a cue from microstructures (shown in Figure 2), the authors concluded that in thixoformed alloy, alpha-Al globules became finer, rosette-shaped grains transformed into coarse and spheroidal due to reheating, Si and Al₂Cu phases dispersed uniformly (volume fraction increased), and samples are free of porosity. Thixoformed alloy displayed better hardness and wear properties compared to the as-cast sample. Considering the DSC result of A319 alloy, 570°C eutectic temperature is concluded to be the best for thixoforming.

Salleh et al. (2016) studied the microstructural effect on mechanical properties of thixoformed A319 alloy. During reheating, eutectic Si particles melted while alpha-Al remained solid. Eutectic Si was rearranged during a holding time of 5 minutes. From the results, it was concluded that the heat-treated thixoformed A319 alloy displayed better ductility compared to the untreated thixoformed alloy.

Salleh et al. (2020) performed heat treatment optimization of thixoformed LM4 alloy. From the results, they concluded that the optimum cooling slope pouring temperature is 660°C. After thixoforming, homogeneously distributed alpha-Al surrounded by eutectic Si were observed. Thixoformed with T6 treatment provided better mechanical properties than as-cast thixoformed samples.

Salleh et al. (2014) studied microstructural variations of heat-treated thixoformed A319 alloy. It was concluded that thixoformed samples displayed better properties than as-cast samples, but T6 treated thixoformed samples were better. Fractography confirmed that the as-cast sample displayed brittle fracture while the thixoformed and T6 treated thixoformed samples displayed a ductile fracture. Parameters used for semisolid treatment are given in Table 1.

There are various manufacturing techniques in the current scenario but stir casting is the most favorable due to its ease, versatility and cost-effective large productions. Stir casting, when combined with other processes such as T6 heat treatment shows better grain refinement and improvement in mechanical properties such as stiffness, reduction of the percentage ductility of the composite materials, tensile strength etc. (Gupta & Srivastava, 2018; Gurusamy et al., 2020). However, hypoeutectic Al-Si alloys cannot meet the tribological characteristics necessary for engine blocks and an effective technique is needed to improve the tribological characteristics of the cylinder bore surfaces (Gupta & Srivastava, 2018).

Given the importance of A319 and A356 alloys in various applications in the aerospace and automobile industry, the present review aims at investigating the effect of traces of metallic elements such as Mg, Sr, Sc, Cu, No, Ti, B, Mn, V, Zr and Ca on A356 and A319 alloys. In addition, the influence of various reinforcements, grain refiners, multistage solutionizing treatment, and aging treatments to enhance the mechanical properties of the above-stated alloys are critically reviewed.

2. Influence of various modifiers and grain refiners on A319 alloy
Various heat treatment processes, grain refiners, and modifiers are used to improve the mechanical properties, which helps to refine the microstructure and Si particles (Haro-Rodríguez et al., 2011). With the addition of certain alloying elements during or after the heat treatments, there is a
possibility of forming intermetallic compounds and poisoning effects. So, there is a need to develop new modifiers, grain refiners, and master alloys (Robles Hernández & Sokolowski, 2009). The basic approach to improve alloy strength is made by adding elements that form intermetallic phases causing microstructural changes (Shaha et al., 2016). In the selection of alloying elements which can help in getting high strength and stability at elevated temperatures, the following factors were considered: (a) Production of suitable precipitates for strengthening (b) Low diffusivity in matrix metal (c) Low solid solubility in matrix metal at varied aging temperatures (d) Ability to preserve the conventional solidification capability of the alloy (Abdelaziz et al., 2020). In the Al-Si system, Cu and Mg are considered as main alloying elements and Fe is considered as an alloying impurity element (Garcia-Garcia et al., 2007). These needle-shaped Fe compounds in alloys are monoclinic beta-Al5FeSi and are detrimental to the toughness and ductility of the alloy (Haro-Rodríguez et al., 2011). Fe alloying element forms platelets (needle structure) which tend to be very brittle and exhibit weak bonds with the Al matrix. Therefore, to reduce the effects caused by Fe and to enhance the properties, it is recommended to add certain neutralizers like Mg, Be, and Co (Tzeng et al., 2014).

During the Al-Si alloy casting process, grain refinement is the foremost treatment that includes the addition of particles to convert non-uniform grains to equiaxed and uniformly distributed grains which contributes to excellent mechanical properties (P. Li et al., 2013). During solidification of Al-Si alloys (hypoeutectic), alpha-Al solidifies with twinned columnar grains and occupies a larger fraction that affects mechanical properties. Grain refinement hinders the twinned columnar grains and forms equiaxed grains. This results in promising mechanical properties due to the modification of needle-like eutectic silicon to fibrous eutectic silicon (Prasad Rao et al., 2006; G. S. V. Kumar et al., 2009). Many researchers have used metals like Nd, Sc, and La for grain refinement purposes (Pramod et al., 2015). Grain refinement is the reason for the grain structure to be fine and equiaxed, which contributes to the improvement in wear and mechanical properties (Prasad Rao et al., 2006). Results of several investigations regarding the influence of various modifiers and grain refiners such as Mg, Sr, Cu, No, Sc, Ti, B, Mn, Zr, V, and Ca on A319 are summarized below.

In Al-Si alloys, Mg is added as the main alloying element to induce age-hardening by forming precipitates with Si (Zhu et al., 2012). In Al-Si alloys (Al-7Si type), the presence of Mg is around 0.4% to 0.7%, which tends to form precipitates after heat treatment resulting in an improvement in the strength of castings (Tzeng et al., 2014). In molten A319 type alloys, Mg addition till 0.5 wt.% forms Mg-rich phases in the form of round particles around eutectic Si (Ibrahim, Samuel, Samuel, Al-Ahmar, et al., 2011b). According to Salleh et al. (2016) till 0.45 wt.% of Mg in A319 improves alloy response to T6 heat treating conditions, providing the best mechanical properties. In the same study, it was observed that Mg was able to refine Si. Also, the presence of Mg has given the highest tensile strength, but elongation to fracture is reduced. Ductile fracture behaviour and mixed-mode fracture behaviour were also observed after the tensile test. Han et al. (2014) compared experimental A319 and industrial A319 alloys with varied Mg. Results show that the addition of Mg increases yield strength (YS) and ultimate tensile strength (UTS) but the percentage of elongation decreases. Efforts were also made to link Mg contents and solution heat treatment temperature for modified and unmodified alloy. It was proved that for up to 0.6 wt.% of Mg, alloy shows high strength than unmodified when the temperature is below 500°C. Alhawari et al. (2017) observed that adding Mg and Si to Al-Si-Cu alloy leads to the formation of Al12Cu4, Al7CuMg2Si5, and Mg2Si phases. Higher Mg content results in increased alloy strength but the formation of coarse Mg2Si results in low ductility and poor fracture toughness. Salleh et al. (2015) observed that as the Mg concentration increased, the elongation to fracture decreased and the UTS increased, but these results were good enough to meet the criteria for automotive applications. Fracture behaviour with
less wt.% of Mg in thixoformed alloys showed cellular morphology type fracture. Also, dimples structure was observed, which is good in terms of ductility.

In A319 alloys adding both Sr and Mg causes segregation of Al$_2$Cu phase (block-like phase is formed). Also, their combination is used to reduce porosity volume fraction (Ibrahim, Samuel, Samuel, Al-Ahmari, Samuel, et al., 2011a). Adding Sr to Al-Si alloys is to convert/modify acicular Si into fibrous form and uplift the mechanical properties (Garcia-Garcia et al., 2007). In addition, the presence of Sr causes the Si structure to be fibrous and it helps in the efficient spheroidization and coarsening processes. The microstructure is also refined by adding Sr minimally while increasing the hardness and solidification rate (Vandersluis & Ravindran, 2020). Espinoza-cuadra et al. (2010) observed that harmful beta phases could be prevented by the combination of overheating temperature (>800°C), modification by Sr, and undercooling. To produce a fine eutectic silicon at the low cooling rates which is generally observed in sand moulds, modifiers such as Sr must be used. This process of modification also influences the formation of secondary phases such as Fe-rich intermetallics. Vandersluis et al. (2019) stated that adding minimal amounts of Sr (50–200 ppm) to A319 alloy changes plate-like Si to fibrous Si. Also, the presence of Sr affects these by altering their morphologies. According to Li et al. (2017), fibrous Si was achieved with the addition of Sr (47–130 ppm additions) but it also improved tensile properties by introducing pores in direct cast alloys.

In Al-Si alloys presence of Cu leads to the formation of the Al$_2$Cu intermetallic phase, which does not easily dissolve during heat treatment. During the solidification process, beta-Al$_2$FeSi acts as an active site for nucleation of the Al$_2$Cu phase (Ibrahim, Samuel, Samuel, Al-Ahmari, Samuel, et al., 2011a). In the Al-7Si series, adding Cu and Mg into Al-7Si-0.5Cu-0.3 Mg alloy improves mechanical properties (Shaha et al., 2016). During heat treatment, if the treatment temperature crosses Cu alloy eutectic temperature, incipient melting of Al$_2$Cu phase occurs at grain boundaries. This allows the formation of shrinkage cavities and tends to lower the properties (Han et al., 2014). Choi et al. (2019) investigated the effects of alloying components on mechanical and thermal characteristics of Al-6Si-0.4 Mg-Cu alloys. The alloys were prepared by stir casting with SHT at 535°C for 6 h, quenching in 80°C hot water, and artificially aging in the air from 180°C to 220°C for 5 h. Specimens were cooled naturally at room temperature after artificial aging. Results indicate that Cu addition was found to be more appropriate than Ti addition for minimizing the reduction in thermal conductivity by increasing mechanical strength simultaneously.

Al-Si alloy by adding Ni neutralizes the formation of Fe-rich needle-like phases (Shaha et al., 2016). Medrano-Prieto et al. (2016) stated that spheroidization was observed post SHT due to the addition of Ni (1 and 2 wt.%). Since the Fe phases have high melting points, fragmentation and size reduction were observed. Hernandez-Sandoval et al. (2014) witnessed that Ni variations (2–3 wt.%) affect specific gravity alone among other physical properties and less than 2 wt.% of Ni does not alter mechanical properties.

Tzeng et al. (2014) studied the effect of Sc on Al-Si alloy. The presence of Fe reduces the ductility during solidification because of its intermetallic phases leading to increased fluidity and reduced shrinkage. Tensile tests showed that 0.04 and 0.12 wt.% Sc increases the percentage elongation. However, 0.04 wt.% Sc improves ductility compared to 0.12 wt.% of Sc. Patakham et al. (2012) reported that Sc is not effective as a grain refiner with Al alloy, because the formation of Al$_2$Sc particles can operate as heterogeneous nucleation sites for primary aluminium phases, other intermetallic compounds that are formed can precipitate as well, and those intermetallic phases cannot effectively act as heterogeneous nuclei. According to Emadi et al. (2010), the refinement effect of Sc (up to 0.17 wt.%) was not observed. The lower solubility of Sc leads to the formation of ternary phases. Reduction in tensile properties was also observed due to the presence of Sc in T6 aging conditions. Zhang et al. (2012) stated that the addition of small amounts of Sc might act as
a hardener in Al alloys because of the formation of secondary precipitates. An average of 50% reduction in grain size is observed compared to other grain refiners (Al-5Ti-1B).

Haro-Rodríguez et al. (2011) noticed grain refinement in Al-Si alloy by adding 0.06 wt.% Sr and 0.00125 wt.% Ti. Reduction in the size of the intermetallic compound was also observed. Tensile strength, elongation and ductility are improved due to 0.06 wt.% of Sr and 0.00125 wt.% of Ti. Samuel et al. (2014) stated that A3XX series grain refinement was done using Al-2.5%Ti-2.5%B and Al-1.7%Ti-1.4%B master alloys. As the B wt.% increases beyond 0.1%, it leads to changes in Si particles, which improves mechanical properties.

Shaha et al. (2016) stated that Al-Si alloys contain the harmful impurity Fe, which forms brittle and complex needle-shaped intermetallics that significantly increase the tendency to form porosity, thereby reducing mechanical properties. During solidification, due to the presence of Mn, A319 alloy shows a reduction in stress concentration which reduces tensile properties and ductility.

Zr particles are very stable at high temperatures as they possess low diffusivity and solubility. Sepehrband et al. (2005) noted that Zr addition did not change the material’s microstructure but reduced the secondary dendrite arm spacing by refinement effect and decreased hardness due to dissolution of precipitates. Hernandez-Sandoval et al. (2014) observed in their work that Zr intermetallic particles maintain their morphology (star-like) during plastic deformation. Wu et al. (2014) observed the effects of Zr and V on Al-Si alloys. Minor additions of Zr and V show a substantial increase in UTS, yield strength due to a strong inhibitory effect on recrystallization.

Kumari et al. (2008) studied if Sr could be replaced by Ca. It was revealed that the optimum range of Ca should be between 0.0085 and 0.017 wt.%, and any higher amount causes porosity and formation of Al-Ca-Si intermetallic. The properties of the alloy after Ca addition are comparable to those of the Sr modifier.

3. Influence of various modifiers and grain refiners on A356 alloy
The results of several investigations regarding the influence of various modifiers and grain refiners such as Sr, Cu, Sc, Mg, Mn, Zr, Sc, Na, Gd, and Mischmetal on A356 can be summarized as below.

