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Improving Mechanical Properties of Al-Si-Cu Alloy Using Thixoforming Process with T6 Heat Treatment

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الملخص

يعتبر تقنية التشكيل الثيكسوفورمي ناجحة لتشكيل السبائك من الحالة شبه صلبة إلى منتجات شبه شبكية تقريبًا. تهدف هذه الدراسة إلى فحص سلوكيات الخواص الميكانيكية مع التغير البلوري بسبائك thixoformed-T6 Al-5.7Si-2Cu-0.3Mg وإجراء مقارنة مع سبائك الصب التقليدية. تم الكشف عن التركيب الكيميائي لسبائك منحدرات التبريد من خلال الأشعة السينية. تم إجراء المعالجة الحرارية للمحلول عند 485 درجة مئوية لمدة 12 ساعة. تم استخدام المجهر الطيفي البصري ، الأشعة السينية المشتتة للطاقة ، الفحص المجهري الإلكتروني وحيود الأشعة السينية لتحليل تشكيل الطور والتركيب المجهري للسبائك. لدراسة الخواص الميكانيكية تم إجراء اختبار الشد. تشير النتائج إلى أن تطبيق المعالجة الحرارية T6 للبنية المجهرية للمعالجة الحرارية thixoformed-T6 Al-5.7Si-2Cu-0.3Mg أظهرت حبيبات α-Al كروية مع جزيئات Si الموزعة بالتساوي. بشكل عام ، تشير نتائج هذا العمل إلى أنه يمكن استخدام سبيكة Al-5.7Si-2Cu-0.3Mg بنجاح لتشكيل مكونات السيارات.

Abstract:

Thixoforming is considered a feasible technology to form alloys in a semisolid state into almost near net-shaped products. This study aims at examining the microstructural and mechanical properties behaviours related to thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloys and make a comparison with the conventional mould cast alloy. Cooling slope alloys' chemical composition was revealed through X-ray fluorescence. Solution heat treatment was carried out at 485°C at solution times of 12 hours. Optical microscopy, energy dispersive X-ray spectroscopy, scanning electron microscopy and X-ray diffraction were employed to analyse the phase formation and microstructure of the alloys. The tensile test was done to define the mechanical properties of alloy. According to the microstructural improvement and the decreasing in porosity of alloy and showing spheroidal α-Al grains with evenly distributed Si particles due to the applying T6 heat treatment during the thixoforming process. In addition, the mechanical properties of thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloys were remarkability improved, so this alloy can be used sucssefully to produce different components in automotive.

Keywords: Thixoforming, microstructural and mechanical properties, thixoformed, Al-Si-Cu Alloy.

Introduction

The use of aluminium can help to reduce fuel consumption in vehicles due to the resultant weight reduction of automotive components containing this material [1], [2]. Moreover, aluminium also use to produce some component that can protect the environment. In particular, extensive research has been conducted on Al-Si with Mg or Cu or both of them as the main alloying element (3XX.X) due to the attractive properties of such alloys, like a high strength to weight ratio, good castability, low coefficient of thermal expansion, and recycling potential [2], [3]. However, there are some drawbacks to using Al-Si alloys in vehicle components because they have relatively low mechanical properties compared to iron-based materials [4]. However, finding a way to inexpensively incorporate the required mechanical properties into these alloys is still a challenge for the automotive industry. Therefore, there is a significant need to develop a means to improve this property in these alloys.

Elements are being applied to reduce the size of engine and improve the mechanical and physical properties of Al-Si alloys [5]. For example, the addition of a steel liner leads to an increase in the production cost and overall weight of the car and also reduces thermal conductivity [6]. This drawback has given rise to the development of hypereutectic alloys such as A390 that can be used without steel liners. Therefore the challenge remains to find a cost-effective method to make Al-Si alloys strong enough for engine applications that are suitable for high-volume manufacturing. Generally, Al-Si alloys are commonly fabricated by conventional casting methods. Conventional casting processes are low cost and high volume, which is advantageous, but they also produce some defects, containing non-uniformly dispersed coarse and acicular Si particles, hot tears, separated microstructures and porosity [7]. These drawbacks must be overcome in order to ensure acceptable mechanical strength, and ductility for use in practical applications.

Various attempts have been made to increase the quality of the microstructure of cast aluminium alloys through, for example, adding minor alloying elements for instance Mg, Cu, and Zn [8], [9]. These alloying additions seem to improve the mechanical properties of cast Al-Si alloys due to solid solution strengthening and precipitation hardening phases, i.e., Al2Cu and Mg2Si [5].

Recently, the use of semi-solid metal (SSM) processing to produce the final shape of non-dendritic microstructure by using a temperature among solidus and liquidus has become widespread [10]. This process can be used instead of casting and plastic deformation methods and leads to improvements in the mechanical properties of aluminium (Al) and magnesium (Mg)alloys [11], [12], as well as steels [13], [14]. For SSM processing to be successful, it is very important to produce feedstock material with non-dendritic microstructures in order to produce thixotropic properties in the alloy. Thixotropic behaviour was defined for the first time by Péterfi in 1927 [12].

More research is required in order to develop the mechanical properties of Al-Si alloys via controlling their microstructures by suitable casting procedures and heat treatments. The main objectives of this study are to investigate the microstructural evolution and mechanical properties of the new hypoeutectic Al–5.7Si–2Cu–0.3Mg alloy using two processing, conventional mold casting and thixoforming-T6.

