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Microstructure and bending behaviour of Thixocast (LM25 – SiC) Composite: Effect of processing temperature

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Abstract

In the present work, microstructure and mechanical properties of composite (LM25 -10 SiC) were correlated and compared between gravity cast and thixocast composite having the same composition. Thixocasting of samples was done at 590°C,600°C and 610°C in a cylindrical die. Microstructures and mechanical properties were observed, correlated and compared. The tensile strength, yield strength, hardness and percentage elongation of the thixocast samples were found to be higher than those of gravity cast samples. Improved mechanical properties of thixocast samples are due to non-dendritic globular structure and morphology of silicon particles. The size of dendrite and volume fraction of eutectic phases changes with thixocasting temperatures which causes changes in tensile properties and hardness.

Introduction

In the solid state metal processing, a metal forming that fills partially-solidified metal with globular structure in a mould takes place instead of casting with liquid metal. The first published experiments with the utilization of thixo properties of metals were carried out in 1972. The characteristics of Semi-Solid metal processing are - lower heat content than liquid metal, partially-solidified metal at the time of mould filling, higher viscosity than liquid metal, flow stress lower than for solid metals [1]. It has early been recognized that the main requirement for thixocasting is a non-dendritic microstructure. The resulting spheroidal microstructure was found to possess adequate viscosity and good flow properties so as to assure smooth mould filling and absence of defects such as porosity and shrinkage voids [2]. In the Al-Si-Mg alloys, as the LM25, silicon particles play an important role on the fracture process because of their breaking or de-cohesion from the matrix [2]. Thixoforming combines the advantages of casting and forming thus enabling the production of components with very complicated shaped designs [3, 4]. It is not practical to cast thick parts in conventional die casting, since so much heat needs to be extracted that the die life is significantly shortened and productivity is lower. Semi Solid Metal processing allows die casting to be used to produce a wider range of products [5]. Thixocasting represents a paradigm change in casting. The flow behaviour enables the use of hot runners making casting more competitive with the plastics industry [6]. In high-pressure die casting applications, parts can be produced with higher quality because less turbulent flow is obtained during the mould filling, thereby producing parts with minimal air entrapment and oxide inclusions. The higher quality consequently gives the parts with higher mechanical properties and allows them to be heat-treated, machined, anodized, and welded. In addition to a higher part quality, the production cost of parts produced by semi solid metal processing is lower than of those, produced by conventional liquid pressure die casting [7]. Semi Solid Metal slurry cast into a die requires significantly less heat to flow into the die before the part can be removed. As a result, the die operates at a lower temperature and the die life increases. In addition, since less heat needs to leave the part, the cycle time can be significantly shorter resulting in an increase of the productivity [8]. These factors result in a significant reduction in operating cost when compared with conventional die casting. The materials in semisolid state have lower flow resistance than the material in solid state that's why parts having complicated configuration and thin walls can also be produced. The energy consumption is lowered by approximate 35 to 40% as compared to the conventional processing [9]. Although a number of metallic materials are being considered, presently the aluminium alloys appear to be the most suitable choice for this process. However, to be successfully thixoformed, these materials must exhibit a non-dendritic microstructure, more precisely, one which is formed by equiaxed primary phase (Al-α) well dispersed into a eutectic "liquid matrix". This microstructure exhibits a favourable rheological behaviour which gives good flow characteristics of the alloy into the mould cavity under applied pressure [10]. Thixocasting process improves the component integrity, its performance and mechanical properties and finally leads to improved quality of the products by reducing porosit . Semi Solid Processing of aluminium alloys has already been implemented in Industries. Some existing limitations are associated with the design of dies so that the possible defects can be eliminated [11]. Relatively more literature are available on thixocasting or thixoforming of Al-Si alloys. Understanding on thixocasting of such alloys is crystallized. But a very limited literature exists on thixocasting of aluminium matrix composites [12]. The present paper deals with the possibility of thixocasting Al – SiC composites and their comparison with gravity cast.