Haskel et al. (2018) studied the effect of strontium (0.017 wt.%) addition on A356 alloy. Changes in Si morphology (round and more compact shape) were observed as ductility and heat treatment time increased. A comparative study showed that T6 unmodified A356 alloy exhibits the best strength, and T6+ Sr-A356 alloy exhibits better ductility. In T6+ Sr alloy, lower strength is because of high porosity levels and ductility improvements are because of the change in Si morphology. Samuel et al. (2016) observed that undissolved phases like Al2Cu increase alloy brittleness and reduce the toughness. This particular problem is resolved with the addition of Sr, which segregates the Al2Cu phase, and also, the combination of Sr with SHT increases the impact energy. Abdelaziz et al. (2020) used the combination of Sr and Na as they are compatible with each other and concluded that the modification of Si depends on the cooling rate. A low amount of Sr or Na causes complete solidification with a high solidification rate and converse.

Kori & Prabhudev (2011) studied the effect of the addition of Cu at elevated temperatures on the wear behaviour of A356. It was reported that coarse Al dendritic structure and plate-like Si are observed in the absence of Cu. The addition of 0.5 wt.% of Cu changed the morphology of Si and structural transformation to coarse equiaxed. These changes are mainly due to partial refinement of dendrites with Cu addition. Prabhudev et al. (2014) performed research on A356 alloy with Cu (5–15 wt.%) addition using a cover flux with KCl, NaCl, and NaF. Results showed that UTS, YS,
modulus of elasticity and ductility were improved compared to as-cast alloy Gopi Krishna et al. (2018).

Pramod et al. (2015) studied the effect of Sc as a grain refiner on A356 and A356-10 wt.% TiB₂, K₂TiF₆ and KBF₄ salts were added in appropriate stoichiometric ratios to form TiB₂ in A356 alloy at 800°C. Al₃Sc precipitates behave as heterogeneous nucleation sites for alpha-Al and cause refinement of grains. A reduction of 50% in secondary dendritic arm spacing was observed with 0.4 wt.% of Sc. It also forms intermetallic compounds with other elements in the alloy by modifying Si, which reduces Sc's overall performance compared to other elements refiners.

Fortini et al. (2016) studied the combined effect of Mn and Mg on Al-Si alloy. It is observed that the addition of Mn suppressed the detrimental effects of Fe, whereas Mg addition improved heat treatment capability. Although tensile properties are not much improved with the addition of Mn due to the availability of Fe in small quantities, the addition of Mg decreases the hardness by improved ductility.

Xu et al. (2015) studied the effect of Zr and Sc on Al-Si alloy and found that 0.2 wt.% of Zr shows minimum grain size and secondary dendrite arm spacing (SDAS). Zr addition decreased the lattice parameters by forming nucleation sites whereas Sc helped in forming Al₃Sc precipitates. This modifies the needle-like phases to harmless nodular Sc-Fe phases resulting in improvement of mechanical properties. Liu et al. (2017) investigated the effect of Zr and Gd on A356; Gd was the best of rare earth metals because of suitable atomic radius and high negative mixing enthalpy. Zr and Gd did not provide much noticeable effect separately, but their combined effect shows substantial wear resistance and hardness improvement.

Zhu et al. (2012) performed a study to identify the effect of mischmetal (MM) on A356 by adding Ce-rich MM, 62.5Ce, 35.2La, and other rare earth elements into the melt (range 0.1 to 0.9 wt.%). Results showed that Si particle size exhibits round morphology, and SDAS was reduced by enhancing the tensile properties. Majeed et al. (2020) investigated the addition of Ce and Er (varying from 0.15, 0.25, 0.4, 0.5, 0.75 wt.%) in stir cast Al-Si alloy and examined using computer-aided cooling curve thermal analysis. Growth and nucleation temperatures decreased with 0.3 wt.% addition. The presence of Er lead to the pseudo passivation effect and Ce improved properties and morphology of alloy. Studies were also done by using various master alloys (Al-5Ti-2 C-15Sr, Al-3Ti-1B-0.2 C, 96Al-2Nb-2B) and were proved to get optimum results for enhancement of mechanical properties (T. A. Kumar et al., 2014; Balzoni & Hari Babu, 2015; P. Li et al., 2013; Prasada Rao et al., 2006).

4. Influence of various reinforcements on A319 and A356 alloy
Aluminum metal matrix composites (AMMCs) are commonly used these days due to their advantages such as low density, lower coefficient of thermal expansion, specific module wear resistance, lower shrinkage, high strength to weight ratio, high specific stiffness improved thermal and mechanical properties. Al-Si alloy strength is poor because it does not contain the solid solution reinforcing effect and cannot shape high hardness intermetallic compound precipitated phases such as Mg, Zn, and Cu (G. Li et al., 2021). Inclusion of ceramic material increases fragility and strength (Sunil Kumar et al., 2020). Much of the MMC investigations and analysis focused on increasing strength and hardness characteristics. These brittle and hard reinforcements cause improved strength and reduced mobility dislocation. Ductility decreases as proper bonding do not establish between matrix and reinforcements (Gopi Krishna et al., 2018).
4.1. Influence of TiB<sub>2</sub> on A356

Karbalaei Akbari et al. (2015) stated that the reason for TiB<sub>2</sub> to gain more importance is due to its high strength, melting point (2790°C), hardness (960 HV), and good corrosion resistance. These properties have enabled the usage of TiB<sub>2</sub> in high-temperature and corrosive environments. Toughness and tensile strength were attained when 1.5 vol.% TiB<sub>2</sub> nanoparticles were introduced into the alloy. Any further increase in the vol.% of nanoparticles would have reduced the strength values. Al<sub>3</sub>Ti can be used as a reinforcement according to Liu et al. (2014) because of its properties like high melting point, good wettability and low density. The addition of 1.5 wt.% Ti powder to base alloy changed α-Al to equiaxed dendrite (100–150 μm). Further spheroidization and UTS improvement (by 42.3%) was caused at 3 wt.% of Ti (50 μm). Samuel et al. (2016) observed that TiB<sub>2</sub> (from 0.0075 to 0.25 wt.%) would reduce alloy grain size by 90%. Exceeding the grain refiner containing Ti would certainly reduce the alloy toughness. In their study, Kumar et al. (Prasada Rao et al., 2006) mentioned that efficiency of refinement of 0.005 wt.% Ti of Al-5Ti-0.8 C and Al-5Ti-1.2 C master alloy and 0.1 wt.% level of Al-3B and Al-1Ti-3B are equal. Mg helps TiC act as nucleating sites by removing the oxygen, improving the wettability, and decreasing agglomeration tendency. No good results were observed after 0.1 wt.% in boron-rich grain refiners due to TiC agglomeration and Si poisoning. Wang et al. (2014) observed an increase in hardness and tensile strength of MMCs by adding 2.12, 4.66, and 8.37 vol.% TiB<sub>2</sub> to A356.

Composites were produced by mixing K<sub>2</sub>TiF<sub>6</sub> and KBF<sub>4</sub> salts into alloy A356 at 850°C by the exothermic reaction. T6 treatment was also done (550°C/12 h, quenching in water and aging first at 120°C/2 h and second at 150°C/8 h). Wang et al. (2015) observed substantial improvement in properties by adding TiB<sub>2</sub> in A356 alloy. Also, they studied the effect of La, which helped in refining SADS of aluminum grains and dispersed TiB<sub>2</sub>.

Karbalaei Akbari et al. (2015) studied the effect of tensile performance and fracture behaviour of composites made of A356 reinforced with TiB<sub>2</sub> (0, 0.5, 1.5, 3, and 5 vol.%) prepared by stir casting. Results suggested that the porosity content of composites increased with an increase in vol.% and reduced particle size. Tensile properties were improved till 1.5 vol.% of TiB<sub>2</sub> and then dropped.

The tribo-mechanical activity of A359/6 wt.% Ti-based particulate reinforced composites (TiB<sub>2</sub>, TiC and TiO<sub>2</sub>) as-cast and heat-treated, manufactured by modified stir casting technique was studied by Radhika et al. (2020). TiB<sub>2</sub> and TiO<sub>2</sub> exhibited superior Al-matrix interfacial bonding, while TiC exhibited marginal wetting. Heat-treated A359/TiB<sub>2</sub> composites outperformed TiC and TiO<sub>2</sub> reinforced composites in terms of hardness, tensile strength, and wear resistance. Together with T6 thermal treatment, the modified two-step stirring technique developed superior mechanical and tribological properties. The developed composite has superior tribo-mechanical features suitable for automobile and industrial applications, especially for applications involving reciprocating wear.

A356-TiB<sub>2</sub> (5 wt.%) composite is manufactured by Deepak Kumar et al. (2019) using the thixoforming method. Results indicate that wear rate is significantly impacted by the redistribution of TiB<sub>2</sub> particles in the matrix, refinement of fine globular alpha-Al grains, and eutectic Si modification. The improved wear resistance is due to fine TiB<sub>2</sub> and plastic deformation in the thixoforming process. In the subsurface zone, hard in-situ TiB<sub>2</sub> particles resist plastic deformation and thereby improve wear resistance.

Kandemir et al. (2014) prepared A356/SiC (14 wt.%) and A356/TiB<sub>2</sub> (16 wt.%) composites using thixoforming with ultrasonic treatment. The key reason for using A356 alloy as matrix material is because 7 wt.% Si could suppress chemical reaction between liquid Al and SiC nanoparticles by
preventing Al\textsubscript{2}C\textsubscript{3} (brittle compound) formation at the particle-matrix interface below 700°C. To overcome the possible poor wettability that can be experienced by Al/SiC composites, TiB\textsubscript{2}, which is proven to be strongly wetted by aluminum compared to SiC, was chosen. Grain refinement is also observed in the matrix alloy.

The sliding wear behaviour of T6 treated A356-TiB\textsubscript{2} (2.5, 5, 7.5, 10 wt.\%) in-situ composites was studied by Mandal et al. (2009). The findings suggest that the composites’ wear rate is a stronger function of the composite’s TiB\textsubscript{2} content than its hardness. However, the addition of 2.5 and 5 wt.\% TiB\textsubscript{2} shows substantial improvement in the wear resistance of the matrix alloy compared to 7.5 and 10 wt.\% of TiB\textsubscript{2} due to decreased coefficient of friction.

4.2. Influence of TiB\textsubscript{2} on A319
A319-TiB\textsubscript{2} (2.5, 4, and 5.5 wt.\%) composite was prepared by Poria, Sahoo, Sutradhar, et al. (2018a, 2018b; Poria, Sutradhar, Sahoo, et al., 2019a) using the stir casting method to study the wear behaviour under lubricated conditions. The stir casting method is preferred over other methods to fabricate the composites as stir casting displays good particle distribution, wettability, and less porosity. TiB\textsubscript{2} reinforced AMMCs show more effective mechanical properties and tribological properties than AMMCs with other reinforcements like Al-SiC, Al-TiC, Al-ZrB\textsubscript{2}, and Al-B\textsubscript{4}C. The optimal combination of parameters to obtain the lowest wear rate is observed to be as follows: TiB\textsubscript{2} (5.5 wt.\%), the lowest level of load (25 N), and the lowest level of speed (400 rpm). Wear of Al-TiB\textsubscript{2} composites increases with an increase in load. Wear decreases with a rise in wt.\% of TiB\textsubscript{2}. However, the importance of wt.\% of TiB\textsubscript{2} and the roller speed as a wear factor is not very significant compared to the effect of load in the presence of a lubricant. The effect of particulate wt.\% and film thickness plays a significant role in wear behaviour control on the interacting surface.

Poria, Sutradhar, Sahoo, et al. (2019b) studied corrosion, wear behavior, and hardness of Al-TiB\textsubscript{2} (2.5, 4, and 5.5 wt.\%) AMMCs prepared by stir-casting technique. TiB\textsubscript{2} particles were preheated at 600°C in a separate muffle furnace before stir casting. Base alloy’s corrosion resistance increases due to TiB\textsubscript{2} incorporation but only up to a certain amount of TiB\textsubscript{2} in the matrix. The composite shows the highest corrosion resistance with 1 wt.\% TiB\textsubscript{2}. It is concluded that the addition of TiB\textsubscript{2} strengthens the composite hardness.

Friction and wear decrease as the percentage of TiB\textsubscript{2} reinforcement in composite rises, while friction and wear increase with the load and speed applied. Due to the harder TiB\textsubscript{2} ceramic particle, the hardness of composite increases, and it has a greater effect on the property improvement of AMMCs than SiC and Al\textsubscript{2}O\textsubscript{3} with the addition of TiB\textsubscript{2} particles (Krishna et al., 2018; Poria et al., 2016).

Abrasive friction behavior of LM4-TiB\textsubscript{2} (0, 2.5, 4, 5.5 wt.\%) AMMCs prepared by the process of stir casting have been studied by Gavel et al. (2019). Results have shown that abrasion friction depends on the size of the abrasive particle. The frictional force increases with an increase in particle size and decreases with an increase in the amount of reinforcement.