Experimental

The X-ray fluorescence (XRF) analysis used to define the chemical composition of the molten alloy of Al-5.7Si-2Cu-0.3Mg alloy based on the criteria of SSM processing. A differential scanning calorimetry (DSC) analysis was carried out to determine the appropriate cooling and heating temperatures for the thixoforming process. The alloy was poured into a mould by utilizing the cooling slope (CS) casting process. The feedstock materials that had a small grain size (GS) and high shape factor (SF) were selected for the thixoforming process.

The procedure used for the preparation of the sample surface and the methods used in the investigation and study of the microstructure, morphology, phases and tensile properties of the thixoformed-T6 alloys are defined. These methods included SEM with energy-dispersive spectroscopy (EDS) as well as the use of an optical microscope (OM), a universal testing machine (UTM) tester.

Aluminium alloys have that can be improved by subjecting them to T6 heat treatment. For the T6 heat treatment, initial the solution treatment was prepared at two temperatures of 485°C, each for a duration of 12 h [15]. The samples were rapidly quenched after solution treatment by plunging them into hot water preheated to a temperature of 60°C where the delay between solution treatment and quenching did not exceed 30s in order to avoid premature precipitation and solid solution maintain. As a final point, the ageing temperature have to be a lower temperature to allow precipitation or precipitation hardening, and this was set at 190°C. The ageing durations for 10 h, and had to be long enough to allow the constituents to enter the solid solution.

The CS plate was arranged to supply different lengths at a 60º inclined angle with cool water circulation underneath as shown in Fig.1.

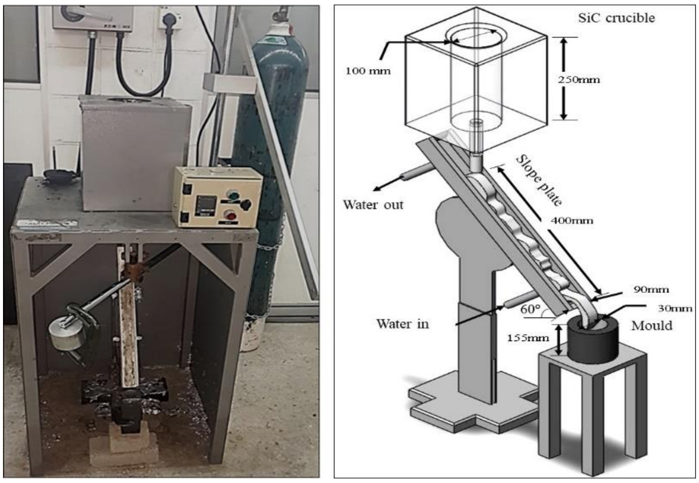

Figure 1.Photograph and schematic of cooling slope casting apparatus.

In this work, feedstock ingots that were produced by using optimum CS processing conditions were thixoformed by a thixoforming press with a vertical pneumatic ram, as shown in Fig.2. The maximum load that could be produced by the pneumatic press used in this experiment was 8 tons at a speed of 85 mm/s. It is very important a high-velocity ram is used so as to reduce the drop in the temperature of semi-solid alloy when it is being compressed by the ram into the die mould.

Prior to being placed in the thixoforming press, the ingots were machined into Ø 25 × 110 mm of bullets. Then, one bullet at a time put on the ram inside an induction coil with, and the bullet placed above the die. A medium frequency used to obtain uniform heating of the globular microstructure to obtain variation in the sample in the semi-solid state. The temperature was checked by using a K-thermocouple that was put in a 3-mm diameter hole drilled in the highest centre of the bullet and other drilled in 5 mm from the outer surface with a depth of 15 mm to a digital temperature display that was situated in a control box. The bullet was quickly heated at a level of about 130°C/min to avoid unwanted grain growing. At that time, after it reached the desired temperature it was maintained isothermally for 5 min to allow spherodisation of the grains to occur. The thermocouple was speedily withdrawn from the slug solely before creating and the bullet was forged inside the die by a pneumatic press. The induction coil system was covered by a closed system of stainless steel casting to establish an argon gas environment because this type of gas helps to reduce oxidation. The argon gas was supplied to the thixoforming compressor at a rate of 2.5 L/min. The mould was heated to 300°C by using a heating coil to minimize the drop in temperature at the top of the mould. Graphite was used as a lubricant.

The thixoforming method was started with placing the rheocast slug in the induction coil on the ram. The slug was placed in a position parallel to the mould that was concentrated with screws at the top of the handle mould. The applied pressure was held for ~15 s and then, the pneumatic ram was lowered back to its original position and the fastening mould was opened, as shown in Fig.3. The ram was also used to push the billet out of the mould. All of the resulting alloy billets had a cyindrical form with the same length and diameter of 80 mm and 30 mm respectively.

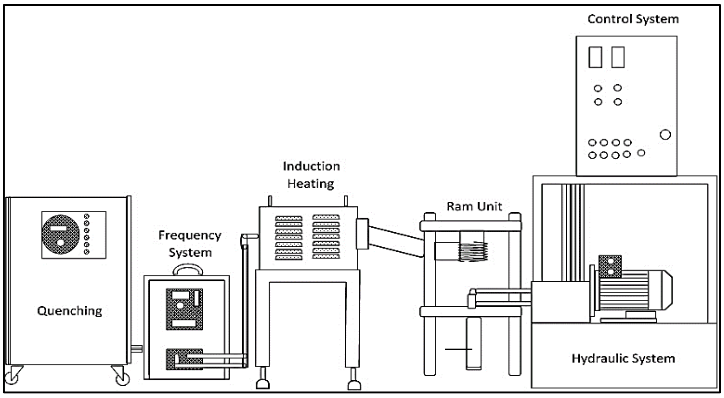

Figure 2. Photograph and schematic of pneumatic thixoforming unit.

