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Microstructure and Tensile behaviour of Thixocast LM25 Alloy: Effect of processing temperature

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Abstract

In the present work, microstructure and mechanical properties of thixocast LM25 alloy were correlated and linked with gravity cast LM25 alloy having the same composition. Thixocasting of samples was done at 590°C, 600°C and 610°C within a cylindrical die. Microstructures and mechanical properties were observed, correlated and compared with those of gravity cast samples. The yield strength, hardness, tensile strength and percentage elongation of the thixocast samples found to be greater than those of gravity cast samples. Improved mechanical properties of thixocast samples are due to non-dendritic globular structure and morphology of silicon particles.

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Introduction

Semi-Solid metal processing is an important metal forming process that fills partially-solidified metal with globular structure in a mould, as a substitute of casting with liquid metal [1]. The first published experiments with the utilization of thixo-properties of metals were carried out in 1972. These experiments were done with tin-lead alloys at a temperature interval between solidus and liquidus, thus in a semi-solid state. These properties almost immediately became the centre of attention of many research groups, which investigated the hidden potential of this method. Semi-solid metal manufacturing properties are: lower heat content over liquid metal, partially solidified metal at mold filling time, higher viscosity than liquid metals, and lower flow stress than solid metals. [2]. For different applications, these features give some possible advantages. Semi-solid metal processing makes it possible to create materials with complex structures, thin walls, high mechanical strength, and high dimensional tolerance and accuracy [3, 4]. The thixocasting process utilizes melt stirring at the time of the crystallization of a continuous cast bar to obtain the globular microstructure [5]. These bars are therefore cut to the parts needed and heated to the temperature of the hotworking phase. A modern technology that provides many advantages over liquid processing and solid processing is semi-solid metal processing (SSM). This approach utilizes semi-solid behaviour and, during the shaping process, decreases macro-segregation, porosity and formation forces. In order to utilize the capacity of this method to make different goods, particularly for the automotive industry, a lot of studies have been carried out by different scientists. [6]. It was shown that processes of semi-solid metal formation have many advantages over many other traditional processes of manufacturing. It include better product quality, decrease in temperature of creation, and a high rate of production. Semi-solid metal processing is a new metal forming technology that provides one-step operation of net-shape metal multi component geometry. [7]. An alloy seems to have a much higher viscosity as a semi-solid slurry than when completely liquid, thus retaining laminar flow and filling the die more uniformly, enabling the creation of the near-net structure with a single phase operation. [8]. It was demonstrated and confirmed many times that the most stable rheocast flow occurs in around 50% solid slurry [9]. Thixoforming combines the features of casting and formation, allowing components with quite complex designs to be made. [6, 10]. Although a number of metallic materials are being considered, presently the aluminium alloys appear to be the most suitable choice for the process. However, to be successfully thixoformed, these materials must exhibit a non-dendritic microstructure, more precisely, one which is formed by a 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 [1]. The aim was particularly to obtain a globular microstructure. Since the first research concerning the forming of steels in a semi--solid state, which were published at the beginning of 1980s, a lot of interesting results have been published. The forming process in a semi-solid state is, however, so useful from the point of view of the shape variations of the product or resulting microstructures, that many innovative variations of this unconventional technology can be expected in the future. Semi solid metal processing or thixo forming is found more suitable in case of Al alloys. As Al is a light metal, it is more effective for the purpose of weight reduction, especially in automobile sector. 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]. It is not practical to cast thick parts in conventional die casting. In addition to high-pressure die forming applications, Semi Solid Metal gravity casting with low solid fractions into such a mould has newly been seen. [12]. Parts can be manufactured with better quality in high-pressure die forming applications because less turbulent flow is generated while mould filling, creating parts with reduced air entrapment and inclusions of oxide. Additionally, the better quality gives better mechanical properties to the components and enables them to be heat-treated, machined and welded. The manufacturing costs of components manufactured by Semi Solid Metal processing are lower than those produced by traditional liquid pressure die casting, in addition to enhanced component quality. [13]. Before the component can be removed, Semi Solid Metal slurry cast into a die needs considerably lower heat to flow into the die. As a result, at a lower temperature, the die works and the life of the die grows. Furthermore, because the component requires less heat, the cycle time can be substantially shorter, contributing to an increase in productivity. [14]. In contrast with traditional die casting, these variables result in a substantial reduction in operating costs. Weight reduction has become one of the transport industry's goals; however, it was shown that replacing steel with Al alloys will lead to a benefit of 20-30 percent, resulting in fuel economy and lower emissions from tail pipes. Advancements in combustion efficiency can, of course, achieve these two final goals, but use of light materials is supposed to be far more efficient. For thick-walled parts with some very simple geometry, thixocasting may be appropriate, in which it can offer low porosity and good ductility for sound castings. These components can-not be manufactured with HPDC and are designed to be machinable, pressure-tight and heat-treatable. Only medium yield strength values are obtained due to fairly coarse grains in the thixocast components. [15]. Today, efforts are being made worldwide to create and incorporate thixocasting because these provide many benefits over traditional methods of processing (liquid casting and forging, die-forging, solid stamping), benefits that derive from the behavior and characteristics of the semi-solid state materials. Thus, high processing rates can be implemented due to the heat content, lower than the liquid metal, with lower wear of the deformation equipment. Thixocasting reflects a shift in paradigm in casting [7, 12]. The solid to liquid ratio varies significantly with minor change in casting temperature especially in Al-Si system. As a result, the microstructure and the mechanical properties of thixocast Al-Si alloy may be changing with casting temperature. The present paper deals with the microstructure and deformation behaviour of thixocast LM25 alloy when cast at three different temperatures.