4.3. Influence of Al\textsubscript{2}O\textsubscript{3} on A356
Beigi Khosroshahi et al. (2015) investigated the bimodal (Al\textsubscript{2}O\textsubscript{3} + SiC) reinforced A356 where SiC coated with Cu is used to improve the wettability. Results showed that there is a significant increase in mechanical properties. Sekar et al. (2014) prepared the alloy by using the electric furnace at 750°C and adding Al\textsubscript{2}O\textsubscript{3} (preheated at 900°C), stirred to improve the uniform distribution followed by T6 treatment. Hardness increased till 1 wt.\% but then decreased because of the clustering effect. Mazaheri et al. (2011) used a mechanical milling method to produce A356 and Al\textsubscript{2}O\textsubscript{3} alloy. The process was carried on a planetary ball mill at room temperature under inert gas
conditions followed by high-velocity oxygen fuel spraying and friction stir processing. Improvement in hardness and tensile properties are observed compared to conventional methods.

By using stir casting and hot rolling methods, A356 strengthened with Al₂O₃ (0.2–0.8 vol.%) is prepared by Li et al. (2021). It is found that hot rolling can improve the uniformity of Si and Al₂O₃ particles in the matrix. Al₂O₃ refined the grain size. In addition to T4 heat treatment, the above improvements triggered an increase in UTS (282 MPa), YS (221 MPa), and percentage elongation to 17.5%.

Using the friction stir processing method, Jalilvand et al. (2019) developed a hybrid composite with A356+ Al₂O₃+ SiO₂. Experimental results indicated enhanced mechanical and corrosion properties in hybrid composites compared to A356 alloy. Microhardness results showed an improvement of 40% in the hardness.

Afkham et al. (2018) studied A356-based composites reinforced by 1.5 wt.% Al₂O₃ and 1.5 wt.% SiC particulates. AMMCs were prepared by two-stage casting methods viz., semi-solid stir casting followed by rolling. Ni and Cu layers were coated separately on ceramic particles for wettability improvement. When coated on ceramic particles, Ni and Cu provide different functionalities of surface energy. The findings showed that the best mechanical properties were obtained for a composite having 1.5 wt.% SiC and 1.5 wt.% Al₂O₃. Wherein SiC particles were coated with Cu, Al₂O₃ particles were coated with Ni. Debonding from the matrix of Ni-coated Al₂O₃ particles may have occurred due to agglomeration, resulting in poor mechanical properties.

A356 and Al₂O₃ (1.5 vol.%) AMMCs were developed by Korbalaeei AKBari et al. (2013) using the vortex method. Al₂O₃ particles were separately milled with Al and Cu powders and added during stir casting. Multi-stage SHT was carried out by heating all the samples at 495°C for 8 h and 520°C for 2 h and quenched in 40°C warm water followed by aging at 180°C for 8 h. Mechanical properties enhanced because of grain refinement and strengthening with A356-Al₂O₃-Cu reinforcement gave better results as compared to single-stage SHT carried at 495°C for 8 h.

A356–nano Al₂O₃ (0.75, 1.5, 2.5, 3.5, and 5 vol.%) composite was prepared by Mazahery et al. (2009) using the stir casting technique. Grain size reduction was observed. Porosity level increased minimally with an increase in %vol of reinforcement. The YS, UTS and ductility of nano-Al₂O₃ reinforced AMMCs improved with the nanoparticles’ volume fraction. Small particle size and uniform distribution of reinforcements in the matrix alloy lead to improvement in UTS due to efficient transfer of applied tensile load.

A356/Al₂O₃/SiC/Gr (1–5 wt.%) reinforced composite was developed by Senthil Kumar et al. (2020) using the squeeze casting method and SHT at 493°C for different duration of time intervals. The density of composites increased with increasing wt.% of reinforcement and A356/3 wt.% Al₂O₃/3 wt.% SiC/3 wt.% Gr showed substantial improvement in hardness (119 BHN) and tensile strength (315 MPa). Further increase in the percentage of reinforcements resulted in a drop in properties.

**4.4. Influence of Al₂O₃ on A319**

Tribological behaviour and hardness of Aluminum-LM4 reinforced with nano alumina (1, 1.5, 2.5, 5 wt.%) and micro Mo (0.5 wt.%) prepared by stir casting method was studied by Shanmugaselvam et al. (2020). The oxide layer, which serves as a barrier for the movements of particles was formed because of the presence of Mo and nano Al₂O₃ particles. With 5 wt.% nano Al₂O₃ and 0.5 wt.% Mo, wear rate decreased and hardness increased.
4.5. Influence of B$_4$C on A356

Aravind Senan et al. (2020) studied the effect of B$_4$C and SiC on A356 alloy. B$_4$C is capable of enhancing mechanical properties and can give the best performance if it is distributed uniformly whereas SiC also promises improvement in mechanical properties when combined with B$_4$C particles. A combination of both reinforcements (up to 5 wt.%) shows an increase in hardness due to the uniform distribution of reinforcements without agglomeration in the matrix.

Lal et al. (2020) fabricated A356 and B$_4$C (0-10 wt.%) composites by an electromagnetic stir casting process in a vacuum. Vacuum helped reduce the porosity. The mechanical properties are improved because of the generation of non-dendritic microstructure due to the effect of continuous stirring. Hybrid composites were prepared from A356-B$_4$C (4 wt.%) -Graphite (4 wt.%) as reinforcements by Jodhav et al. (2017) using a two-stage melt stirring process. Two-stage melt stirring is introduced as this prevents particle agglomeration and results in better composite properties. Composite density has been lower than base alloy and hardness, UTS, and YS have been enhanced with reinforcement addition.

Khademian et al. (2017) studied the effect of hot-rolled and extruded B$_4$C (3 wt.%) reinforced A356 AMMCs produced by the stir casting method. Optimal stirring time and pouring temperature values have been identified as 15 min and 850°C, respectively. The deformation process enhances substantial improvement in mechanical properties and microstructural characteristics.

Effect of heat treatment on A356-10 wt.% B$_4$C cast composites were studied by Lashgari et al. (2010). Composites were fabricated by stir casting method, SHT was done at 540°C for 5 h, and aging was done at 170°C for 8 h. Results indicate that heat treatment can modify eutectic silicon resulting in better tensile properties.

4.6. Influence of SiC on A356

Mousavian et al. (2020) studied the effect of stir cast A356-SiC (50 nm)-Ni and Ti (modifiers) AMMCs. The resulted composites exhibit better mechanical properties compared to as-cast alloy. Ghandvar et al. (2017) conducted experimental research on microstructure, wear properties and impact strength of A356 alloy having 10, 20, and 25 wt.% of SiC$_p$ reinforcement prepared by semisolid stirring technique. Results indicated that the hardness of the material increased with an increase in the percent of reinforcement. Also, 25 wt.% exhibits better hardness by decreasing impact strength.

Yuan et al. (2019) used ultrasonic vibration (UV) treatment and squeeze casting methods to develop A356+ Nano SiC$_p$ (2 wt.%) composites. By controlling the distribution of nano-SiC$_p$ in composites, both the UV & squeeze casting processes can affect the refining effects on the alpha-Al and Si phases. Higher the nano-SiC$_p$ dispersion better the refinement of alpha-Al and eutectic Si process.

Yaghobizadeh et al. (2019) prepared A356+ SiC (0-5 wt.%) AMMCs by using stir casting technique. Before developing the composite, SiC particles are coated with Al because they do not have proper wettability in Al melt. Experimental results proved that the strength and hardness of the coated reinforcement composites improved. Also, with proper casting temperature (850°C), prevention of Al$_6$C$_3$ phase (harmful phase) was also observed.

Ultrasonic and hybrid (both mechanical and ultrasonic) stirring methods were applied to produce a composite made of A356-SiC (1 wt.%) by Aybarc et al. (2019). Experimental results revealed that the composites prepared by ultrasonic stirring possess high YS due to finer microstructure with a higher percentage of elongation (7.5). The highest UTS of 387 MPa was obtained for hybrid stirring, which produced better results than other methods.
MMNCs based on A356 reinforced with Al₂O₃ and SiC nanoparticles were fabricated using the vortex casting process by Behnamfard et al. (2019). Before being injected into the melt of A356 alloy, ceramic nanoparticles were ball-milled with Ti, Cu and Cr powders followed by hot rolling. For the composites containing A356-Ti+SiC, an increase of more than 36% in strength and 68% in hardness was obtained.

Amirkhanlou and Niroumand (2011) prepared composite with A356 and SiC (5 vol.%, 3 μm) reinforcement by stir casting and compocasting methods. SiC particles have been introduced into melt in three different forms viz., SiC untreated, Al-SiC milled composite powder and Al-Mg-SiC milled composite powder. SiC particle distribution (of milled powder) is stronger compared to others. Compared to stir-casting, compocasting is stronger. Tensile properties of compocasting Al-Mg-SiC₉₃ melt increased to a better extent than others.

Dehghan Hamedan and Shahmiri (2012) studied the influence of stirring rate, stirring temperature, and master powder type on A356-1 wt.% SiC nanocomposites prepared by modified stir casting method. At 650°C, 700°C, 750°C, and 800°C, the melt was stirred at 450, 700, and 950 rpm. Stirring temperature of 750°C and stirring rate of 700 rpm exhibited better UTS and YS of the nanocomposite while ductility decreased.

A356-SiC (5, 10, and 15 wt.%) composites were prepared by Dwivedi et al. (2014) using the electromagnetic stir casting method. Minimum porosity was observed for 5 wt.% of reinforcement. This process led to greater grain refinement, hardness, and tensile properties.

In a study by Mousavian et al. (2017), Ni-SiC and Fe-SiC composite powders were produced with Fe and Ni powders and fragmented micron-sized SiC particles (using ball milling process). Composites were prepared with A356 and SiC powders (3 wt.%). Lower-sized reinforcement particles have been found to blend more readily into the melt whereas large-sized particles remain in their original form resulting in stress concentration and low-strength aluminum matrix. Better UTS and YS values were obtained in AMMCs in which nickel serves as the carrier of fine ceramic particles.

A356-SiC (0-9 wt.%) + Gr (3 wt.%) composites were fabricated by Viswanatha et al. (2013) by using the stir casting method. A decrease in machinability and improvement in physical and mechanical properties with an increase in SiC content were observed. Graphite addition was done to improve machining property. The 9 wt.% of SiC AMMC showed that there is an increase in hardness with the inclusion of SiC. Lower wt.% of SiC addition to A356 caused improvement in tensile strength and reduction in the percentage of elongation.

Studies on bulk aluminum matrix nano-composite fabricated using ultrasonic dispersion (non-linear ultrasonic effects namely transient cavitation and acoustic streaming) of nano-sized SiC (0.5, 1.0, and 2.0 wt.%) particles in molten aluminum alloy were conducted by Yang et al. (2004). The studies revealed that the nano-sized SiC particles are well scattered in the matrix, and with just 2 wt.% of nano-sized SiC particles, the YS of the A356 alloy was increased by more than 50%. The formation of SiO₂ in the matrix resulted in partial oxidation of SiC nanoparticles.

Accumulative roll bonding (ARB) and continual annealing and roll-bonding (CAR) processes were used in a study by Jamaati et al. (2012) for improving the microstructure and mechanical properties of A356/10 vol.% SiC AMMC. The results indicated that the use of ARB and CAR processes resulted in the following: (i) Increased silicon and SiC uniformity in the Al matrix (ii) Spheroidal and finer Si particles (iii) Reduced porosity (iv) Improvement in bonding efficiency between matrix/reinforcement (v) Disappearance of particle-free zone resulting in improvement of the tensile
strength (TS) and elongation of MMCS. Based on the results of the study, it can be concluded that the CAR method is better compared to the ARB technique.

Hu et al. (2018) prepared nano-SiC/A356 composites using squeeze casting after ultrasonic treatment. Results indicate that the addition of SiC has a significant impact on primary α(Al) crystals in SiC/A356 nanocomposites. Morphology of α(Al) grains changes from coarse dendrites to rosette crystals with the increase in nano-SiC content and grain size is reduced. The average SDAS of α(Al) reduced compared to that of the matrix alloy with an increase in the SiC<sub>p</sub> content, particularly when SiC content is 2 wt.% (mass fraction).

Characterization of centrifugally cast functionally graded A356-SiC<sub>p</sub> (5, 10 vol.%) AMMCs was done by Mohan & Sajikumar (2020). The final cast composite shows uniform distribution of reinforcements in the matrix due to centrifugal effect during processing resulting in augmented hardness, UTS, YS, and tribological properties compared to matrix alloy.

### 4.7. Influence of SiC on A319

Rajeev, Dwivedi, Jain, et al. (2010a) studied the effect of normal load and reciprocating velocity on the transition from mild to severe wear of A319+ SiC (15 wt.%), A336+ SiC (15 wt.%) and A390+ SiC (15 wt.%) composites prepared by stir casting method. Samples were SHT at 500°C for 6 h and artificially aged at 190°C for 12 h. It was observed that increasing the normal load increases the wear rate. It was also observed that depending on the reciprocating velocity and type of composites, the mode of wear changes from mild oxidative to severe metallic wear. A319 has displayed better tensile strength (170 MPa) and ductility but hardness is lower for A319 when compared with A336 and A390.

The wear behaviour of stir cast A319/SiC and A390/SiC (15 wt.%) under reciprocating conditions was studied by Rajeev, Dwivedi, Jain, et al. (2010b) using fractional factorial design methodology. SiC particles were preheated at 720°C for 3 h and then added to semi-solid alloy A319 at 590°C, and to A390 at 610°C. 2 wt.% of Mg was added to melt before the addition of preheated SiC to improve the wettability. A319-SiC showed better wear resistance with high Si content than the ones with lower Si content.