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Experimental Procedure

Synthesis of LM25-10SiC composite:

LM125-10SiC composite was made by adding 10 weight% of preheated SiC particles in the LM25 alloy melt. SiC particles were preheated at 600-700°C for around 6 hours before adding in the alloy melt which is simultaneously stirred for making LM25-10SiC composite. The chemical composition of LM-25 alloy is given in Table-1. Initially, LM25 alloy is melted in the electric resistance furnace at temperature range of 700-720°C. Coveral 11 is used as cover flux and dry Nitrogen gas as degasser. Then, during the stirring operation (approx. 500-600 rpm for 3-4 minutes), preheated SiC particles (10 wt%, size: 20 to 60 µm) were added in the melt. Al – TiB_2 master alloy was added in composite melt prior to pouring into the die for casting to achieve relatively globular dendritic structure and grain refinement of matrix material. The liquid composite has been solidified in preheated cast iron molds and cast in the form of fingers and cylindrical billets (Fig. 1).

Table 1 - Chemical Composition (weight %) of LM25 Alloy

Si	Mg	Cu	Mn	Zn	Pb	Sn	Fe	Ni	Ti	Al
7.5	0.2	0.1	0.3	0.1	0.1	0.05	0.5	0.1	0.2	Remainder

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Fig. 1. Composite Finger Castings

Thixocasting

The billets of composite samples were cut from the cylindrical billets of size 75mm×210mm (Fig. 2 a) and were used as feed stock of size 75mm×100mm (Fig. 2 b). These feed stock were heated within cylindrical die (115mm×40mm) at 590°C, 600°C and 610°C to achieve various amount of liquid phases. Finally, these billets were pressurised within the closed cylindrical die (Fig. 2 c) by using a 400 ton pressure die casting machine. Samples were prepared in the cylindrical shape of diameter 15 to 25 mm. The microstructures of the samples were observed and the phases formed were identified. Optical Microscope (Model: RMD-MPD-EQP-1 Leitz, METALLOPLAN, Germany) and Scanning Electron Microscope (Make: FEI) were used. The mechanical properties were measured by UTM (Instron make, Model 8801). The samples were prepared as per ASTM standard.

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Fig. 2 Composite : (a) Cylindrical Billet , (b) Feed Stock , (c) Die Used for Thixocasting

Microstructure Characterization

The composite samples were cut into cube samples of 25mm size and used for microstructure characterization. The samples impregnated with mounting material and then polished & etched using standard metallographic techniques. The polished samples etched in Keller's reagent (2 ml HF +3 ml HCL + 5 ml NO3+ 190 ml water). The microstructures were observed under an optical microscope (Model : RMD-MPD-EQP-1 Leitz, METALLOPLAN, Germany) and Scanning Electron Microscope (Make : FEI). Samples were gold sputtered prior to SEM examination. The grain size determination has been done by Intercept Method as per ASTM E112-13. Volume fraction determination was carried out by Point Counting Method as per ASTM E562-11. Fracture surface study has also been done by Scanning Electron Microscope (Make : FEI) for analysing mode of failures of the specimen during tensile loading. The types and causes of fractures in the material under study were interpreted on the basis of fractography.

Mechanical Properties

Hardness Test

Vickers's Hardness Tester / Micro Hardness Tester (Model: LEICA VMHT 30A) has been used to measure hardness of the gravity cast and thixocast samples, at 1 kg loading. For microhardness test the specimens were sectioned small enough so that it could fit into the tester. Also, the specimen's surface was smoothed enough to allow a regular indentation shape and to ensure that it could be held perpendicular to the indenter. For each sample, hardness was measured at twenty five different locations and the average of these values is taken for analysis of results.

3-Point Bending Test

3 Point Bending or Flexural test is a method to determine the flexural strength of materials. This test was carried out for alloy and composite, gravity cast and thixocast samples, on UTM (Instron make, Model 8801) with 3 point bend fixture with 70mm span length. For each category, samples were tested and the average value is taken for analysis of results.