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Experimental Procedure

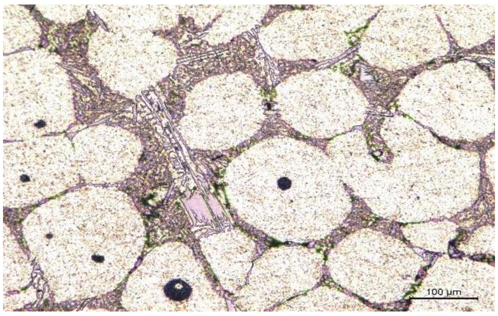
Synthesis of LM25 Alloy

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), Al – (5 weight%) TiB_2 master alloy was added in alloy melt prior to pouring into the die for casting to achieve relatively globular dendritic structure and grain refinement of matrix material. The liquid alloy has been solidified in preheated cast iron molds (Fig. 1 (a)) to get cylindrical billets. The chemical composition of LM-25 alloy is given in Table-1. The microstructure of the feed stock is shown in Fig. 1 (b) which indicate globular dendrite. If TiB_2 would have not been added than columnar dendrite structure would be obtained, which is not suitable for thixocasting.

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

(a)



(b)

Fig. 1 (a) LM25 alloy Finger Castings, (b) Microstructure of Feed Stock

Thixocasting

The billets of alloy (LM25 + TiB_2) samples (75×210 mm) were used as stock. These feed stock were heated within cylindrical die (115×40 mm) 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) by using a 400 ton pressure die casting machine. Samples were prepared in the cylindrical shape of diameter 15 to 25 mm for microstructural observation. Optical Microscope (Model : RMD-MPD-EQP-1 Leitz, METALLOPLAN, Germany) and Scanning Electron Microscope (Make : FEI) were used for microstructural observation. The mechanical properties were measured by UTM (Instron make, Model 8801).

Fig. 2 Die Used for Thixocasting

Microstructure Characterization

The alloy samples were cut into cube samples of 25mm size and used for microstructure characterization. The samples were impregnated with mounting material and after that polished through normal metallographic techniques and etched. The polished samples are etched with 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 (SEM) (Make: FEI). Samples were gold sputtered prior to SEM examination. The grain size determination has been done following Intercept Method (as per ASTM E112-13). Volume fraction of phases was measured with Point Counting technique (as per ASTM E562-11). Fracture surface study has also been done by SEM (Make: FEI) for analysing mode of failures of the specimen during tensile loading.

Mechanical Properties

Tensile Test

The tensile test of gravity cast and thixocast samples were passed out at a strain rate of 0.01per second on standard tensile specimens (as per ASTM standard B557). During the test, the samples were pulled until failure. The stress and strain were recorded in the system interfaced with UTM (Instron make, Model 8801). For each category, three samples were tested and the average of these is taken for analysis of results.

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. The surface of the specimen was also sufficiently softened to permit a periodic indentation form and to assure that it might be kept 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.

Results & Discussions

Thixocast Alloy Before and After Machining

The feed stock was thixocast into simple cylindrical billets. The feedstock had the dimension of 40mm×115 mm. These feed stocks 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 2.70 gm/cc and that of gravity cast samples was 2.68 gm/cc. This signifies that thixocast alloy samples are denser than the gravity cast ones. Thixocast samples will have less defects like blow holes and porosity. 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.