Sachit et al. (2018) studied particle size (16, 32 and 50 wt.%) on the mechanical and tribological behaviour of stir cast LM4/SiC-based MMC. Mechanical and tribological behaviour of MMCS showed increased strength and good wear resistance compared to the cast alloy. Reinforcement dispersion was uniform and covered a wider surface area which increased the wear properties of MMCS. Findings show that mechanical properties (hardness and UTS) increased as particle size decreased while wear properties increased as the particle size of the composites increased.

### 4.8. Influence of Si<sub>3</sub>N<sub>4</sub> on A356

The composite A356-Si<sub>3</sub>N<sub>4</sub> was fabricated by Fernández et al. (2019) using the process of powder metallurgy. X-ray powder diffraction examined the structural and microstructural modifications that occur during the milling. In order to homogenize the microstructure and to get nanoscale crystalline, long milling times are necessary. The benefit of long milling times is that it helps in increasing the dislocation density that can be useful for subsequent sintering. The presence of Si<sub>3</sub>N<sub>4</sub> in the matrix alloy shows substantial improvement in tribological properties in addition to mechanical properties such as hardness, UTS, YS.

The gravity die-stir casting method is used by Ambigai and Prabhu (2019) to fabricate Al-Gr(3 wt. %)-Si<sub>3</sub>N<sub>4</sub>(3 wt.%) hybrid composite. Results show that wear rate and coefficient of friction decreased by 25% and 15% respectively for hybrid composite compared to Al-Si<sub>3</sub>N<sub>4</sub>
nanocomposite. However, very minimal wear rate and friction coefficient were noticed for Al-Gr. The Al-Gr-Si$_3$N$_4$ hybrid composite’s Micro Vicker hardness is higher than that of the nanocomposite and no major difference is noticed for the nano Al-Si$_3$N$_4$ and Al-Gr AMMCs.

A359-SiC+Si$_3$N$_4$ (5, 10, 15 wt.%) hybrid composite was prepared by Shalaby et al. (2016) using stir + squeeze casting techniques. SHT was done at 538°C for 8 h and aging was done at 155°C for 0–16 h. Results showed that hardness increased till 4 h of aging time and then decreased. So optimum aging time is said to be for 4 h.

Raghavendra Rao and Mohan (2020) prepared LM6 and Si$_3$N$_4$ (2–10 wt.%) using stir casting. Si$_3$N$_4$ (6 wt.%) is proved to be the optimum reinforcement content for substantial grain refinement that increases the efficiency of the material by improving the tensile strength by 39% and hardness by 25%. If reinforcement is increased to 8 wt.%, tensile strength decreases which contributes to the agglomeration of reinforcements in the matrix alloy. The composite hardness, UTS, and YS are greater than the matrix alloy. The results obtained support the use of Si$_3$N$_4$ to increase the mechanical efficiency of metal matrix systems based on aluminum for structural applications.

Radhika (2018) used liquid metallurgy and centrifugal casting methods for preparing LM25-Si$_3$N$_4$ (10 wt.%) AMMCs and compared functionally graded (FG) and homogeneous silicon nitride composites. The outer region of the FG composite was harder while the homogeneous composite had a higher tensile strength. Improvement in the wear resistance was observed at the outer periphery of FG composites. This property can be used in components of automotive industries such as cylinder liners for improved performance. The Si$_3$N$_4$ reinforced composites exhibited a greater tensile strength (212 MPa) in comparison to all other tested specimens due to the uniform distribution of the reinforced particles in the matrix. A decrease in tensile strength (198 MPa) was observed in the outer part of FG composites. Therefore, it was concluded that the outer region of the FG composite, unlike the homogeneous composite, does not withstand the load equally, and hence, the specimen deformation takes place non-uniformly resulting in reduced tensile strength.

4.9. Influence of hematite on A356
Sunil Kumar et al. (2020) observed the effect of copper chills in A356-Hematite (0–12 wt.%) AMMCs developed by stir casting technique followed by sand moulds with and without copper chills. It was observed that the alloy hardness and tensile strength increased up to 9 wt.% of reinforcements and then decreased due to poor wettability. Finally, relative to normal casting, the properties of copper chilled casting alloy showed better mechanical properties.

4.10. Influence of graphene nanoplatelets GNP on A356
Ajay Kumar et al. (2020) prepared A356-graphene nanoplatelets (grade M5) composites by squeeze casting and friction stir processing technique. The combination of these two methods resulted in finer silicon nanosized and intermetallic particles. Due to a decrease in Al grain size and improvement in the work hardening rate, YS increased from 120 to 190 MPa and UTS increased from 238 to 357 MPa. The authors acknowledged that the best materials for improving strong electrical and thermal properties for aluminum alloys are carbon fibers, graphene, and carbon nanotubes (CNT).

4.11. Influence of fly ash on A356
Kumar et al. (2020) developed A356-fly ash (2.11 μm)-red mud (0.4 μm) composites by using the friction stir processing technique. The results showed an improved UTS, wear-resistance, and ductility reduction due to the removal of porosity and refinement of grains. The authors proposed that industrial waste is a cheaper alternative than pricey ceramic reinforcements. Sridhar et al. (2020) prepared A356+ Ash (2–10 wt.%) composite using liquid metallurgy technique followed by
530°C/2 h SHT and 120°C/6 h aging treatment. The results indicated that wear resistance improved with an increase in reinforcement content and 10 wt.% of fly ash inclusion had demonstrated greater resistance to abrasive wear than lower fly ash wt.%.

4.12. Influence of WC on A356
In their work, Krishna et al. (Gavel et al., 2019) observed that stir cast A356-WC (1–5 wt.%) reinforced composites display better mechanical properties than unreinforced alloy wherein 4 wt.% of WC proved to be the best reinforcement combination with A356 alloy to enhance hardness, UTS, and wear resistance.

4.13. Influence of WC on A319
The sliding wear behaviour of the A319 alloy reinforced with WC particles at room and elevated temperatures has been investigated by Kumar et al. (2020). The results show that a higher weight percentage of WC particles improves wear resistance at room temperature.

4.14. Influence of TiC on A356
A356-TiC (10 wt.%) composite was developed using the stir casting process by Joseph et al. (2020). SHT for 12 h at 525°C followed by a water quench and aging was performed for 3 h at 155°C. Age hardened reinforced composites showed an improvement in mechanical properties due to the undissolved intermediate particles. Compared to the base alloy, a 55% increase in hardness was observed.

Borodianskiy et al. (2011) developed A356-TiC composite using mechanochemical activation process + stir casting to avoid floating oxide layer on the metal surface. TiC particles were mechanochemically triggered. The experimental results show that the average grain size is reduced and the structure becomes finer. In the Al crystallization process, TiC nanoparticles serve as nucleation accelerators. With the decrease in grain size, a dislocation moves lesser distance before reaching a grain boundary, and as a result, aluminum strength increases. The alloy’s mechanical properties improved by 6.5% tensile strength, 9% yield strength, and 22% elongation owing to finer Al structure.

4.15. Influence of ZrO₂ on A356
Abdizadeh and Baghchesara (2013) prepared composite A356+ ZrO₂ (5, 10, 15 vol.%) using the stir casting method at 750°C, 850°C and 950°C. In contrast to other specimens, composite containing ZrO₂ (15 vol.%) manufactured at 750°C showed the highest hardness and UTS which could be due to the increasing dislocation density and their pile-ups behind the uniform distributed ZrO₂ particles.

4.16. Influence of multi-walled carbon nanotubes (MWCNT) on A356
Hanizam et al. (2019) prepared composites with A356 as base alloy and MWCNT (0.5–1 wt.%)+Mg (0.25–0.5 wt.%) as reinforcement material by the stir casting process. As compared to base alloy, age-hardened (SHT for 1 h at 540°C and aging for 2 h at 180°C) specimen shows improved hardness, UTS, and an 11% reduction in porosity.

4.17. Influence of AIN (Aluminium nitride) on A319
According to Mohanavel (2019), the test outcomes of stir cast A319 and AIN (0–12 wt.%) composites show extreme stiffness, UTS, compression strength than that of unreinforced matrix alloy. As the content of AIN (Aluminium nitride) particles increases, the mechanical properties of composites increase, and it is much better than that of the LM4 alloy. Composite LM4/AIN (12 wt.%) exhibits 40% higher hardness, 64% higher tensile strength, and 33% greater compression strength than monolithic alloys.
Table 2. Solution heat treatment parameter data used by different authors for A319 and A356 with different modifiers

| S. No | Matrix | Modifier | Solution heat treatment parameters | Reference |
|-------|--------|----------|------------------------------------|-----------|
|       |        |          | Temp (°C) | Time (h) |                                     |
| 1     | Al-Si-Cu | Zr, V and Ti | 400        | 6       | (Shi et al., 2021)                  |
| 2     | A319    | -        | 500, 515, 530 | 2, 4, 6, 8 | (Lombardi et al., 2015)             |
| 3     | A319    | Mg (varied) | 585        | 20, 40, 60, 80 (min) | (Yadav & Chakrabarty, 2020)         |
| 4     | A319    | Mg (varied) | 490–540 | 8; (60 °C warm water quench) | (Mohamed et al., 2012) |
|       |         |          | (505) + (530) | 8 + (2); (60 °C warm water quench) |           |
| 5     | Al-7Si-0.6 Mg | Sc | 540        | 10       | (Tzeng et al., 2014)                |
| 6     | Al-7Si-0.3 Mg | Ca and Sr | 534        | 12; (80 °C water quench) | (Kumari et al., 2008)              |
| 7     | A319    | Cu (varied) | 485        | 5       | (García-Garcia et al., 2007)       |
| 8     | A356    | Ti       | 540        | 2       | (Z. Liu et al., 2014)               |
| 9     | A356    | Mischmetal | 535        | 8       | (Zhu et al., 2012)                 |
| 10    | A356    | Al-3Ti-1B-0.2 C (master alloy) | 490        | 5       | (P. Li et al., 2013)               |
| 11    | A319    | Mg (varied) | 505        | 8; (60 °C warm water quench) | (Salieh et al., 2016)             |
| 12    | A356    | Gd, Zr | 535        | 10      | (W. Liu et al., 2017)              |
| 13    | A319    | Mn       | 510, 525   | 30 min; 4.5 | (Shaha et al., 2016)             |
| 14    | A356    | Zr, Sr | 550        | (0, 8, 50, 100, 200, 400) (60 °C warm water quench) | (Abdelaziz et al., 2020)         |
| 15    | A319    | -       | 500        | 8; (60–100 °C warm water quench) | (Mo et al., 2010)                |
| 16    | A319    | Ni       | 495        | 5, 7; (60 °C warm water quench) | (Medrano-Prieto et al., 2016)    |

(Continued)
| S. No | Matrix | Modifier | Solution heat treatment parameters | Reference |
|-------|--------|----------|-----------------------------------|-----------|
| 17    | A319   | Mg, Sr   | 495, 8 (65 °C warm water quench)  | (Ibrahim et al., 2011) |
| 18    | A319   | Mg       | 488, 8                           | (Hwang et al., 2009) |
| 19    | 319    | Mg       | 450, 490, 500, 520, 8             | (Han et al., 2014) |
| 20    | 319    | Sr       | 200, 500, 0, 24                  | (Vandersluis & Ravindran, 2020) |
| 21    | A356   | Sr       | 540, 6                           | (Haskel et al., 2018) |
| 22    | Al-Si-Cu-Mg alloy | Zr, Ti, Ni | 495, 8 (60 °C warm water quench) | (Hernandez-Sandoval et al., 2016) |
| 23    | A319   | Sc       | 505, 10                           | (Emadi et al., 2010) |
| 24    | A356.2 | Ti, B, Sr | 540, 8 (60 °C warm water quench)  | (E. Samuel et al., 2014) |
| 25    | A356   | Mn, Mg   | 535, 4.5, 6 (60 °C warm water quench) | (Fortini et al., 2016) |
| 26    | A319   | Zr       | 503, 4-36                         | (Sepehrband et al., 2005) |
| 27    | Al-Si-Mg | Zr, V   | 535, 6                            | (Y. Wu et al., 2014) |
| 28    | Al-7Si-0.65 Mg | Sc + Zr | 535, 10                           | (Xu et al., 2015) |
| 29    | LM25   | Al-5Ti-1B (master alloy) | 540, 6 (60 °C warm water quench) | (T. A. Kumar et al., 2014) |
| 30    | A319   | -        | 495; 515; 527 (74 °C warm water quench) | (Sokolowski et al., 2001) |
| 31    | Al-Si  | Mn, Sr   | 495, 8 (65 °C warm water quench)  | (Elseboie et al., 2014) |
| 32    | A319   | -        | 500, 6.25, 90 °C warm water quench | (Vandersluis et al., 2015) |
| 33    | A319   | Sr       | 505, 12                           | (Firouzdor et al., 2007) |
Table 2. (Continued)

| S. No | Matrix | Modifier | Solution heat treatment parameters | Reference |
|-------|--------|----------|------------------------------------|-----------|
| 34    | LM4    | -        | Temp (°C) 530 Time (h) 30          | (Salleh et al., 2020) |
| 35    | Al-5Si-3Cu | - | Temp (°C) 500 Time (h) Varying    | (Akhil et al., 2019) |
| 36    | Al-6 wt.%Si-0.4 wt.%Mg | Cu | Temp (°C) 535 Time (h) 6 (80 °C warm water quench) | (Choi et al., 2019) |
| 37    | Al-Si-Cu-Mg | - | Temp (°C) 505 Time (h) 8 (60 °C warm water quench) | (Cáceres et al., 2003) |
| 38    | A319    | -        | Temp (°C) 504; 545 Time (h) 4; 8 (60 °C warm water quench) | (Haro et al., 2009) |
| 39    | AlSi7MgMn | - | Temp (°C) 475; 525 Time (h) 15; 60; 240; 480 min | (Timelli et al., 2008) |
| 40    | A356    | -        | Temp (°C) 540 Time (h) 1           | (Abdulwahab et al., 2011) |
4.18. Influence of activated carbon + mica on A356

Hardness and wear characteristics of stir cast LM25 with activated carbon (10 wt.%), and mica (10 wt.%) hybrid AMMCs were studied by Sarada et al. (2015). The addition of hybrid reinforcement instead of single reinforcement increased the composite strength and wear resistance.