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Results & Discussions

Thixocast Composite before and after Machining:

The feed stock was thixocast into simple cylindrical billets. The feedstock had the dimension of 40mm×115 mm. These feed stock were again melted in semi-solid regions and cast as per the Al-Si phase diagram. The extent of liquid and solid varies with the variations of temperature of casting. As the casting temperature increases, the volume fraction of liquid phase in the feed stock increases. Hence during casting , the microstructure as well as mechanical properties changes with casting temperature. The volume of feed stock was intentionally made slightly higher as compared to the volume of die cavity. The excess material in feed stock get splashed out of the die cavity after casting (Fig. 3 a). The material flow during casting also visible from the lateral surface of the thixocast billet. When these billets are machined around 1mm the surface does not show any cracks (Fig. 3 b). The density of these machined thixocast samples was also measured. It was noted that the density of thixocast samples is about 2.72 gm/cc and that of gravity cast samples was 2.69 gm/cc. This signifies that thixocast composite samples are more dense than the gravity cast ones. Thixocast samples will have less defects like blow holes and porosity. This observation signifies that LM25-10SiC composite can also be thixocast like Al alloy. The machined billet of thixocast samples (at different temperatures) (Fig. 3 c) showed that the thixocast parts are very sound at every temperature of casting.

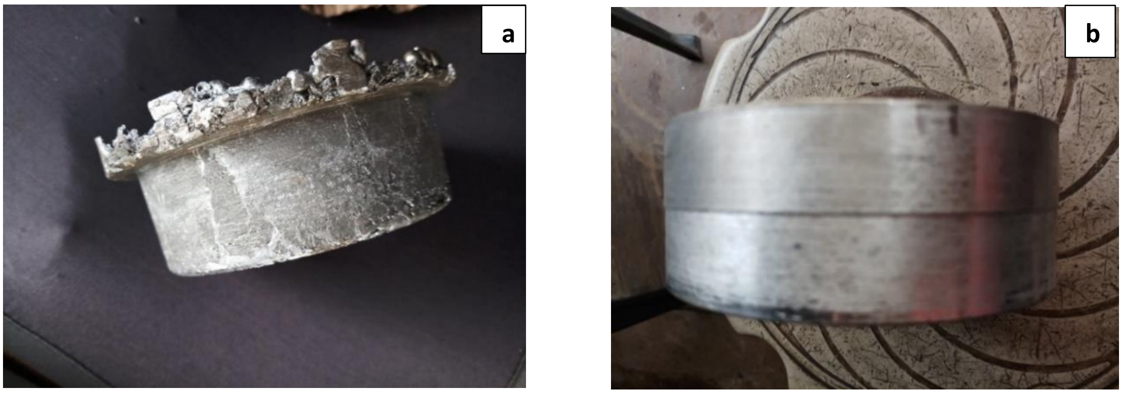

Fig. 3. Thixocast Composite billet : (a) Before Machining (b) After Machining

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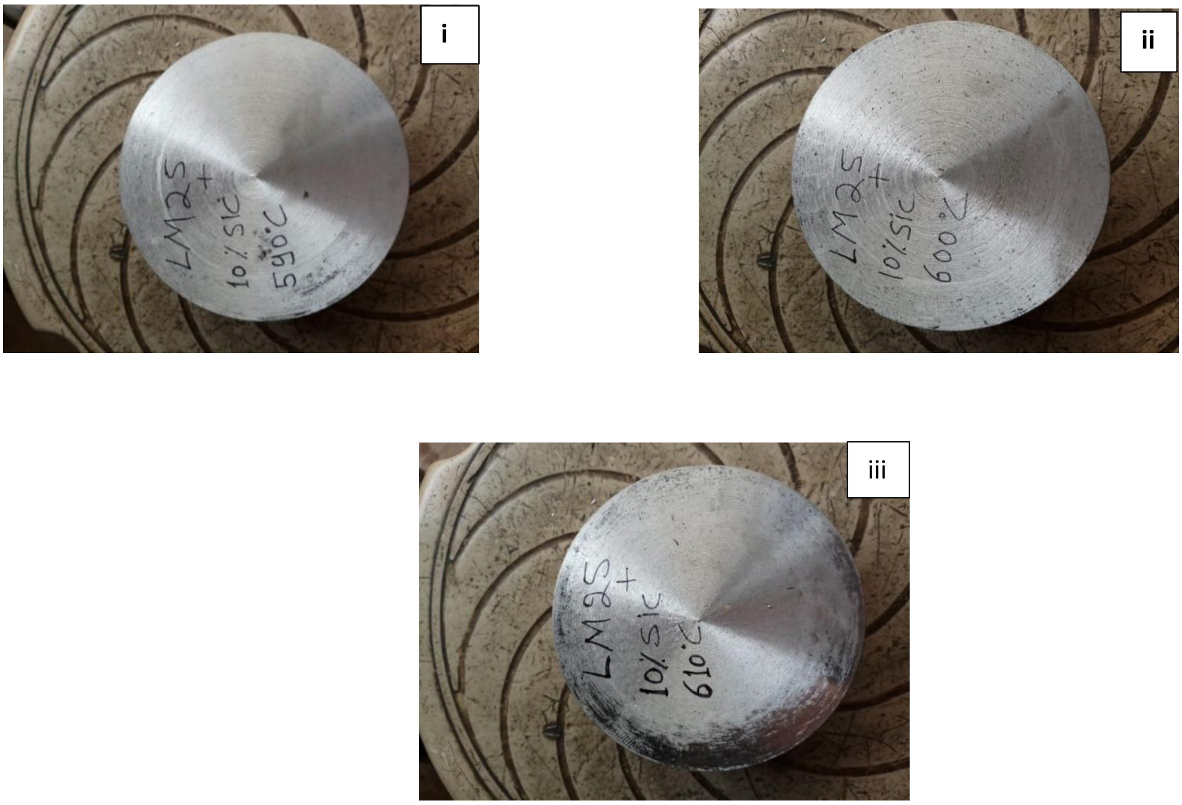