The microstructural morphology and hardness property were investigated by carrying out analyses on the thixoformed-T6 alloy. The sample preparation procedures included sectioning, mounting, grinding, polishing, and etching of the studied alloys that were produced under conventional cast, CS, and thixoformed-T6. The samples were transversely cut from the middle into smaller pieces with a diameter of 20 mm and a height of 10 mm. These samples were ground and polished in accordance with the ASTM-E407-2002 standard and ground with 400–1200 SiC grinding paper. Next, an etching treatment was carried out by using Keller reagent. The samples were immersed in the Keller solution for 10 s and then rinsed in flowing water before drying under a hot air flow.

After taking photographs of the samples, the images were analysed to determine the shape factor and grain size. For this purpose Image-J software was used. A high-resolution field emission FESEM equipped with EDS was utilized to observe the morphology of the samples and to analyse the composition of the phases. The different phases in each of as-cast, and thixoformed-T6 alloys were analysed using X-ray diffraction (XRD).

The tensile properties of the alloys were measured by a 100 kN Zwick Roell UTM at 100 N, as shown in Fig.3. The tensile tests were performed in three specimens in each conditions (as-cast and thixoformed-T6) to calculate the main value to obtain reliable tensile results.

The typical gauge dimensions were 30 mm in length in accordance with B 577M-02a. The tensile tests were performed on the three sets of specimens for each condition so as to compute the essential value and get reliable tensile results. Additionally, the yield stress was created on a 0.002 plastic strain offset, while SEM-EDX analysis was used to analyse the fracture surface of the tensile test samples. The test was studied the ultimate tensile strength, yield strength, and elongation before fracture.

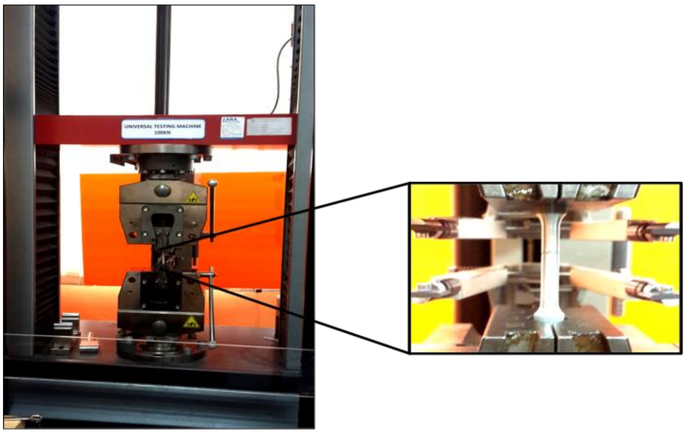

Figure 3. Universal testing machine.

Results and Discussion

All of the as-cast, and thixoformed-T6 samples were analysed by using optical microscopy, SEM-EDX, and XRD to determine the microstructures and phases of each type of sample. The as-cast and thixoformed-T6 alloys were subjected to two mechanical tests to determine their hardness and tensile strength.

The XRF was used to characterize the chemical composition of the as-cast alloy produced by using the permanent mould casting method.

TABLE 1: Chemical composition of the molten alloy.

Alloy	Si	Fe	Cu	Mg	Mn	Zn	Ni	S	Cl	Cr	Ca	Al
	5.67	0.32	1.92	0.32	0.12	0.03	0.02	0.16	0.12	0.05	0.04	Bal.

DSC analysis was performed to obtain data on the as-cast alloy that was more accurate with respect to its thixoformability. Fig.4.shows the results of the DSC analysis and the profile of the liquid contents found in the alloy that was fabricated by using the permanent mould casting method. This analysis was carried out to define exactly the solidus and liquidus temperatures and temperature at 30%–50% of the liquid content of the liquid before the CS casting process.

Based on the results of the DSC analysis, the working window temperature of Al-5.7Si-2Cu-0.3Mg alloy is between 30%–50% liquid fraction at a range of roughly 6ºC. The working window temperature of the alloy is increased to 570ºC. Thus the temperature of the eutectic reaction at 575ºC is above the knee temperature.

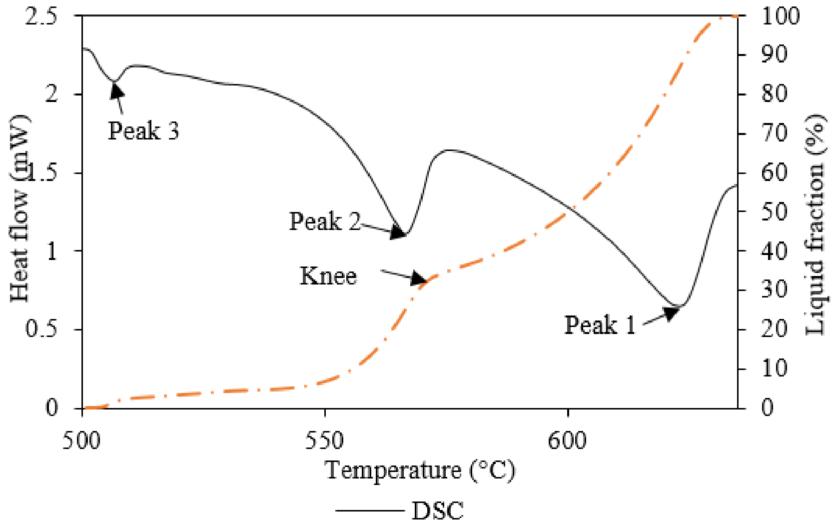

Figure 4. Fraction liquid vs. temperature from DSC graph.