5. Influence of solution heat treatment and aging treatment on A319 and A356

Solution heat treatment is a treatment wherein the alloy is heated to a predetermined temperature and held for a certain amount of time followed by a water quench to form an unstable supersaturated solid solution.

Vandersluis and Ravindran (2020) stated that, in solution heat treatment, the solubility of Cu in Al lattice is increased with increasing temperature. Heating above Al-Cu solvus temperature (505°C for 4–12 h for A319), enables the Al₃Cu phase to dissolve into the matrix enabling finer and uniformly dispersed particles. Eutectic Si particles in Al-Si alloys (hypeutectic) are found to spheroidize, fragment and coarsen during solution heat treatment. Han et al. (2014) explained that the main aim of solution heat treatment is to embed hardening solutes like Cu and Mg into solid solution in the Al matrix. With the increase in SHT time, tensile properties increase and during multi-step SHT, dissolution of Al₃Cu phase and Si particle spheroidization occurs which are the main reasons for the improvement in mechanical properties. Ibrahim, Samuel, Samuel, Al-Ahmari, Samuel, et al. (2011a) noted that SHT at 515°C for 8–16 h followed by 60°C warm water quench results in better strength and ductility. Higher SHT temperatures resulted in the melting of the Cu phase. Also, mechanical properties are greatly altered by the effect of precipitation hardening/age-hardening treatment by heating quenched Al-Si-Cu alloy between the range of 95–205°C. Mohamed et al. (2012) quoted in their paper that high-temperature two-step SHT (495°C/2 h followed by 515°C/4 h) shows better strength and ductility as compared to single-step 495°C/8 h. In a two-stage process, the temperature should not cross 520°C even if it homogenizes the alloy. In their study, SHT was done at temperatures ranging from 490°C to 540°C for 8 h each and then quenched in warm water at 60°C followed by aging at 155°C for 5 h. Results suggest that the two-stage solution treatments (above 530°C) cause the deterioration of the mechanical properties by affecting UTS and YS. As a result, for two-stage SHT, the second-stage solution temperature should not exceed 520°C, particularly at Mg levels of 0.6%.

Zhu et al. (2012) noticed that SHT is important to homogenize the alpha-Al dendrites and influence precipitation behaviour. Homogenization of the alpha-Al phase can be achieved at 540°C for 10 min which results in spheroidization, coarsening, and an increase in particle spacing of Si. Wang et al. (2015) stated that to dissolve Mg₂Si and spheroidize eutectic Si, it is important to perform SHT in the range of 540–550°C. During aging, nanoparticles act as obstacles and provide intense age-hardening which helps in strengthening the material.

T6 heat treatment on the thixoformed LM4 alloy was studied by Salleh et al. (2020) by using response surface methodology (RSM). The duration of T6 is 9 h, according to the American Society for Testing and Materials (ASTM B917) (SHT between 6–12 h and aging between 3 and 5 h). The optimum parameters of T6 heat treatment based on the RSM responses are SHT at 530°C for 30 minutes and 2 h of aging at 180 °C. With UTS of 252.3 MPa, 98.9 HV surface hardness, and friction coefficient (CoF) of 0.4299, the overall strength of LM4 improved significantly.

Akhil et al. (2019) performed an experiment where Al-5Si-3Cu was prepared by the squeeze casting method with different time periods and SHT at 500°C followed by aging at 170°C (0–16 h). The eutectic Si underwent necking and was divided into segments during solution treatment. There was a reduction in the average particle size because of this fragmentation and the fragmented segments...
| S. No | Matrix | Reinforcement | Solution heat treatment parameters | Reference |
|-------|--------|---------------|------------------------------------|-----------|
| 1     | A356   | TiB$_2$ (5 µm and 20 nm were) | 520 | 8 | (Karbalaei Akbari et al., 2015) |
| 2     | A356, 413 | TiB$_2$, Sr (modifier) | 540 | 8; (65 °C warm water quench) | (A. M. Samuel et al., 2016) |
| 3     | A356   | TiB$_2$ | 550 | 12 | (M. Wang et al., 2014) |
| 4     | A356   | TiB$_2$, La | 540 | 8 | (T. Wang et al., 2015) |
| 5     | A356   | Al$_2$O$_3$ | 460 | 6 | (Sekar et al., 2014) |
| 6     | Cylinder-head aluminum alloys | Nano clay particles | 500 | 5 | (Rashnoo et al., 2020) |
| 7     | A356   | TiC | 525 | 12 | (Joseph et al., 2020) |
| 8     | A356   | Ash | 530 | 2 | (Sridhar et al., 2020) |
| 9     | A356   | MWCNT, Mg (modifier) | 540 | 1 | (Hanizom et al., 2019) |
| 10    | A356   | SiC (50-56 µm) | 540 | 4 (80 °C warm water quench) | (Aybarc et al., 2019) |
| 11    | A356   | TiB$_2$ (20 nm and 5 µm) | 520 | 8 | (Karbalaei Akbari et al., 2015) |
| 12    | A356   | Al$_2$O$_3$ (20 nm) | 495; 520 | 8; 2 (40 °C warm water quench) | (Karbalaei Akbari et al., 2013) |
| 13    | A356   | B$_4$C (65 µm) | 540 | 5 | (Lashgari et al., 2010) |
| 14    | A356   | Al$_2$O$_3$ (20 nm) | 495; 520 | 8; 2 (40 °C warm water quench) | (Akbari et al., 2013) |
| 15    | A359   | SiC+Si$_3$N$_4$ (35 and 3 µm) | 538 | 8 | (Shalaby et al., 2016) |
| 16    | A359   | TiB$_2$, TiO$_2$, and TiC (15–25 µm) | 540 | 10; hot water quench (50–75 °C) | (Radhika et al., 2020) |
| 17    | A319, A336 and A390 | SiC (32 µm) | 500 | 6 | (Rajeev, Dwivedi, Jain, et al., 2010a) |
| 18    | A319, A390 | SiC (32 µm) | 500 | 6 | (Rajeev, Dwivedi, Jain, et al., 2010b) |
Table 4. Aging parameters data used by different authors for A319 and A356 with various modifiers

| S. No | Matrix | Modifier | Aging parameters | Reference |
|-------|--------|----------|------------------|-----------|
|       |        |          |                 |           |
| 1     | A319   | -        | 240 °C 5.5 h    | (Lombardi et al., 2015) |
| 2     | A319   | Mg (varied) | 155 °C 5 h   | (Mohamed et al., 2012) |
| 3     | Al-7Si-0.6 Mg | Sc | 160 °C 6 h   | (Tseng et al., 2014) |
| 4     | Al-7Si-0.3 Mg | Ca and Sr | 164 °C 8 h  | (Kumari et al., 2008) |
| 5     | A319   | Cu (varied) | 230 °C 3 h and 20 min | (Garcia-Garcia et al., 2007) |
| 6     | A356   | Ti       | 170 °C 7 h   | (Z. Liu et al., 2016) |
| 7     | A356   | Mischmetal | 160 °C 6 h | (Zhu et al., 2012) |
| 8     | A356   | Al-3Ti-1B-0.2 C (master alloy) | 200 °C 8 h | (P. Li et al., 2013) |
| 9     | A319   | Mg (varied) | 158 °C 4 h   | (Salleh et al., 2016) |
| 10    | A356   | Gd, Zr | 175 °C 8 h | (W. Liu et al., 2017) |
| 11    | A319   | Mn       | 200 °C 1 h   | (Shoja et al., 2016) |
| 12    | A319   | -        | 155 °C 4 h   | (Mo et al., 2010) |
| 13    | A319   | Ni       | 170 °C 30–5760 min | (Medrano-Prieto et al., 2016) |
| 14    | A319   | Mg, Sr | 180;220 °C 2–24 h | (Ibrahim, Samuel, Samuel, Al-Ahmari, Samuel, et al., 2011a) |
| 15    | A319   | Mg       | 193 °C 8 h   | (Hwang et al., 2009) |
| 16    | Al-5Si-Cu | Mg | 155 °C 4 h   | (Salleh et al., 2015) |
| 17    | A356   | Sr       | 155 °C 5 h   | (Haskel et al., 2018) |
| 18    | Al-Si-Cu-Mg alloy | Zr, Ti & Ni | 155–350 °C 2–100 h (range) | (Hernandez-Sandoval et al., 2014) |
| 19    | A319   | Sc       | 155; 255 °C 5 h | (Emadi et al., 2010) |
| 20    | A356.2 | Ti, B, Sr | room temp; 155 °C 24; 5 h | (E. Samuel et al., 2014) |
| 21    | A356   | Mn, Mg  | 155 °C 4.5 h | (Fortini et al., 2016) |
| 22    | A319   | Zr       | 195 °C Up to 48 h | (Sepehrband et al., 2005) |
| 23    | Al-7Si-0.65 Mg | Sc + Zr | 160 °C 7 h   | (Xu et al., 2015) |

(Continued)
Table 5. Aging parameters data used by different authors for A319 and A356 with various reinforcements

| S. No | Matrix | Reinforcement | Aging parameters | Reference |
|-------|--------|---------------|------------------|-----------|
| 1 | A356 | TiB₂ (5 µm and 20 nm) | 180 | 8 | (Karbalaei Akbari et al., 2015) |
| 2 | A356, 413 | TiB₂, Sr (modifier) | 155, 180, 200, 220 and 240 | 5 | (A. M. Samuel et al., 2016) |
| 3 | A356 | TiB₂ | 120; 150 | 2; 8 | (M. Wang et al., 2014) |
| 4 | A356 | TiB₂, La (modifier) | 155 | 0, 1, 2, 3, 4, 5, 5.5, 6, 6.5, 7, 8, 9, 10 | (T. Wang et al., 2015) |
| 5 | A356 | Al₂O₃ | 190 | 4 | (Sekar et al., 2014) |
| 6 | Cylinder-head aluminum alloys | Nano clay particles | 180 | 2 | (Rashnoo et al., 2020) |
| 7 | A356 | TiC | 155 | 3 | (Joseph et al., 2020) |
| 8 | A356 | Ash | 120 | 6 | (Sridhar et al., 2020) |
| 9 | A356 | MWNT, Mg (modifier) | 180 | 2 | (Hanizam et al., 2019) |
| 10 | A356 | SiC (50-56 µm) | 155 | 3 | (Aybarc et al., 2019) |
| 11 | A356 | TiB₂ (20 nm and 5 µm) | 180 | 8 | (Karbalaei Akbari et al., 2015) |
| 12 | A356 | Al₂O₃ (20 nm) | 180 | 8 | (Karbalaei Akbari et al., 2013) |
| 13 | A356 | B₄C (65 µm) | 170 | 8 | (Lashgari et al., 2010) |
| 14 | A356 | Al₂O₃ (20 nm) | 180 | 8 | (Akbari et al., 2013) |
| 15 | A359 | SiC+Si₃N₄ (35 and 3 µm) | 155 | 0–16 | (Shalaby et al., 2016) |
| 16 | A359 | TiB₂, TiO₂, and TiC (15–25 µm) | 155 | 10 | (Radhika et al., 2020) |
| 17 | A319, A336 and A390 | SiC (32 µm) | 190 | 12 | (Rajeev, Dwivedi, Jain, et al., 2010a) |
| 18 | A319, A390 | SiC (32 µm) | 190 | 12 | (Rajeev, Dwivedi, Jain, et al., 2010b) |
were spheroidized. The squeeze-cast alloy samples aged at 170°C for a period of 7 h exhibited the highest hardness of 110 BHN (better than gravity-cast samples aged for a period of 12 h).