Fig. 3 Thixocast Composite billet after machining (c) : (i) Thixocast at 590°C, (ii) Thixocast at 600°C and (iii) Thixocast at 610°C

Microstructures : Gravity Cast and Thixocast Composite (LM 25 + 10 SiC)

In gravity cast samples a typical dendritic shape of the α-Al phase was observed (Fig. 4(a)), whereas in thixocast samples a non-dendritic (spherical) primary α-Al phase was observed (Fig. 4(b)). The samples thixocast at 590°C shows a very small level of sphericity of α-Al (Fig. 4 (b)). Samples thixocast at 600°c showed little more globular α-Al particles (Fig. 4(c)). At 600°C the primary α-Al phase was more continuous as compared to 610°C processing (Fig. 4 (d)). The eutectic Si phase and α-Al phase (marked 'arrow') in thixocast samples changes with the temperature of casting. The size of α-Al phase here considered as dendrite size or grain size. The sphericity of the dendrite is noted to be higher in case of thixocast samples as compared to gravity cast one. The concentration of α-Al phase decreases with

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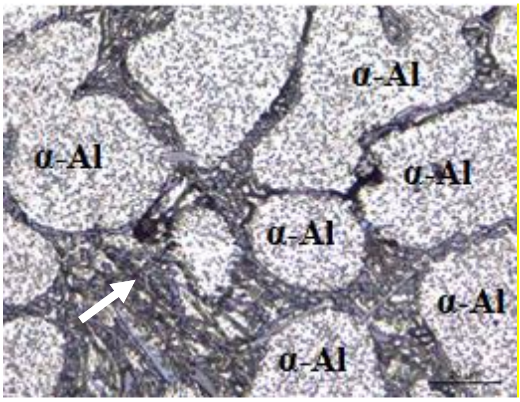
increasing thixocasting temperature. This is quite obvious from the Al – Si phase diagram. It is noted from this observation that casting at higher temperature causes more fluidity and thus casting become more easy. Therefore, porosity present in the materials also reduces which increase the mechanical properties. Improved sphericity in feed stock (Fig. 4(c)) due to TiB_2 addition make this material suitable for thixocasting. But at the same time, after casting, there is a possibility of coarser dendrite size. This will also cause difficulty in casting. As a result, there would be chance of elongation of α-dendrites. As a result, the aspect ratio of α-Al phase (grain) increases marginally. But, in all the cases for thixocasting, the aspect ratio varies in the range of 1.01 to 1.05, which indicates almost spherical shape of the secondary dendrites in the matrix (Table-2). Under pressure, cooling rate may be more. But, when the sample is heated at higher temperature, there is a possibility of growth of α- dendrites and its merger. But, the size of Si in eutectic phase reduces and become more fibrous type when thixocast at higher temperatures. This causes eutectic phase to be stronger when thixocast at higher temperatures. The overall effect of these microstructural characteristics causes an improvement in strength and hardness of the thixocast samples as compared to that of gravity cast ones (Table-2). However, because of the microstructural variation, there is a possibility of optimum temperature of thixocasting for getting maximum strength and hardness.