The outcomes of the DSC analysis presented that the fraction liquid sensitivity to temperature of Al-5.7Si-2Cu-0.3Mg alloy is 0.03ºC^{-1}. According to the DSC result in Fig.7, the thixoforming process for Al-5.7Si-2Cu-0.3Mg alloy should generally be carried out at 575ºC at 33% liquid content of binary eutectic reaction.

From Fig.4 it can be seen that the solid temperature and the liquid temperature of Al-5.7Si-2Cu-0.3Mg alloy is 510ºC and 635ºC, respectively. As mentioned before, the solidification temperature is the temperature between the solidus and liquidus temperature. Thus the solidification temperature of Al-5.7Si-2Cu-0.3Mg alloy is 125ºC.

T6 heat treatment is one of the main processes that is utilized to achieve desired mechanical properties, improve the bonding between the intermetallic phases and the Al matrix, reduce the segregation of elements in the Al alloys, and improve the shape and deformation of Si particles. The main reason for applying a heat treatment solution in this study is to obtain a supersaturated solid solution. The artificial ageing treatment is applied to Al-Si alloys not only to improve their mechanical properties, but also to achieve precipitation hardening.

In this study, the morphology of the as-cast samples was modified via two different solution temperatures and multiple ageing treatments to increase the hardness of the alloy. The solution temperature should be less than the melting point of Al_2Cu to prevent any incipient melting. Therefore, the solution heat treatment in this study was carried out in the temperature range of 485 ºC for times of 10 h.

Fig.5 shows the microstructure of Al-5.7Si-2Cu-0.3Mg samples after undergoing T6 heat treatment under the following conditions: 485ºC/12 h and ageing at 190ºC for 10h. It was showed that a incredible change occurs in the Si particles look like elliptical nodules diffusion within the eutectic phase with large α-Al particles occur primary on grain boundaries [15]. As shown in Fig.6, the boundary of eutectic grain that happen in the as-cast sample are flush and mainly eutectic. The Si particles gradually come to be coarsened and rounded. The spherodisation of eutectic Si and improved distribution is clearly evident in the alloy heat-treated under this condition. The phase of eutectic Al-Si with almost spherical Si particles is well dispersed inside the Al-matrix [16].

The as-cast sample shows a graphical element spreading, and afterward heat treatment the microstructure becomes more homogeneous. It can be obviously seen that the heat-treated sample has a greater microstructure with good dispersed Si particles. Most acicular Si have be changed to a granular form in the T6-treated alloy according to the dissolution and spherodisation of eutectic Si particles. This change was taking place according to the needles in the eutectic Si arm were broken down to angles of grain boundary, which eventually spheroidize. These outcomes are in good agreement with the results reported by Samuel (1998) [17] who examined the microstructure of as-cast with heat treatment of A319 alloy and contrasted the result with that for as-cast A319 alloy.

The iron present in the as-cast alloy as β-AlFeSi phase changes to α-Al(Fe,Mn)Si after heat treatment. In addition, β-AlFeSi needles regularly go through necking and fragmentation through heat treatment, whereas the α-AlFeSi needles, which are recognized as 'Chinese-script' particles, remain no-affected [18], [19]. The α-AlFeSi precipitation have a tendency to to steady at the grain boundaries at a solidification high rate and where there is a high content of Si or Fe elements [20]. As regards their particular compacted formula, the α-Fe intermetallics were fewer destructive to the mechanical properties of an alloy compared to the than the β-Fe ones, therefore an α-Fe phase is desirable to a β-Fe phase in the cast microstructure.

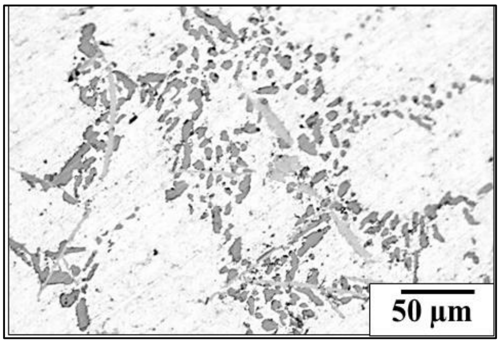

Figure 5. Optical micrographs of thixoformed Al-5.7Si-2Cu-0.3Mg alloy under T6 heat treatment.

It is well recognized that it is not appropriate to use cast alloys directly for SSM processing owing to the presence of dendrites in their microstructure, that made the thixotropic flow of a metal stay incredible [21]. A suitable grain size and a suitable degree of spherodisation are required to promote thixotropic behaviour [22]. However, the shape, size, and supply of the globular solid grains that are enclosed with liquid in the soft zone according to the preparation way [23]. Due to the estimating amount of the average GS and SF for the CS ingots that are presented in the figure the parameters achieve the smallest GS of 31 ± 3 µm and the highest SF of 0.66 ± 0.09.