Cáceres et al. (2003) studied the strength-ductility behaviour of Al-Si-Cu-Mg casting alloys in T6 treatment and found that when short-term heat-treated at 505°C for 8 h and quenched in warm water at 60°C, finer dendrite arm spacings can be observed which result in more uniform microstructures. It was also observed that porosity reduced as SDAS decreased. Ductility improved with

### Table 6. Effect of temperature and changes observed in Al-Si alloy

| S. No | Alloy | Temperature in °C | Conclusions | References |
|-------|-------|-------------------|-------------|------------|
| 1     | LM25  | Pouring temperature (720, 740, 760) | At low pouring temperature reduced DAS, fine structure, smaller Si and improved properties were observed | (Srinivasan et al., 2006) |
| 2     | A356  | Pouring temperature (590, 600, 610) | 600 °C is found to be the optimum pouring temperature | (M. Li et al., 2020) |
| 3     | A356  | Pouring temperature (590, 595, 600, 605) | 595 °C is found to be the optimum pouring temperature | (Luo et al., 2019) |
| 4     | Al-7Si-0.3 Mg | Pouring temperature (680-740) | 700–720 °C is found to be the optimum pouring temperature | (Ravi et al., 1998) |
| 5     | A319  | Testing temperature range (-90 to 400) | Temperature below 200 °C can hold the properties without failure | (Rincón et al., 2007, Rincón et al., 2009) |
| 6     | LM4   | Pouring temperature (703, 723, 743 & 763) | Surface finish improved with pouring temperature | (Singh & Gupta, 2015) |

![Figure 3. Optical microstructures of LM25 alloy a) poured at 720°C, b) poured at 760°C (Srinivasan et al., 2006) (Reproduced with permission from Inderscience Publishers).](image-url)
reduced SDAS. Strength normally increases with the increasing content of Cu and Mg, and the ductility decreases. The ductility and strength of low Si alloys are significantly lowered by increased Fe (at Fe/Mn ratio 0.5). Generally, increased Si content increases strength and ductility. When the Fe content is high, the rise in ductility with increased Si is especially important. For alloys with high Si content, Cu+Mg content should be below 1.95 wt.% to get better ductility. If the content (Mg+Cu) is more than 2 wt.% with high Fe and low Si, it may lead to failure. So, Cu should be maximum 3 wt. % for alloys having Mg above 0.1 wt.%.

Haro et al. (2009) studied the effect of solutionizing and aging temperatures on mechanical properties and microstructure of cast Al-Si-Cu alloy. It was observed that solidification of A319 reveals lower melting point phases (495–520°C) like Al–CuAl12, Al2Mg9, Cu2Si6, etc. This temperature limit is generally used for SHT. Best mechanical properties were observed when SHT was done at 504°C for 8 h, water quenching at 60°C, and aging at 154°C for 6 h.

Timelli et al. (2008) studied the effect of SHT (475°C and 525°C for 15, 60, 240, and 480 min followed by artificially aging at 170°C for 8 h) on microstructure and mechanical properties of a die-cast AlSi7MgMn alloy. Results showed that to spheroidize and increase the distance between
tectic Si particles, SHT of 15 min at 475°C or even higher at 525°C is enough. Mechanical properties are improved by rising solutionizing temperature from 475°C to 525°C.

Sokolowski et al. (2001) studied the effect of single and multi-stage SHT on mechanical properties of 319 Al alloy and determine the effect of strontium addition on characteristic temperatures of copper-rich eutectic phases. Dissolution of Cu-rich phases and modification of Si was not sufficiently attained during single-step SHT (495°C/8 h). In two-stage SHT heating at (495°C/2 h + 515°C/4 h), quenching at 74°C and aging at 250°C/3 h was done and this could attain better mechanical properties compared to single-stage SHT.

Han et al. (2014) studied the tensile properties of Al-Si-Cu-Mg (319) alloys subjected to single-stage SHT (450–490°C for 4–8 h), multistage SHT (500–520°C for 4–8 h), and triple-stage SHT (above 520°C for 4–8 h). Results showed lower tensile properties for triple-stage SHT samples. This might be due to the incipient melting and coarsening of Si. Thus, triple step heat treatments are not ideal for 0.3 wt.% Mg industrial 319 alloys.

Tables 2 and 3 show the data of solution heat treatment parameters used by various researchers in their study for A319 and A356 with different modifiers and reinforcements, respectively. The alloying elements precipitate and disperse from the solid solution when Al alloy is cooled slowly from a high temperature. These elements gather at grain boundaries as undissolved particles, imperfections, and small voids. For optimum properties and to maintain alloying elements in solid solution, it is desirable to postpone the diffusion process. This is carried out after SHT by quenching in hot water. Increasing cooling rates produce thermal gradients, higher thermal stresses and distortion. To attain high strength, corrosion resistance, and ductility, the diffusion process must be delayed until age hardening is performed. Selection of the quenching condition is highly important because if rapidly cooled, distortion occurs and if slow cooled, unwanted precipitation occurs. Usually, 10–32°C cold water is used as quenchant to attain better mechanical properties but if distortion/cracking occurs, 60–70°C hot water is used as quenchant (Tiryakioglu & Totten, 1998). Sokolowski et al. (2001) proved that temperatures less than 495°C are not suitable for the dissolution of Cu phases and cannot modify Si morphology during solutionizing heat-treatment process.

5.1. Aging temperature
Elsebaie et al. (2014) observed that aging at 240°C causes a greater increase in impact energy values of A3XX alloy with less Mn wt.% due to thermal softening. By increasing the aging period from 4 to 44 h at 180°C, no major change in energy impact values was observed. Tavitas-Medrano et al. (2008) proved that the standard parameters of aging in T6 (2–5 h at 155°C) is not the best option as treating at 170°C for 8 h produced higher values of properties.
| S. No | Matrix | Modifier | Wt% or vol% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|----------|--------------------------|-------------|---------------------|-----------|
| 1     | Al-Si-Cu | Zr, V and Ti | 0.38; 0.32 and 0.09 | Casting    | Improved properties at high temperatures | (Shi et al., 2021) |
| 2     | A319    | - | - | Billet casting | Tensile properties | (Lombardi et al., 2015) |
| 3     | A319    | Mg (varied) | 5 and 10 | Cooling slope casting | Hardness, Tensile strength, Dry sliding wear properties | (Yadav & Chakraborty, 2020) |
| 4     | A319    | Mg (varied) | 0–0.6 | Conventional casting | Tensile properties | (Mohamed et al., 2012) |
| 5     | Al-7Si-0.6 Mg | Sc | 0.04, 0.12 | Conventional casting | Tensile properties | (Tseng et al., 2014) |
| 6     | A356    | Cu (varied) | 0.11, 14.7 | Conventional casting | Wear resistance and hardness | (Prabhudev et al., 2014) |
| 7     | Al-7Si-0.3 Mg | Ca and Sr | Ca (0.0085–0.017), Sr (0.02) | Casting | Both are on par with properties | (Kumari et al., 2008) |
| 8     | A356    | Cu (varied) | 0.1, 14.8 | Casting | Sliding wear properties | (Kori & Prabhudev, 2011) |
| 9     | A319    | - | - | Spray forming | Ductility | (Ootani et al., 2019) |
| 10    | A319    | Cu (varied) | 3.0, 3.8 | Casting | - | (Garcia-Garcia et al., 2007) |
| 11    | A319    | Sr | - | Casting | - | (Espinoza-cuadra et al., 2010) |
| 12    | A356    | Ti | 1.5 and 3.0 | Casting + high-intensity ultrasonic vibration | Hardness, Tensile strength and elongation | (Z. Liu et al., 2014) |
| 13    | A356    | Mischmetal | La, Ce (0.1–0.9) | Stir casting + T6 | UTS, YS and El | (Zhu et al., 2012) |
| 14    | A356    | Al-3Ti-1B-0.2 C (master alloy) | 0.2 | Stir casting | Mechanical | (P. Li et al., 2013) |
| 15    | A319    | - | - | Electromagnetic stirring | - | (Robles Hernández & Sokolowski, 2009) |

(Continued)
| S. No | Matrix | Modifier | Wt.% or vol.% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|----------|---------------------------|-------------|---------------------|-----------|
| 16    | Al-Si  | Mg (varied) | 0.3–2 | Cooling slope + thixoforming | Hardness, UTS and EL | (Alhawari et al., 2017) |
| 17    | A319   | Mg (varied) | 0.3, 1, 1.5 | Cooling slope + thixoforming | Ductility | (Salleh et al., 2016) |
| 18    | A319   | -         | -     | Lost foam casting | - | (L. Wang et al., 2016) |
| 19    | Al-Si-Mg | Ti, Sr | Ti(0.00125–0.015), Sr (0.04–0.06) | Casting, porous plug method | Mechanical | (Haro-Rodríguez et al., 2011) |
| 20    | A356   | Gd, Zr | Gd (0.4–0.6), Zr (0.25–1) | Casting | Optimal tensile properties | (W. Liu et al., 2017) |
| 21    | A319   | Mn      | 0.19 | Casting + T6 | Tensile properties | (Shaha et al., 2016) |
| 22    | A356   | Zr      | 0.3  | Casting | Limited effect | (Abdelaziz et al., 2020) |
| 23    | A319   | -       | -    | T6 | Fatigue | (Ma et al., 2010) |
| 24    | LM25   | Al-Ti-C; Al-Ti-B (master alloys) | 0.1–1.0 | Casting | - | (G. S. V. Kumar et al., 2009) |
| 25    | A319   | Ni      | <2.0 | Casting | Hardness | (Medrano-Prieto et al., 2016) |
| 26    | LM25   | Al-Ti-C-Sr (master alloy) | (0.2, 0.5 and 1.0) | Casting | Strain hardening, Wear | (Prasada Rao et al., 2006) |
| 27    | Al-7 wt.% Si | Sc | 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, and 0.4 | Casting | - | (W. Zhang et al., 2012) |
| 28    | A356   | Sc, TiB₂ (reinforcement) | 0.2, 0.4 | Casting | Hardness, Wear resistance | (Pramod et al., 2015) |
| 29    | A319   | Mn, Sr | Mn (0.22), Sr (0.0098) | Casting | Mechanical | (Liu & Chen, 2019) |
| 30    | A319   | Mg, Sr | - | T6, T7, casting | Mechanical | (Ibrahim, Samuel, Samuel, Al-Ahmari, Samuel et al., 2011a) |
| 31    | A319   | Mg     | 0.45 | Casting + T6 | - | (Hwang et al., 2009) |
| S. No | Matrix | Modifier | Wt.% or vol.% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|----------|---------------------------|-------------|---------------------|-----------|
| 32    | 319    | Mg       | 0.3, 0.6                  | Casting     | Tensile             | (Han et al., 2014) |
| 33    | Al-5Si-Cu | Mg       | 0.5, 0.8, 1.2             | Cooling slope castine + thixoformed + T6 | Mechanical | (Saleh et al., 2015) |
| 34    | 319    | Sr       | Al-10 wt.% Sr            | Stir casting + SHT | Mechanical | (Vandersluis & Ravindran, 2020) |
| 35    | A319   | Sr       | Al-10 wt.%Sr             | Casting, neutron diffraction study | - | (Vandersluis et al., 2019) |
| 36    | AlSi7Cu3 | Sr, Fe, Mn | Al-10 wt.%Sr, Al-25 wt. %Fe and Al-25% Mn | Casting | Mechanical | (Z. Li et al., 2017) |
| 37    | A356   | Sr       | 0.014–0.017              | Casting + T6 | Fatigue life | (Haskel et al., 2018) |
| 38    | Al-Si-Cu-Mg alloy | Zr, Ti, Ni | (Al-5Ti-1%B), Al-20 wt. %Zr and Al-20 wt.% Ni | Casting + SHT | Tensile properties | (Hernandez-Sandoval et al., 2014) |
| 39    | A356   | Sc       | 0.2, 0.4                  | Casting     | - | (Patakhom et al., 2012) |
| 40    | A319   | Sc       | 0.051, 0.11 and 0.17     | Casting + T6+ T7 | Mechanical | (Emadi et al., 2010) |
| 41    | A356.2 | Ti, B, Sr | Ti (0.02–0.5), B (0.01–0.5) | Casting + T6 | Mechanical | (E. Samuel et al., 2014) |
| 42    | A356   | Mn, Mg   | Mn (0.39), Mg (0.27–0.38) | Casting + T6 | Ductility, YS | (Fortini et al., 2016) |
| 43    | A319   | Zr       | 0.15                     | Casting     | Hardness | (Sepehrband et al., 2005) |
| 44    | Al-Si-Mg | Zr, V     | 0.112; 0.075             | Smelting casting | UTS, YS, EL | (Y. Wu et al., 2014) |
| 45    | Al-7Si-0.65 Mg | Sc + Zr | 0.5                       | Casting     | Mechanical | (Xu et al., 2015) |
| 46    | LM25   | Er, Ce   | 0.15, 0.25, 0.4, 0.5 and 0.75 | Casting | - | (Majeed et al., 2020) |
| 47    | Al-7Si-0.7 Mg | Sm | 0–0.9                   | Casting | Tensile properties | (Qiu et al., 2013) |
| 48    | LM25   | 96Al-2Nb-2B (master alloy) | 0.1 wt.% of Nb | Casting | - | (Bozorgi & Hari Babu, 2015) |