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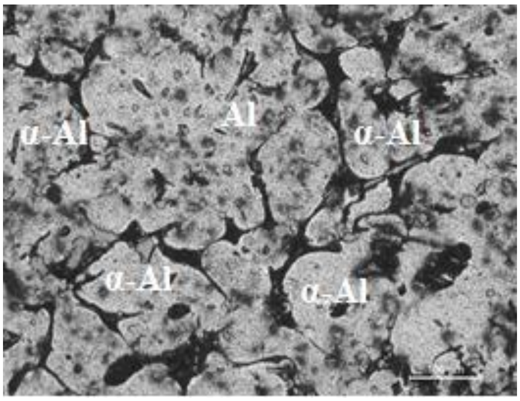

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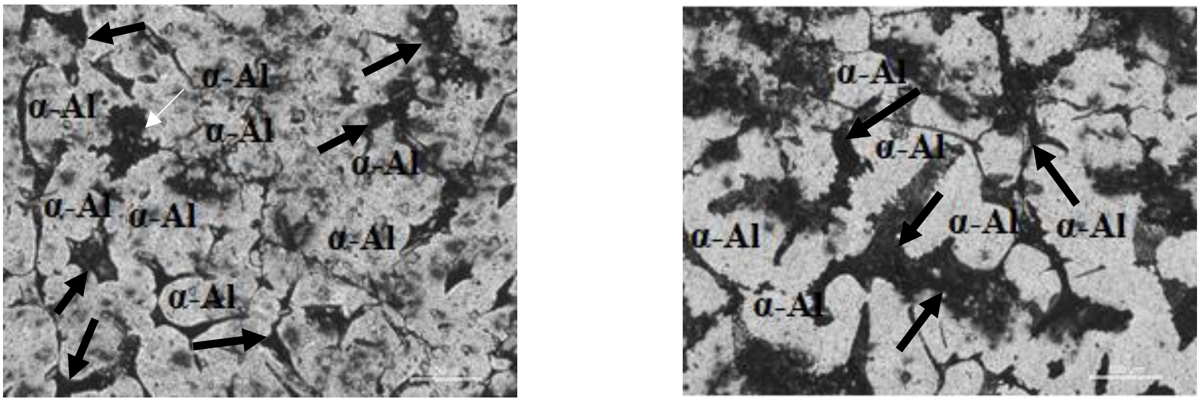

(c) **(d)**

Fig. 4. Microstructures – Gravity Cast and Thixocast Composite: (a) Gravity Cast, (b) Thixocast at 590°C, (c) Thixocast at 600°C and (d) Thixocast at 610°C

Table 2 – Composite (LM 25 + 10 SiC)

Type of Processing	Grain Size (μm)	Aspect Ratio	Hardness HV	Volume Fraction	
				Eutectic	α – Al
Gravity Cast	158	1.26	75	30	70
Thixocast at 590°C	54	1.01	96	48	52
Thixocast at 600°C	78	1.01	99	58	42
Thixocast at 610°C	117	1.05	89	62	38

Hardness & Tensile Properties

The hardness of composite increased after thixocasting. This is due to soundness in casting, spherical α-Al phase, finer silicon needles and fibers. It is observed that the hardness of