It is worth noting that a superior microstructure of the billet for thixoforming should be composed of spherical grains and α-Al with an average GS of less than 100 µm and a SF of more than 0.6 [24]. The heating temperature and holding time parameters strongly affect the microstructural evolution during the thixoforming process. Hence, in this study, isothermal heating temperature was applied to the alloy at a liquid fraction of ~35%. At this temperature, the eutectic phase has melted completely while α-Al remains in solid form, as shown in the DSC graph. Melting the eutectic phase completely provides stability during the thixoforming process and can prevent a decrease in the mechanical properties of alloys [25]. A short holding time in the semi-solid state is desired to minimize coarsening of the aluminium primary phase and silicon particles, that caused reducing the mechanical properties.

To examine this problem in this work, the pre-deformed partly isothermally has heated the microstructure of the cooling slope cast alloys was investigated. In order to determine a suitable isothermal soaking time, initially an Al-5.7Si-2Cu-0.3Mg sample was heated to a temperature of 35% liquid fraction (i.e., 575°C) and then soaked at this temperature for 5min before it was quickly quenched in water at room temperature to retain the semi-solid state morphology Fig.6. The micrograph clearly shows that the soaking time was increased to 5 min to attempt to change the spheroidizing shape of the α-Al solids into one that was entirely globular. It is clear from the figure that the microstructure has changed very significantly as the distribution of α-Al particles has become uniform and almost globular with new grain boundaries and spherical particles, when compared with the distribution of the α-Al phase that is obtained by the CS casting process.

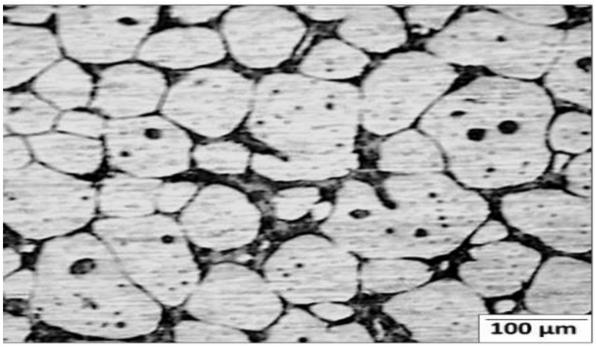

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Figure **6.** Microstructure of Al-5.7Si-2Cu-0.3Mg alloy after isothermal heating at a liquid fraction of 35% for (a) 3 min and (b) 5 min.

Fig.7 presents the optical and SEM morphology of thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloy. Now the thixoformed-T6 sample, the microstructure was not observed to undergo any important changing in comparison with the thixoformed sample, excepting in regards to the morphology of the Si particles and Al_2Cu precipitation. The thixoformed-T6 sample had the highest precipitation of intermetallic Al_2Cu dissolved into the α-Al phase, which is known as the solidification phase, after heat treatment. The microstructure of the thixoformed-T6 sample contains a Cu-rich phase (intermetallic phase Al_2Cu) and spheroidize eutectic Si phase. The Al_2Cu precipitation in the thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloy sample has more intensity than that of the samples made by using other processes.

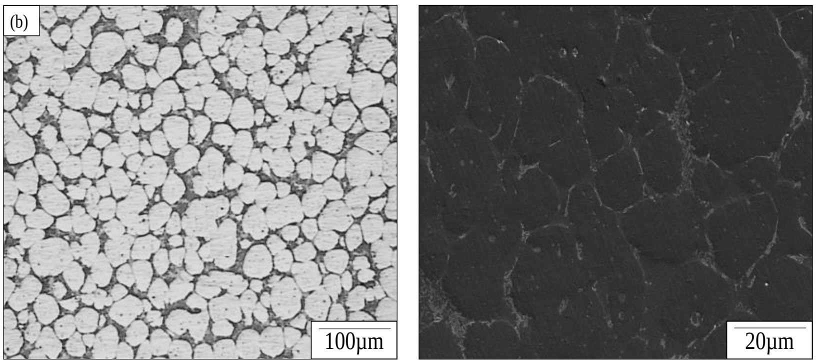

Figure 7. Optical and SEM morphologies of thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloys

Fig.8 observed the XRD results for the as-cast, and thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloy samples. This figure illustrations that the main phases in Al-5.7Si-2Cu-0.3Mg alloy are α-Al dendrites, coarse Al_2Cu, $Al_{15}(Mn\text{-}Fe)_3Si_2$ and β-Al_5FeSi. Furthermore, the Si particles exhibited a homogeneous build-up in the region around the globular α-Al matrix and these particles appear globular inside the α-Al grains in thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloys. The elements Cu, Mg, Fe and O are also homogenously distributed in the microstructure of both alloys. Moreover, β-Al_5FeSi appears in in cooperation the thixoformed and thixoformed-T6 as a needle-like microstructure, which can have an adverse effect on mechanical properties and is difficult to dissolve after solution treatment because the temperature of Fe is higher than the heat treatment temperature. However, when Mn is added to the alloy it moderates the high Fe in Al-Si alloy and reduces the harmful effect of the β-phase by promoting the formation of the α-phase, i.e., $Al_{15}(Mn\text{-}Fe)_3Si_2$ [11]. This process is known as iron neutralization or iron correction, at Mn:Fe ratios of ~0.5 [26].