Table 7. (Continued)
| S. No | Matrix | Modifier | Wt.% or vol.% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|----------|-----------------------------|-------------|-------------------|-----------|
| 49    | LM25   | Al-5Ti-1B (master alloy) | 2 wt.% (Al-5Ti-1B) | Electromagnetic induction + T6 | Mechanical, Wear | (T. A. Kumar et al., 2014) |
| 50    | A319   | -        | -                           | -           | Tensile           | (Rincón et al., 2007) |
| 51    | A319   | -        | -                           | Two step SHT | Durability        | (Sokolowski et al., 2001) |
| 52    | Al-Si  | Mn, Sr   | 0.45; 0.65                  | Casting     | Impact energy     | (Elseboie et al., 2014) |
| 53    | A319   | Sr, Mg   | Sr (0.02), Mg (0.4)         | Casting     | Mechanical        | (Tavitas-Medrano et al., 2008) |
| 54    | A319   | -        | -                           | -           | Mechanical        | (Vandersluis et al., 2015) |
| 55    | A319   | Sr       | -                           | T6, T7      | -                 | (Firouzdar et al., 2007) |
| 56    | LM4    | -        | -                           | Thixoforming | Hardness, Tensile | (Salleh et al., 2020) |
| 57    | Al-5Si-3Cu | -     | -                           | Squeeze casting | Hardness, Tensile | (Akhil et al., 2019) |
| 58    | Al-6 wt.%Si-0.4 wt.% Mg | Cu | -                           | Stir casting | Mechanical        | (Choi et al., 2019) |
| 59    | A319   | -        | -                           | Stir casting + T6 | Mechanical | (Haro et al., 2009) |
| 60    | AlSi7MgMn | -     | -                           | High pressure die casting | Tensile, Hardness | (Timelli et al., 2008) |
| 61    | A356   | -        | -                           | Multiple-step thermal aging treatment | Tensile, Hardness | (Abduwahab et al., 2011) |
Table 8. Effect of reinforcements with respect to method employed for dispersion with type of property for Al 319/356 AMMCs

| S. No | Matrix | Reinforcement | Wt.% or vol.% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|---------------|----------------------------|-------------|---------------------|-----------|
| 1     | A356   | TiB₂ (5 µm and 20 nm) | 0.5, 1.5, 3, and 5 | Stir casting | Tensile strength and toughness | (Karbalaie Akbari et al., 2015) |
| 2     | LM25   | Si₃N₄ | 4 to 12 | Stir casting | Tensile strength | (Ahmad et al., 2020) |
| 3     | A356, 413 | TiB₂, Sr (modifier) | TiB₂ (0.0075-0.25) | Casting | Hardness | (A. M. Samuel et al., 2016) |
| 4     | A356   | TiB₂ | 2.12, 4.66 and 8.37 | Stir casting + T6 | Mechanical | (M. Wang et al., 2014) |
| 5     | A356   | TiB₂, La (modifier) | A356-2.5 wt.% TiB₂ and A356-6.25 wt.% TiB₂-0.1 wt.% La | Casting + T6 | Peak hardness | (T. Wang et al., 2015) |
| 6     | A356   | Al₂O₃, SiC | 3 | Stir casting, coating, rolling | Strength, Hardness | (Beigi Khorasroshahi et al., 2015) |
| 7     | A356   | Al₂O₃ | 0.5–1.5 | Stir, squeeze, T6 | Mechanical | (Sekar et al., 2014) |
| 8     | A356   | Al₂O₃ | - | Friction stir processing | Microhardness, Strength | (Mazaheri et al., 2011) |
| 9     | Al-6.6Si-0.4 Mg | SiC, B₄C | 5 and 10 | Stir casting | Mechanical | (Aravind Senan et al., 2020) |
| 10    | A356   | Al₂O₃ | 0.2–0.8 | Stir casting | Tensile | (G. Li et al., 2021) |
| 11    | A356   | Hematite | 0–12 | Stir casting | Hardness, Tensile | (Sunil Kumar et al., 2020) |
| 12    | A356   | B₄C | 0–10 | Electromagnetic stir-casting process with vacuum | Hardness, Tensile | (Lal et al., 2020) |
| 13    | AA2014 | SiC (20–30 µm) with fly ash | 2–6 | Stir casting | Hardness, Tensile | (Gurusamy et al., 2020) |
| 14    | A356   | Graphene nanoplatelets (GNPs) (M5 grade) | - | Squeeze casting + FSP | Tensile | (Ajay Kumar et al., 2020) |

(Continued)
| S. No | Matrix                        | Reinforcement       | Wt.% or vol.% of additions | Methodology               | Properties enhanced                          | Reference                                      |
|-------|-------------------------------|---------------------|---------------------------|---------------------------|----------------------------------------------|------------------------------------------------|
| 15    | Cylinder-head aluminum alloys | Nano clay particles | -                         | -                         | Hardness, Tensile                            | (Rashnoo et al., 2020)                         |
| 16    | A356                          | Fly ash (2.11 µm) and red mud (0.4 µm) | -                         | FSP                       | Hardness, Tensile                            | (H. Kumar et al., 2020)                       |
| 17    | A356                          | SiC (50 nm)         | 1                         | Stir casting, hot rolling | Tensile                                      | (Mousavian et al., 2020)                      |
| 18    | A356                          | WC                  | 1–5                       | Stir casting               | Hardness, Tensile                            | (Krishna et al., 2018)                        |
| 19    | A356                          | Cu                  | 5–15                      | Stir casting               | Hardness                                     | (Gopi Krishna et al., 2018)                  |
| 20    | A356                          | SiC                 | 10,20,25                  | Semi solid stir casting    | Hardness                                     | (Ghandvar et al., 2017)                       |
| 21    | A356                          | TiC                 | 10                        | Stir casting               | Hardness                                     | (Joseph et al., 2020)                        |
| 22    | A356                          | Ash                 | 2–10                      | Liquid metrological technique | -                                           | (Sridhar et al., 2020)                       |
| 23    | A356                          | B₄C                 | 4                         | Two stage melt stirring process | Hardness                                    | (Jadhav et al., 2017)                        |
| 24    | A356                          | Al₂O₃ and SiO₂      | -                         | Friction stir processing   | Hardness                                     | (Jalilvand et al., 2019)                     |
| 25    | A356                          | Nano SiCₚ           | 2                         | Ultrasonic vibration (UV) treatment and squeeze casting | Tensile                                    | (Yuan et al., 2019)                          |
| 26    | A356                          | SiC (80 nm)         | 0–5                       | Stir casting               | Hardness                                     | (Yaghobizadeh et al., 2019)                  |
| 27    | A356                          | MWNT, Mg            | 0.5–1; 0.25–0.5           | Stir casting               | -                                            | (Hanizam et al., 2019)                       |
| 28    | A356                          | SiC (50–56 µm)      | 1                         | Ultrasonic and hybrid (both mechanical and ultrasonic) stirring methods were applied | Tensile                                     | (Aybarc et al., 2019)                        |
| S. No | Matrix | Reinforcement | Wt.% or vol.% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|---------------|---------------------------|-------------|---------------------|-----------|
| 29    | A356   | SiC<sub>x</sub> and Al<sub>2</sub>O<sub>3</sub> <sub>np</sub> | 1 | Semi-solid vortex casting process and hot rolling | Hardness, Tensile | (Behnamfard et al., 2019) |
| 30    | A356   | SiC and Al<sub>2</sub>O<sub>3</sub> | 1.5 | Electroless metallic coating followed by stir casting | Hardness, Tensile | (Afkham et al., 2018) |
| 31    | A356   | SiC<sub>p</sub> (3 µm) | 5 | Stir casting and compocasting | - | (Amirkhanlou & Niroumand, 2011) |
| 32    | A356   | ZrO<sub>2</sub> | 5, 10, 15 | Stir casting | Hardness, Tensile | (Abdizadeh & Baghchesara, 2013) |
| 33    | A356   | TiB<sub>2</sub> (20 nm and 5 µm) | 0, 0.5, 1.5, 3, and 5 | Stir casting | Tensile | (Karbalaee Akbari et al., 2015) |
| 34    | A356   | Al<sub>2</sub>O<sub>3</sub> (20 nm) | 1.5 | Stir casting | Tensile | (Karbalaee Akbari et al., 2013) |
| 35    | A356   | SiC | 1 | Modified stir casting | Tensile | (Dehghan Hamedan & Shahmri, 2012) |
| 36    | A356   | SiC | 5; 10; 15 | Electromagnetic stir casting | Hardness, Tensile | (Dwivedi et al., 2014) |
| 37    | A356   | Al<sub>2</sub>O<sub>3</sub> (16 µm) | 0.75, 1.5, 2.5, 3.5 and 5 | Stir casting | Hardness, Tensile | (Mazahery et al., 2009) |
| 38    | A356   | TiC | - | Mechanochemical activation process + stir casting | Tensile | (Borodianskiy et al., 2011) |
| 39    | A356   | SiC | 3 | Stir casting | Hardness, Tensile | (Mousavian et al., 2017) |
| 40    | A356   | SiC<sub>p</sub> (25 µm); Gr (44 µm) | SiC (0–9); Gr (3) | Stir casting | Hardness, Tensile | (Viswanatha et al., 2013) |
| 41    | A356   | B<sub>4</sub>C | 3 | Stir casting | - | (Khademian et al., 2017) |

Table 8. (Continued)
| S. No | Matrix | Reinforcement | Wt.% or vol.% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|---------------|----------------------------|-------------|---------------------|-----------|
| 42    | A356   | SiC           | 0.5, 1.0 and 2.0           | Transient cavitation and acoustic streaming | -         | (Yang et al., 2004) |
| 43    | A356   | B₄C (65 µm)   | 10                         | Stir casting | Hardness, Tensile  | (Lashgari et al., 2010) |
| 44    | A356   | Al₂O₃ (20 nm) | 1.5                        | Stir casting | -                   | (Akbari et al., 2013) |
| 45    | A356   | SiC (5 µm)    | 10                         | Accumulative roll bonding (ARB) and continual annealing and roll-bonding (CAR) | -         | (Jamaati et al., 2012) |
| 46    | A356   | SiC           | -                          | Squeeze casting after ultrasonic treatment (UT) | Tensile   | (Hu et al., 2018) |
| 47    | A356   | SiC₉₀ (34 µm) | 5, 10                      | -           | Hardness, Tensile  | (Mohan & Sajikumar, 2020) |
| 48    | A356   | Si₃N₄         | 10; 20; 30 mf              | Powder metallurgy | -       | (Fernández et al., 2019) |
| 49    | LM6    | Graphite, Si₃N₄ | 3; 3                      | Gravity die stir casting | Wear | (Ambigai & Prabhu, 2019) |
| 50    | A359   | SiC+ Si₃N₄ (35 and 3 µm)  | 5; 10; 15                | Stir + squeeze casting | -        | (Shalaby et al., 2016) |
| 51    | A356   | Al₂O₃, SiC and Gr | 1-5                      | Squeeze casting method | Hardness, Tensile | (Senthil Kumar et al., 2020) |
| 52    | A359   | TiB₂, TiO₂, and TiC (15-25 µm)  | 6                        | Gravity casting technique | Hardness, Tensile | (Radhika et al., 2020) |
| 53    | LM4    | WC            | -                          | -           | Wear                | (P. N. S. Kumar et al., 2020) |
| 54    | A356   | TiB₂          | 5                          | Thixoforming | Wear                | (Deepak Kumar et al., 2019) |
| 55    | LM4    | TiB₂ (14 µm)  | 2.5, 4 and 5.5             | Stir casting | Wear                | (Poria, Sutradhar, Sahoo, et al., 2019a) |
| S. No | Matrix | Reinforcement | Wt.% or vol.% of additions | Methodology | Properties enhanced | Reference |
|-------|--------|---------------|---------------------------|-------------|---------------------|-----------|
| 56    | LM4    | TiB₂ (5 μm to 40 μm) | 2.5, 4, and 5.5 | Stir casting | -                  | (Poria, Sahoo, Sutradhar, et al., 2018a) |
| 57    | LM4    | TiB₂ (5-40 μm) | 2.5, 4, and 5.5 | Stir casting | -                  | (Poria, Sahoo, Sutradhar, et al., 2018b) |
| 58    | LM4    | TiB₂ (5-40 μm) | 2.5, 4, and 5.5 | Stir casting | -                  | (Poria et al., 2017) |
| 59    | LM25   | Activated carbon, Mica | 10 | Stir casting | Hardness | (Sarada et al., 2015) |
| 60    | A356   | SiC, TiB₂ (20 and 30 nm) | 14; 16 | Thixoforming, ultrasonic treatment | Tensile | (Kandemir et al., 2015) |
| 61    | LM6    | Si₃N₄ (20 μm) | 2-10 | Stir casting | Hardness, Tensile | (Raghavendra Rao & Mohan, 2020) |
| 62    | LM4    | AlN | 0-12 | Stir casting | Hardness, Tensile | (Mohanavel, 2019) |
| 63    | LM4    | TiB₂ (5 to 40 μm) | 1, 2.5, 4, and 5.5 | Stir casting | Hardness | (Poria, Sutradhar, Sahoo, et al., 2019a) |
| 64    | LM4    | WC (150 to 200 nm) | 0-2 | Powder metallurgy | Wear | (Manuscript, 2019) |
| 65    | LM25   | Si₃N₄ (40 μm) | 10 | Liquid metallurgy and centrifugal casting | Hardness, Tensile | (Radhika, 2018) |
| 66    | LM4    | TiB₂ (5-40 μm) | 1, 2.5, 4, and 5.5 | Stir casting | Hardness | (Poria et al., 2016) |
| 67    | A356   | TiB₂ | 2.5, 5, 7.5, 10 | In-situ technique | - | (Mondal et al., 2009) |
| 68    | A319, A336 and A390 | SiC (32 μm) | 15 | Stir casting | Wear | (Rajeev, Dwivedi, Jain, et al., 2010a) |
| 69    | A319, A390 | SiC (32 μm) | 15 | Stir casting | Wear | (Rajeev, Dwivedi, Jain, et al., 2010b) |
| 70    | LM4    | TiB₂ (14 μm) | 0, 2.5, 4, 5.5 | Stir casting | Wear | (Gavel et al., 2019) |
| 71    | LM4    | Al₂O₃, Mo | 1, 1.5, 2.5 and 5; 0.5 | Stir casting | Hardness, Wear | (Shanmugaselvam et al., 2020) |
| 72    | LM4    | SiC (16 μm, 32 μm and 50 μm) | 0, 6, 12 | Stir casting | Hardness, Tensile, Wear | (Sachit et al., 2018) |
Cáceres et al. (2003) observed the aging of Al-Si-Cu-Mg alloy at 165°C for 8 h. The presence of phases like Al-Cu, Al-Mg-Cu, Al-Mg-Cu-Si alloy, etc. may cause an increase in strength relative to A356 alloy depending on the amount of Mg and Cu and aging temperature. When over-aging is performed, (Mg2Si) precipitates that strengthen dislocations easily cut Al-Mg-Si alloys. In contrast, Cu-rich precipitates become resistant to cut by dislocations which causes an increase in strain hardening because of Orowan looping.