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thixocast sample is at least 20% higher than that of gravity cast sample. It is noted that hardness is maximum when samples are thixocast at 600°C. This may be the optimised microstructural characteristics obtained at a temperature of 600°C. At higher temperature α-Al become coarser and Si become finer. But at lower temperature α-Al become finer and Si needles become coarser. In addition, at higher temperature more SiC pushed by the dendrites which may get either embedded in α-Al matrix or segregated to the inter-dendritic region. The results shows that the tensile strength for the thixocast composite samples improved considerably as compared to that of gravity cast samples. It may further be noted that the strength of thixocast samples varies with the thixocasting temperature. The percentage increase in ultimate tensile strength and yield strength for thixocast composite (thixocast at 590°C) is about 37% and 30% respectively as compared to gravity cast composite. The ductility of thixocast composite increased by 20 to 40%. However, the overall ductility is very low (1 to 1.25%). The slight improvement in ductility is due to better bonding between SiC and the matrix. The improvement in strength and ductility in case of thixocast composite is due to microstructural modifications (spherical dendrites) and better bonding between SiC and the matrix. In case of thixocasting, distribution of SiC particles also become more uniform which also would cause high strength and ductility. The decrease in strength with increase in thixocasting temperature is due to coarser dendrite, coarser Si needles and lower amount of α-Al. Because of the same reason the hardness of thixocast sample also varies. It is therefore demonstrated that it is better to conduct thixocasting of composite at lower temperature (590°C). The true stress-strain curves of the investigated materials are compared in Fig.- 5. It may be noted that in each of the materials there is no sharp yield point. In fact, the strain before fracture under tensile loading is very low. This is because of the composite material, where the coarse particles are making primarily the mechanical bonding. The particles are also angular shaped and contain flaws. As a result, under tensile loading, load transfer from particle to matrix may not be effective and causes stress or strain localisation. At the interface, stress get intensified and above a critical stress, debonding on particles took place. If that is not the fact, the particle get sheared. This could be observed from the fractography of fracture samples. From the stress-strain curve yield stress (0.2% proof stress) and ultimate tensile strength are determined and recorded in Table – 3.

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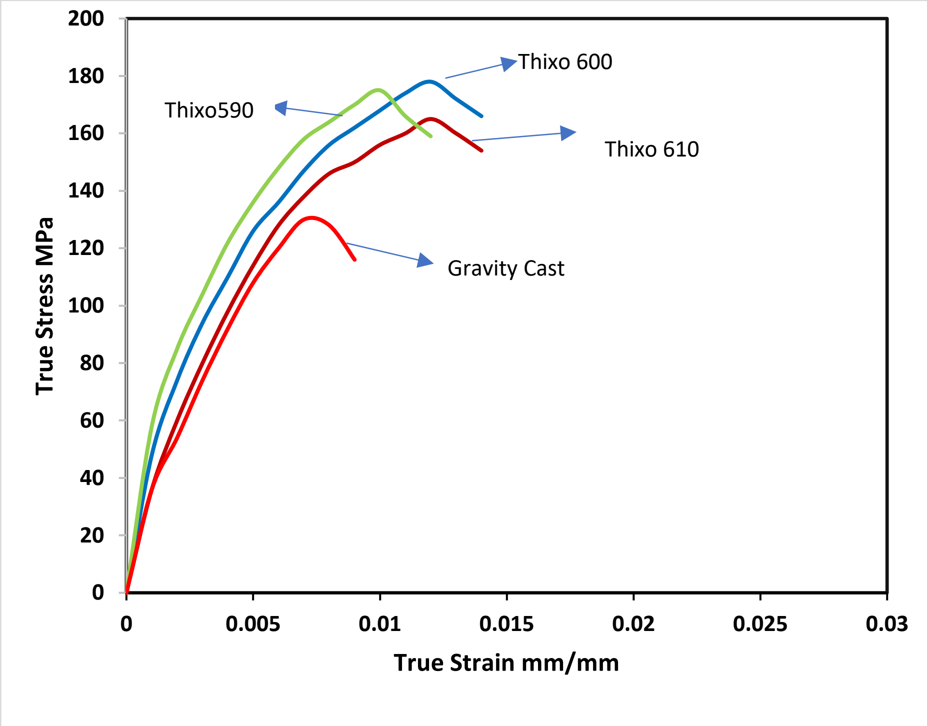
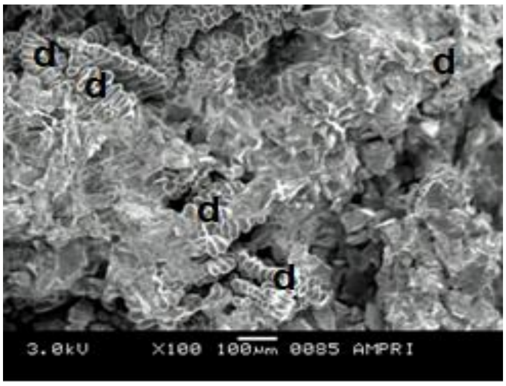