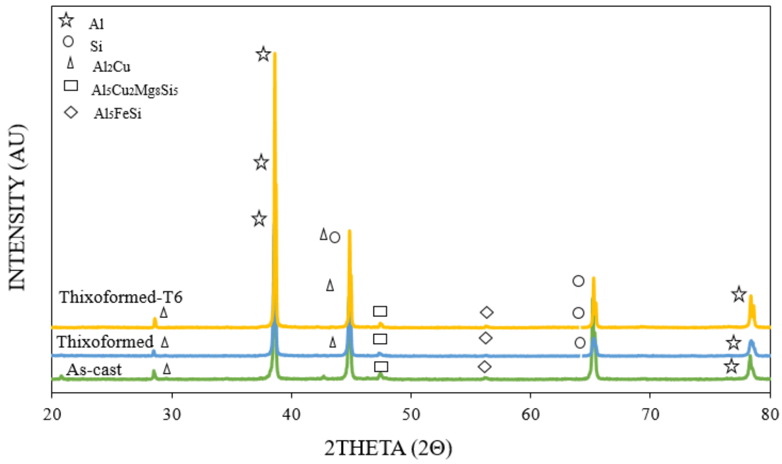

Figure 8. XRD pattern of as-cast, thixoformed and thixoformed-T6 Al-5.7Si-2Cu-0.3Mg.

After obtaining the macrohardness results, tensile test was done to define the ultimate tensile strength (UTS), yield strength (Ys), and elongation to fracture (ε) to further compared the mechanical properties of the samples produced by the different processes. Table.2 shows the average values, which are based on three samples of each of the tested alloys.

In this study, the tensile properties of thixoformed-T6 alloy exhibited the best improvements, with an increase in ultimate tensile strength to about 110% (UTS = 330 MPa) and yield strength increasing by 78% (Ys = 230 MPa) as well as an increase in elongation by 94% (ε = 3.5%) compared to those of the as-cast Al-5.7Si-2Cu-0.3Mg alloy. The increase in the tensile properties of the thixoformed-T6 sample is according to an raise dislocation density, a smaller GS, and an increase in the precipitation hardening of the solid solution. The results for the thixoformed-T6 condition were obtained because the tensile properties are a function of the modified microstructure after solution heat treatment and artificial ageing.

TABLE.2: Tensile properties of as-cast, rheocast, thixoformed and thixoformed-T6 alloys.

Process	TTS (MPa)	Error	YS (MPa)	Error	ε (%)	Error
As-cast	**156**	**4.20**	**106**	**3.30**	**1.80**	**0.03**
Thixoformed-T6	**330**	**4.60**	**230**	**5.10**	**3.50**	**0.04**

It had better noted that the as-cast alloy showed poor tensile properties compared to thixoformed-T6 alloy. The yield strength (Ys), ultimate tensile strength (UTS), and elongation of the as-cast sample is 106 MPa, 156 MPa, and 1.8%, respectively. The thixoformed-T6 alloy exhibits significantly enhanced tensile strength including an ultimate tensile strength of 330 MPa.The UTS of thixoformed-T6 alloy also shows an development in ductility and a reduce in the shape and the size of the eutectic Si particles as well as reduced pore shrinkage, which were due to the T6 heat treatment. Peng et al. (2011) [27] found that the tensile strength and ductility of Al-Si alloys hardly be influenced by on the contraction of the pores. Thus, the thixoformed-T6 Al-5.7Si-2Cu-0.3Mg alloy has the higher mechanical properties.

Based on the results of the tensile tests, the alloys produced by thixoforming-T6 has high ultimate tensile strength compared to the alloys produced by the permanent mould casting processes. The homogeneous and the liquid segregation of the microstructure, beside the size of the α-Al sphere particles, and the unchanging distribution of the compound phase among the metals into the eutectic regions caused the raise in the tensile strength of thixoformed alloys [28], [29]. Therefore, using the thixoformed-T6 process caused in an increase in the tensile properties and strength of alloy because this process produced a microstructure with a uniform morphology, spherical α-Al phase, less porosity and a unchanging distribution of Si and metal compounds in the eutectic alloy.

Fig.9 shows presentative SEM micrographs of the fracture surface of tensile samples of alloys that fabricated using permanent mould casting and thixoforming-T6 process. Tensile properties in as-cast alloy showed less tensile strength and disaster in surface due to needle shape of Si particles and great gas contented that appear due to combine oxides with further elements during solidification liquid material like; Al_2O_3, SiO_2, Mg_2O which attribute to porous as mentioned by the arrow in Fig.9a. When the casting start solidification, the dendrites nearby were shaped coherent networks after the solid fraction varieties from 0.1-0.2 [30], which stops the liquid feeding and great number of reduction pores in the regions, which solidified last. The crack start in intermetallic regions due to limit plasticity in the form of cavities near Si particles. Therefore, the interdendritic region is weak points of as-cast alloy and fracture surface behaviour were explained due to interdendritic mode.

Therefore, the crack in as-cast is high in compared with rheocast sample that observed blocking crack owing to amount of aluminum matrix [31]. The grains retained their shape during deformation by the help of liquid flow and the fine and equiaxed grains and the porosity in thixoformed alloy is extremely decrease due to the quickly compression process of alloy between (7-10 seconds) into a mould while the process runs can be attributed to better mechanical properties in thixoformed and thixoformed-T6 products. α-Al phase was the main the fracture appear primarily by shearing of α-Al phase in thixoformed-T6 samples and they occurred well dimple per void in the eutectic Si particles as presented in Fig.9b.