Haro et al. (2009) observed that at an aging temperature of 200°C, the hardness, UTS, and ductility decrease as compared to the aging temperature of 150°C due to a faster rate of diffusion. Tables 4 and 5 show the aging parameters selected by different authors for A319 and A356 alloy with various modifiers and reinforcements, respectively.

Abdulwahab et al. (2011) studied the effect of multiple-step thermal aging treatment on hardness characteristics of A356 alloy. In single thermal aging treatment (STAT), aging of quenched samples was performed at 150°C, 180°C, and 210°C for 1, 5, 18, and 20 h, and then air-cooled. In double thermal aging treatment (DTAT), quenched samples were pre-aged at 105°C for 5 h followed by aging at 150°C, 180°C, and 210°C for 1, 5, 18, and 20 h before cooling in air. Results show that aging at 180°C for 20 h attained the highest peak hardness value (134.9 HVN). However, a hardness of 133 HVN was achieved when the samples were aged at 180°C for 2 h. Therefore, DTAT at 180°C for 2 h aging is preferred but keeping cost in mind (STAT), T6 treatment is the preferred economical choice as far as hardness is concerned.

5.2. Pouring and working temperature

Shi et al. (2021) studied the effect of temperature on Al alloy and observed that at higher temperatures, Cu and Mg-rich phases either coarsen or dissolve into the matrix by affecting the mechanical properties. The formation of tri-aluminide compounds offers alternative solutions because they are more thermally stable and resistant to coarsening.

Vandersluis and Ravindran (2020) stated that continuous spheroidization and coarsening of eutectic Si particles were observed with a high-temperature solutionizing heat-treatment process. Espinoza-cuadra et al. (2010) observed that the rapid cooling helps to achieve small grain size, secondary dendrite arm spacing, and fine eutectic structure after heating to a particular temperature. Medrano-Prieto et al. (2016) stated that the solubility temperature must be below Cu melting temperature to avoid incipient melting. However, it should be high enough to form the Cu phase and achieve the spheroidization of Si. Hernandez-Sandoval et al. (2014) reported that all alloys undergo softening because of changes in density and morphology while testing at high temperatures. Rincón et al. (2007) observed that at temperatures below 270°C, the mode of failure is controlled by continuous cracking of intermetallic particles, including Si, and that at temperatures above 270°C, the mode of failure becomes ductile.

Srinivasan et al. (2006) studied variations in microstructure and mechanical properties of LM25 alloy with different pouring temperatures viz., 720°C, 740°C, and 760°C. Finer structure, DAS, less porosity, and eutectic Si (small-sized) were observed for samples cast at 720°C pouring temperature. At 760°C large Si particles and more pores were observed as shown in Figure 3.

Li et al. (2020) studied the effect of pouring temperature (590°C, 600°C, and 610°C) on die-cast A356 alloy. The results indicated that the number of alpha-Al grains increases with a decrease in pouring temperature and the grain size decreases with an increase in pouring temperature. UTS increased when pouring temperature decreased from 610°C to 600°C. UTS decreased when temperature decreased from 600°C to 590°C. The percentage elongation increased with a decrease in pouring temperature.
Luo et al. (2019) studied the effect of pouring temperature (590°C, 595°C, 600°C, and 605°C) on micro-fused cast A356 alloy. The results revealed that the best-developed grains with uniform microstructure was observed at 595°C pouring temperature when compared to other pouring temperatures. Further, strength and microhardness were higher for samples poured at 595°C.

Ravi et al. (1998) studied microstructures of Al-7Si-0.3 Mg alloy cast at varied pouring temperatures (680–740°C). They concluded that at pouring temperatures below 700°C, Al and Si form intermetallics which slow down the feeding efficiency causing shrinkage porosity. It was also observed that large grains and potential nuclei were destroyed in samples prepared with pouring temperature above 720°C. At pouring temperatures 700–720°C optimum mechanical properties were obtained.

Rincon et al. (2009; Rincón et al., 2007) studied the effect of temperature on tensile property variation in A319 alloy. Tests were conducted from −90°C to 400°C. From the results, they concluded that properties were not much affected below 200°C. Above 200°C, properties attained by heat treatments did not hold well. Below 270°C mode of failure was controlled by intermetallic particle cracking. Above 270°C, it was found to be ductile and manifested by dimple fracture.

Singh and Gupta (2015) studied the pouring temperature (703°C, 723°C, 743°C and 763°C) effect on the surface roughness of A319 alloy. With the increase in pouring temperature surface finish improved. Effects of temperature and changes observed in alloys are shown in Table 6.

According to Dwivedi (2004), initially, wear rate decreases with an increase in temperature. However, the wear rate initially decreases and increases with respect to certain temperatures. Oxidation is the main reason for the initial decrease and silicon content (proportional to critical temperature) is the reason for the increase after a particular temperature. For hypoeutectic Al-Si alloy, 70°C is the critical temperature.

Kumar et al. (2020) studied the wear behaviour of Al-5Si alloy reinforced with WC at elevated temperatures. Load, sliding distance, and track diameter were kept constant to understand the effect of sliding temperature. The results indicated that the wear resistance of composite increased at room temperature and decreased at elevated temperature.

Abdelgnei et al. (2020) studied the wear behaviour of Al-5.7Si alloy (as cast, thixoformed and T6 treated thixoformed) at varying sliding temperatures (25, 150, 300°C), distances, and loads. Compared to as-cast, both the thixoformed samples exhibited better wear properties. T6 + thixoformed samples showed better wear resistance at 300°C sliding temperature as the grains were found to be equiaxed and globular. The best coefficient of friction was observed with T6 + thixoformed sample at 150°C sliding temperature.

Rajeev, Dwivedi, Jain, et al. (2010b) studied the wear behaviour of Al-Si alloy reinforced with SiC particulates. Sliding distance, wt.% of SiC, load, velocity, and counter surface temperature (60°C and 120°C) were varied. The results showed that counter-surface temperature had caused minimal changes in wear, but other parameters had a strong impact on the wear of the material.

From their work, Rajaram et al. (2010) concluded that with an increase in temperature, wear resistance also increases because of the oxide layer formation.

Zhang et al. (2020) studied the wear behaviour of Al-Si alloy reinforced with Al2O3. The results disclosed that the composite displayed better wear properties than the alloy. However, the trend observed was similar in both cases. In the 100–200°C temperature range, wear resistance
increased with an increase in temperature. The decreasing trend started when the temperature was raised from 200°C to 300°C.

5.3. Cooling rate
Robles Hernández and Sokolowski (2009) observed that size, eutectic Si, pore size, shape, phase distribution, and dendrites are directly affected by cooling rates. Ibrahim, Samuel, Samuel, Al-Ahmari, Samuel, et al. (2011a) reported that under cooling rates close to equilibrium conditions and at 540°C for A3XX alloys, results in the formation of Mg2Si precipitates, at the lowered temperature 490–530°C precipitation of Al2Cu intermetallic phase was observed in the microstructure. Vandersluis et al. (2015) noted that the higher cooling rate leads to the formation of fine dendritic structure, intermetallic compounds, and less porosity. Firoozdor et al. (2007) observed that mechanical properties are directly affected by cooling rates that change secondary dendrite arm spacing and grain size.

Ibrahim, Samuel, Samuel, Al-Ahmari, Samuel, et al. (2011a, 2011b) studied the effect of cooling rate on microstructure and hardness variations in A319 alloy with varying Mg and Sr content. Two molds, one for a higher cooling rate (star mold) and one for a lower cooling rate (L-shaped), were used. From the microstructures (Figure 4), the cooling rate can control the size and distribution of intermetallic phases. The decreased cooling rate increases the size of the intermetallic phase, which directly affected the hardness of the alloy (hardness, impact toughness increased with an increase in cooling rate).

Vandersluis et al. (2015) stated in their work that increasing the cooling rate of a casting reduces secondary dendritic arm spacing (SDAS), resulting in increased casting strength and reduced casting porosity. Faster cooling rates also encourage the development of finer and rounder eutectic Si particles, as well as a reduction in interdendritic eutectic pockets, both of which improve conductivity.

Firoozdor et al. (2007) studied the effect of the cooling rate of A319 alloy modified with Sr; they found that as cooling rate increases, SDAS decreases, as shown in Figure 5. Elongation percentage, UTS, and YS improved with faster cooling rates.

Lombardi et al. (2014) tried to replicate the microstructure of the engine block cylinder bridge by varying cooling rates of billet cast A319 alloy, which is similar to producing the above-mentioned component. After many iterations, cooling rates 1.5°C/s, 3.8°C/s, and 12.5°C/s successfully replicated SDAS micrographs of the cylinder’s top, middle, and bottom. Higher cooling rate caused decrement in SDAS; also mechanical property improvements were observed.

Bolzoni and Hari Babu (2015) proved that with the addition of Nb-based intermetallic to A356 alloy, columnar grain formation could be avoided, which happens due to slow cooling rates.

Wu et al. (2018) studied the effect of cooling rates and Co addition on Al-7Si alloy. They concluded that with an increase in cooling rate from 2 to 20k/s, the size of Fe-rich intermetallics decreased (acicular to granular), as shown in Figure 6. Finally, Tables 7 and 8 show the effect of modifiers, reinforcements concerning the method employed for dispersion with the type of property expected. It can be used as a research guide for Al319/356 matrix composites.

6. Conclusion
The overall literature analysis reflects that A356, A319 alloy display better castability, good corrosion resistance, and few other characteristics, such as hardness, tensile strength, and tribological characteristics, compared to other aluminum alloys, making it the first choice for aerospace and automotive applications. The stir casting method was favored over other techniques due to its ease, versatility, and cost-effectiveness in mass production. Two-stage melt stirring is preferred as this
eliminates the agglomeration of particles. Stir casting parameters like 15 min and 850°C have been defined as the optimum stirring time and pouring temperature values to eliminate the formation of harmful Al₄C₃ phase. Alloying metals like Mg are added to improve wettability and induce age-hardening behaviour by forming precipitates with Si. 0.45 wt.% of Mg improved alloy response to T6 heat treatment and gave best tensile properties as it refined Si. Tensile properties have improved with an increasing Sr weight percentage, as it helps to refine the eutectic Si. Cu can form an intermetallic phase of Al₃Cu that does not easily dissolve into the matrix. In contrast to other reinforced aluminum matrix composites (Al-SiC, Al-TiC, Al-ZrB₂, and Al-B₄C), TiB₂ reinforced aluminum matrix composites have more efficient tribological and mechanical properties. TiB₂-5.5 wt.% AMMCs gave better results in the as-cast condition. In aluminum matrix (A356) alloy, the presence of Si₃N₄ reinforcement reveals major improvements in grain refinement during solidification. A356 gave better results when reinforced with Si₃N₄ with 6 wt.%, but further increase in the weight percentage of Si₃N₄ reinforcement reduces mechanical properties. Results obtained support the use of Si₃N₄ reinforcements on aluminum alloy for structural applications, and property improvement in the case of cylinder liners in automotive tribo-components for improved performance. Also, TiB₂ particles do not react with molten aluminum, which helps avoid the reaction product of brittle phase compared with SiC and Al₂O₃ on aluminum. To increase wettability and remove the moisture content, TiB₂ particles should be preheated at 600°C to 700°C. Similarly, to achieve better performance, Si₃N₄ particles should be preheated at 300–500°C for around 2–3 h. Multi-phase solution heat treatment gave better results compared to single-step solution heat treatment, and for multi-step solution heat treatment, the optimal solution temperature is 495°C for 2 h and 520°C for 4 h, followed by hot water quenching (60–80°C). Aging is carried out after solution heat treatment, and the optimal temperature for this process is noted to be 170°C for 4 h. The ideal time is 6–12 h for solution heat treatment and 3–5 h for aging.

As a result of studies conducted worldwide on various types of reinforcements on AMMCs, it appears that the combined effect of reinforcement such as TiB₂ and Si₃N₄ on A319 and 356 alloys using different manufacturing methods has remained a less studied area. In light of the scientific understanding and commercial importance, further study is required, particularly the effect of multistage solutionizing, aging treatment, varying weight percentage, and particle size of reinforcement using a low-cost manufacturing stir casting technique. Another open-ended area in which much meaningful research can be done is the behaviour of hybrid composites under solid particle erosion.

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