Fig. 5 - Stress-Strain Curves

Fractography

In gravity cast samples, the eutectic phase is the preferred region for crack growth and cause of decreased ductility. Ductility is affected by the aspect ratio of secondary dendrites and distribution of silicon carbide particles. In gravity cast samples, the tensile crack path propagate along the clusters of eutectic silicon particles and the dendrites (marked 'd') are clearly visible on the fractography (Fig.6 (a)). In this case, the SiC is pushed in the eutectic region during solidification, have weak bonding (arrow mark) which causes debonding of SiC particles and decohesion of particles. (marked 'V'). A few particles also get shared (Fig. 6 (b)). Decohesion of particles mostly took as at particle clustering (Fig 6 (b)). But in case of thixocast sample, especially when cast at 590°C, the tree like dendrites structure as was observed in (Fig. 6 (a)) was not observed. Here, the particle matrix interface are more strongly adhered (marked 'arrow', Fig 6 (c)). The fracture surface show ridges and relatively globular matrix structure (marked 'g'). In this case the SiC particles mostly get sheared (marked S, Fig. 6 (c)). Strong particle bonding with shearing even at higher magnification is clear (Fig. 6 (d)). Almost similar kind of fractograph is noted in the sample thixocast at 600°C (Fig. 6 (e)) where particle shearing with strong bonding and globular dendrites are noted. However, in this case, at few places particles get clustered, where particle debonding takes place (Fig. 6 (f), marked 'C'). Particle clustering and their debonding during tensile loading causes reduction in tensile strength. Tendency of particle clustering increases when thixocast at 610°C and as a result particle matrix interface decohesion (marked 'arrow') and particle clustering (marked 'C') increases as compared to that one when cast at 590 or 600°C (Fig. 6 (g)). The clustering of particles, debonding and finally decohesion become more clear at higher magnification (Fig. 6 (h)). This may be another reason for reduction in strength as well as ductility with increase in thixocasting temperature in LM25-10SiC composites. The columnar and coarser dendrite, weak bonding between matrix and SiC are the major causes of lower ductility and strength in gravity cast samples. Thixocast samples shows improved tensile properties due to the low aspect ratio of silicon particles along with low level of porosity. Fracture in thixocast samples found mostly in dimple fracture mode. Dimples formed around the silicon particles which causes the stress concentration. Elongated particles break more frequently than the spherical ones. However, slope in the initial period in stress-strain curve (Fig. 5) showed almost same. This indicate that the Young's Modulus remained unchanged in thixocast or gravity cast composite.



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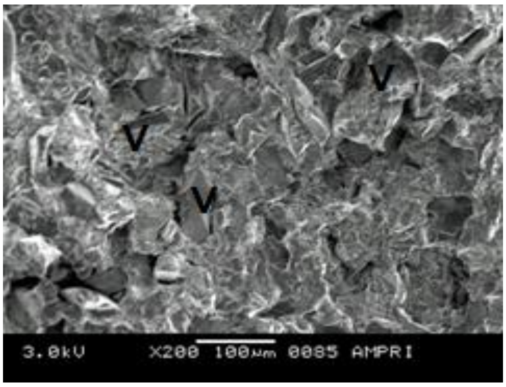

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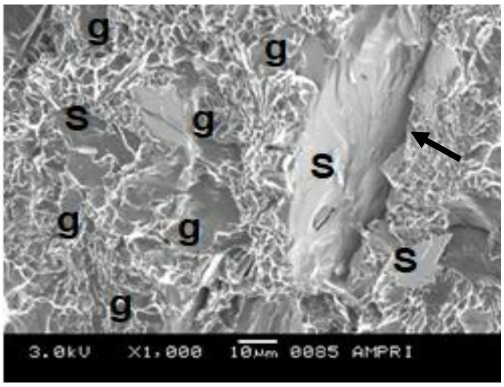