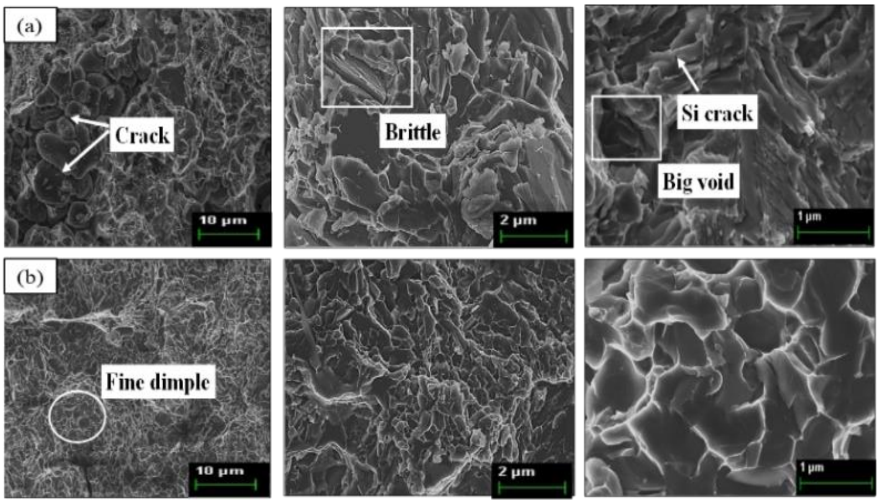

Figure 9. SEM fractographs of (a) as-cast and (b) thixoformed-T6 of Al-5.7Si-0.3Mg alloys.

Conclusion

The major conclusions on the basis of experimental results are as follows:

1) The Al-5.7Si-2Cu-0.3Mg alloy can be successfully used as feedstock material for the thixoforming process due to its large working window temperature, less liquid fraction sensitivity and low solidification temperature range.
2) The use of T6 heat treatment can improve the mechanical properties of Al-Si alloy. However, because Al-5.7Si-2Cu-0.3Mg is a new alloy, In the as-cast sample the microstructure contains α-Al, Si particles, Al_2Cu, and an AlFeSi phase. The T6 heat treatment has a significant influence in terms of improving the microstructure.

3) A rosette-like morphology replaces the dendritic morphology of the primary phase in the as-cast alloy by utilizing the cooling slope casting technique. This change in the primary phase morphology is attributed to the low superheat pouring temperature, fractional solidification of the molten alloy on the cooling plate and the shear forces exerted on the layers of melt during its flow down the plate, which leads to the breaking of the growing dendritic arms. The non-dendritic microstructure of the rheocast Al-5.7Si-2Cu-0.3Mg alloy shows a significant improvement in terms of its mechanical properties due to an improved morphology where the primary crystal α-Al phase is transformed completely from a dendritic to a fine spheroidal microstructure, which has less porosity and shrinkage than the as-cast alloy.
4) The microstructure of the thixoformed Al-5.7Si-2Cu-0.3Mg with T6 heat treatment shows spheroidal α-Al grains with evenly distributed Si particles. The decreased porosity results in a considerable increase in both the tensile properties of the thixoformed-T6 sample. Therefore, currently, the best mechanical properties can be obtained with the thixoformed-T6 alloy, including a yield strength of 330 MPa, an ultimate tensile strength of 230 MPa and an elongation of 3.5%.

References

[1] S. Samat, M. Z. Omar, A. H. Baghdadi, I. F. Mohamed, and A. M. Aziz, “Mechanical properties and microstructures of a modified Al-Si-Cu alloy prepared by thixoforming process for automotive connecting rods,” *Journal of Materials Research and Technology*, vol. 10, pp. 1086–1102, 2021.

[2] S. Manani and A. K. Pradhan, “Effects of melt thermal treatment on cast Al-Si alloys: A review,” *Materials Today: Proceedings*, 2022.

[3] A. Fabrizi, S. Ferraro, and G. Timelli, “The influence of Sr, Mg and Cu addition on the microstructural properties of a secondary AlSi9Cu3(Fe) die casting alloy,” *Materials Characterization*, vol. 85, pp. 13–25, 2013.

[4] E. Vandersluis, A. Bois-Brochu, C. Ravindran, and F. Chiesa, “Mechanical Properties and Conductivity of Low-Pressure Die-Cast 319 Aluminum Prepared with Hot Isostatic Pressing, Thermal Treatment, or Chemical Treatment,” *Journal of Materials Engineering and Performance*, vol. 29, no. 4, pp. 2335–2345, 2020.

[5] A. S. Anasyida, A. R. Daud, and M. J. Ghazali, “Dry sliding wear behaviour of Al-12Si-4Mg alloy with cerium addition,” *Materials and Design*, vol. 31, no. 1, pp. 365–374, 2010.

[6] M. Elmadagli, T. Perry, and A. T. Alpas, “A parametric study of the relationship between microstructure and wear resistance of Al-Si alloys,” *Wear*, vol. 262, no. 1–2, pp. 79–92, 2007.

[7] D. V. Tamayo, G. L. Brollo, J. R. de Oliveira, F. Miani, and E. J. Zoqui, “The Thixoforming Process Window for Al-Si-Zn Alloys Using the Differentiation Method: The Role of Si, Heating

Rate and Sample Mass," *Metals*, vol. 12, no. 5, p. 734, 2022.

[8] K. S. Alhawari, M. Z. Omar, M. J. Ghazali, M. S. Salleh, and M. N. Mohammed, "Dry sliding wear behaviour of thixoformed hypoeutectic Al-Si-Cu alloy with different amounts of magnesium," *Composite Interfaces*, vol. 23, no. 6, pp. 519–531, 2016.

[9] M. Beder and Y. Alemdag, "Microstructural , mechanical and tribological properties of Al-7Si-(0-5) Zn alloys," *Materials and Design*, vol. 63, pp. 159–167, 2014.