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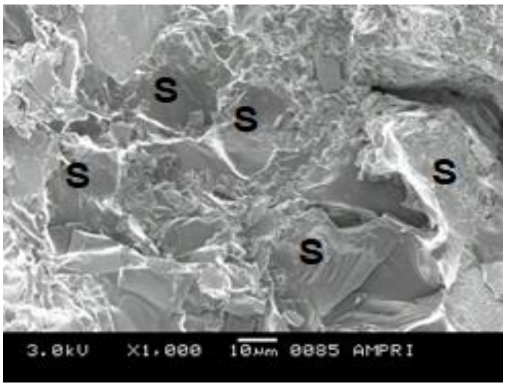

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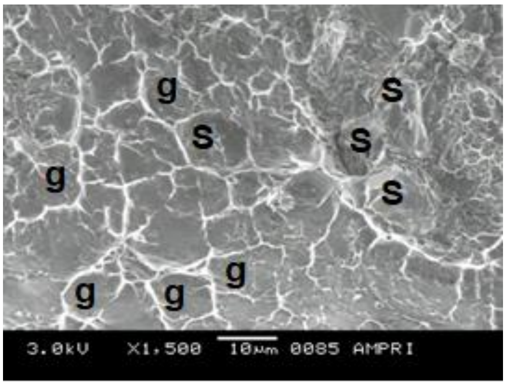

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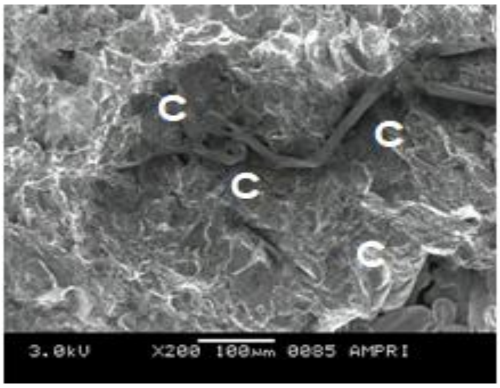

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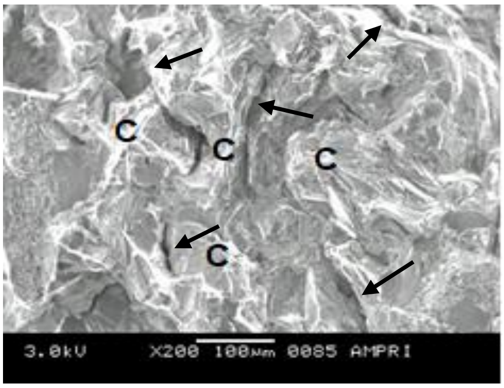
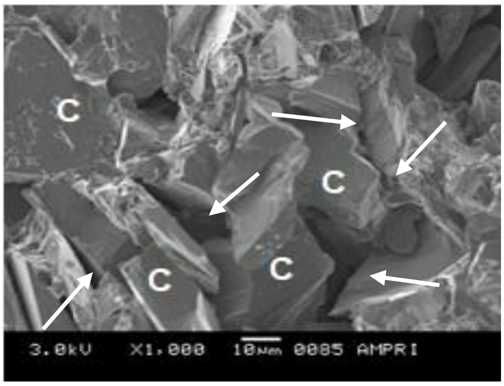


(g)



(h)

Fig. 6. Fractographs : (a) & (b) Gravity Cast, (c) & (d) Thixocast at 590°C, (e) & (f) Thixocast at 600°C and (g) & (h) Thixocast at 610°C

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Conclusion

Thixocast composite (LM25-10SiC) samples were found with significant improvement in tensile properties as compared to the gravity cast samples due to fine and globular microstructure with smaller globular secondary dendrites. Microstructural changes and morphological aspects of silicon phase causes the difference in the tensile fracture paths. The possibilities of fracture increases with long and elongated silicon particles as compared to spherical α-Al dendrites . The size of dendrite and volume fraction of eutectic phases changes with thixocasting temperatures which also causes changes in tensile properties and hardness. In case of gravity cast samples, primarily, decohesion of SiC particles takes place during tensile fracture. But in thixocast sample, particle shearing is the major mechanism of tensile fracture. The SiC particle distribution and its interface bonding are much better when thixocast at 590°C. But with increase in thixocasting temperature, the possibility of particle clustering and its decohesion from specimen surface increases. These causes reduction in strength and ductility with increase in thixocasting temperature. Thixocasting at lower temperature is expected to give better microstructure and mechanical properties.

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