[10] B. Shayegh Boroujeny, M. R. Ghashghaei, and E. Akbari, "Effects of SIMA (strain induced melt activation) on microstructure and electrochemical behavior of Al-Zn-In sacrificial anodes," *Journal of Alloys and Compounds*, vol. 731, pp. 354–363, 2018.

[11] M. S. Salleh, M. Z. Omar, J. Syarif, K. S. Alhawari, and M. N. Mohammed, "Microstructure and mechanical properties of thixoformed A319 aluminium alloy," *Materials and Design*, vol. 64, pp. 142–152, 2014.

[12] F. Czerwinski, "Semisolid processing-origin of magnesium molding," in *Magnesium Injection Molding*, Springer, 2008, pp. 81–147.

[13] L. Rogal, J. Dutkiewicz, T. Czeppe, J. Bonarski, and B. Olszowska-Sobieraj, "Characteristics of 100Cr6 bearing steel After thixoforming process performed with prototype device," *Transactions of Nonferrous Metals Society of China*, vol. 20, pp. 1033–1036, 2010.

[14] M. Z. Omar, A. Alfan, J. Syarif, and H. V. Atkinson, "Microstructural investigations of XW-42 and M2 tool steels in semi-solid zones via direct partial remelting route," *Journal of Materials Science*, vol. 46, no. 24, pp. 7696–7705, 2011.

[15] M. A. Abdelgnei, M. Z. Omar, M. J. Ghazali, and M. N. Mohammed, "Investigation of the Optimal Heat Treatment of As-Cast," *Advances in Science and Technology*, vol. 105, pp. 48–58, 2021.

[16] B. Bhushan, *Principles and applications of tribology*, vol. 98, no. 4. John Wiley & Sons, 2013.

[17] F. H. Samuel, "Incipient melting of Al5-Mg8-Si6-Cu2 and Al2Cu intermetallics in unmodified and strontium-modified Al–Si–Cu–Mg (319) alloys during solution heat treatment," *Journal of Materials Science*, vol. 33, pp. 2283–2297, 1998.

[18] S. Alkahtani, "Mechanical performance of heat treated 319 alloys as a function of alloying and aging parameters," *Materials and Design*, vol. 41, pp. 358–369, 2012.

[19] M. Tash, F. H. Samuel, F. Mucciardi, and H. W. Doty, "Effect of metallurgical parameters on the hardness and microstructural characterization of as-cast and heat-treated 356 and 319 aluminum alloys," *Materials Science and Engineering: A*, vol. 443, no. 1–2, pp. 185–201, 2007.

[20] C. F. Ferrarini, C. Bolfarini, C. S. Kiminami, and W. J. F. Botta, "Microstructure and mechanical properties of spray deposited hypoeutectic Al – Si alloy," *Materials Science and Engineering: A*, vol. 375, pp. 577–580, 2004.

[21] K. Flemings, M C Riek, RG Young, "Rheocasting," *Materials Science and Engineering*, vol. 25, pp. 103–117, 1976.

[22] J. Jiang, H. V. Atkinson, and Y. Wang, "Microstructure and mechanical properties of 7005 aluminum alloy components formed by thixoforming," *Journal of Materials Science and Technology*, vol. 33, no. 4, pp. 379–388, 2017.

[23] L. Rogal, "On the microstructure and mechanical properties of alcocrcuni high entropy alloy processed in the semi-solid state," *Materials Science and Engineering: A*, vol. 709, no. 7, pp. 139–151, 2018.

[24] M. A. Abdelgnei, M. Z. Omar, M. J. Ghazali, and M. N. Mohammed, "MICROSTRUCTURE EVALUATION AND MECHANICAL PROPERTIES OF THIXOFORMED," *International Journal of Metalcasting*, no. January, pp. 1–15, 2021.

[25] E. J. Zoqui and M. a. Naldi, "Evaluation of the thixoformability of the A332 alloy (Al-9.5 wt%Si-2.5 wt%Cu)," *Journal of Materials Science*, vol. 46, pp. 7558–7566, 2011.

[26] J. a Taylor, "The effect of iron in Al-Si casting alloys," in *35th Australian Foundry Institute National Conference*, 2004, vol. 31, pp. 148–157.

[27] J. Peng, X. Tang, J. He, and D. Xu, "Effect of heat treatment on microstructure and tensile properties of A356 alloys," *Transactions of Nonferrous Metals Society of China*, vol. 21, no. 9, pp. 1950–1956, 2011.

[28] S.-Y. Lee and S. Il Oh, "Thixoforming characteristics of thermo-mechanically treated AA 6061 alloy for suspension parts of electric vehicles," *Journal of Materials Processing Technology*, vol. 130, pp. 587–593, 2002.

[29] S. Tahamtan, M. A. Golozar, F. Karimzadeh, and B. Niroumand, "Microstructure and tensile properties of thixoformed A356 alloy," *Materials Characterization*, vol. 59, no. 3, pp. 223–228, 2008.

[30] P. B. Li, T. J. Chen, and H. Qin, "Effects of mold temperature on the microstructure and tensile properties of Sic p / 2024 Al-based composites fabricated via powder thixoforming," *Materials and Design*, vol. 112, pp. 34–45, 2016.

[31] L. Kyuhong, Y. N. Kwon, and S. Lee, "Effects of eutectic silicon particles on tensile properties and fracture toughness of A356 aluminum alloys fabricated by low-pressure-casting, casting-forging, and squeeze-casting processes," *Journal of Alloys and Compounds*, vol. 461, no. 1–2, pp. 532–541, 2008.