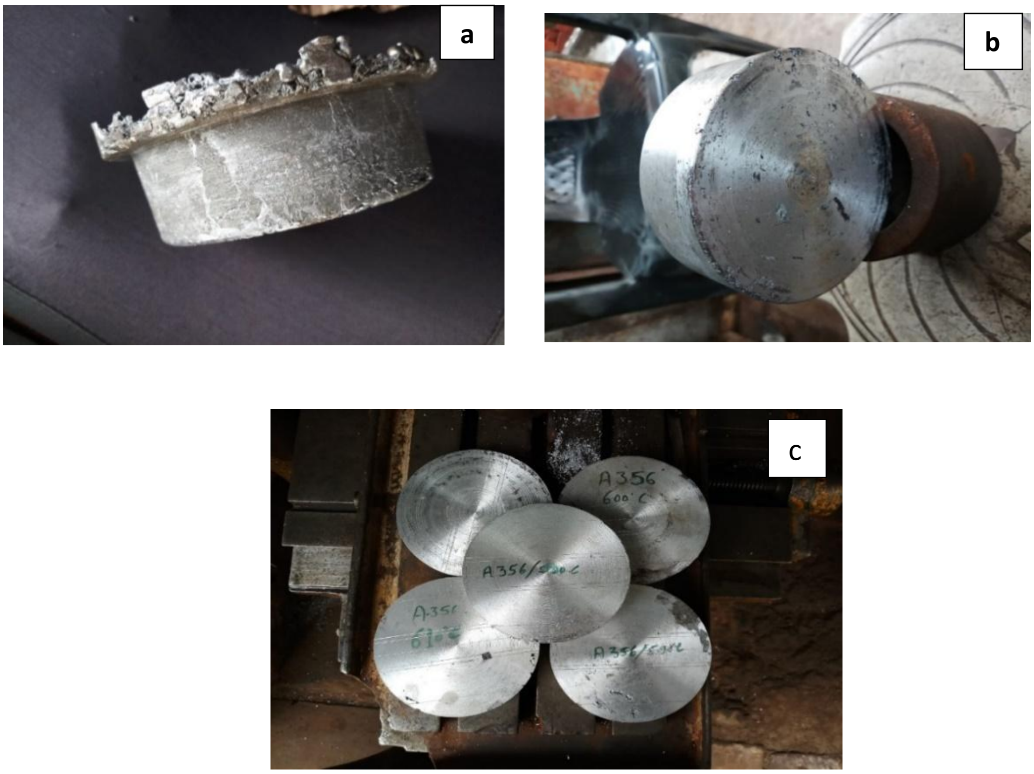


Fig. 3 Thixocast Alloy (a) Before Machining, (b) After Machining &

(c) After Machining (at diff. processing temperatures)

Microstructures: Gravity Cast and Thixocast LM 25 Alloy

In gravity cast samples a classic dendritic shape of the α-Al phase was witnessed, whereas in thixocast samples a non-dendritic (spherical) primary α-Al phase was observed (Fig. 4(a)). The samples thixocast at 590°C shows a very small level of porosity. The microstructure of alloy thixocast at 590°C is shown in Fig. 4 (b). The secondary dendrite became globular. But their sizes are much finer. In between globular dendrites the Al-Si eutectic phases are present. Samples thixocast at 600°C showed little more globular α-Al particles. At 600°C the primary α-Al phase was more coarser as compared to that in 590°C. The eutectic Si phase and α-Al phase 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 volume fraction of α-Al phase decreases with increasing thixocasting temperature. This is quite obvious from the Al – Si phase diagram under applied pressure. It is noted from this observation that casting at higher temperature causes more fluidity and thus casting become more easy. But at the same time, after casting , there is a possibility of coarser dendrite size. This could be observed from micrograph of thixocast samples when thixocast at 600°C (Fig. 4 (b)) and 610°C (Fig. 4 (c)). The secondary dendrite size becomes much coarser at these temperatures. The silicon needle also become larger and thicker. 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 1.42, 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 the fibrous silicon becomes coarser needle shape. This causes eutectic phase to be stronger when thixocast, but its strength decreases 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), but it varies with thixocasting temperature. Excellent mechanical properties of thixocast specimens are not only due to nondendritic microstructure but also due to the finer size of the primary α- Al, which specially results in enhanced elongation to fracture (Fig. 4 (e)). When the aspect ratio increases (more elliptical), tensile and elongation properties decreases. However, because of the microstructural variation, there is a possibility of optimum temperature of thixocasting for getting maximum strength and hardness. Again, when the size of globular dendrite increases, the strength and hardness decreases. It may also be noted that the fibrous silicon (eutectic silicon) are primarily being accommodated at inter globular dendrite sites. It may be noted that in sample thixocast at 590°C, these are finer and no microcracks are present in these regions (Fig. 4 (a)). But when the samples are thixocast at 600°C, the eutectic Si regions shows the presence of microcracks (Fig. 4 (b), marked ‘arrow’). This is also because of coarser dendrite size which is difficult to rotate or move or shared under applied pressure on the semisolid melt. As a result, the cracks are generated. This also causes lowering of strength. It is therefore, understood that thixocasting should be done at higher temperature. It should be conducted at the possible minimum temperature.

Table 2 – LM 25 Alloy

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Type of Processing	Grain Size (µm)	Aspect Ratio	Hardness HV	Volume Fraction	
				Eutectic	α – Al
Gravity Cast	210	1.42	72	48	52
Thixocast at 590°C	42	1.02	81	48	52
Thixocast at 600°C	82	1.01	84	50	50
Thixocast at 610°C	130	1.05	88	60	40

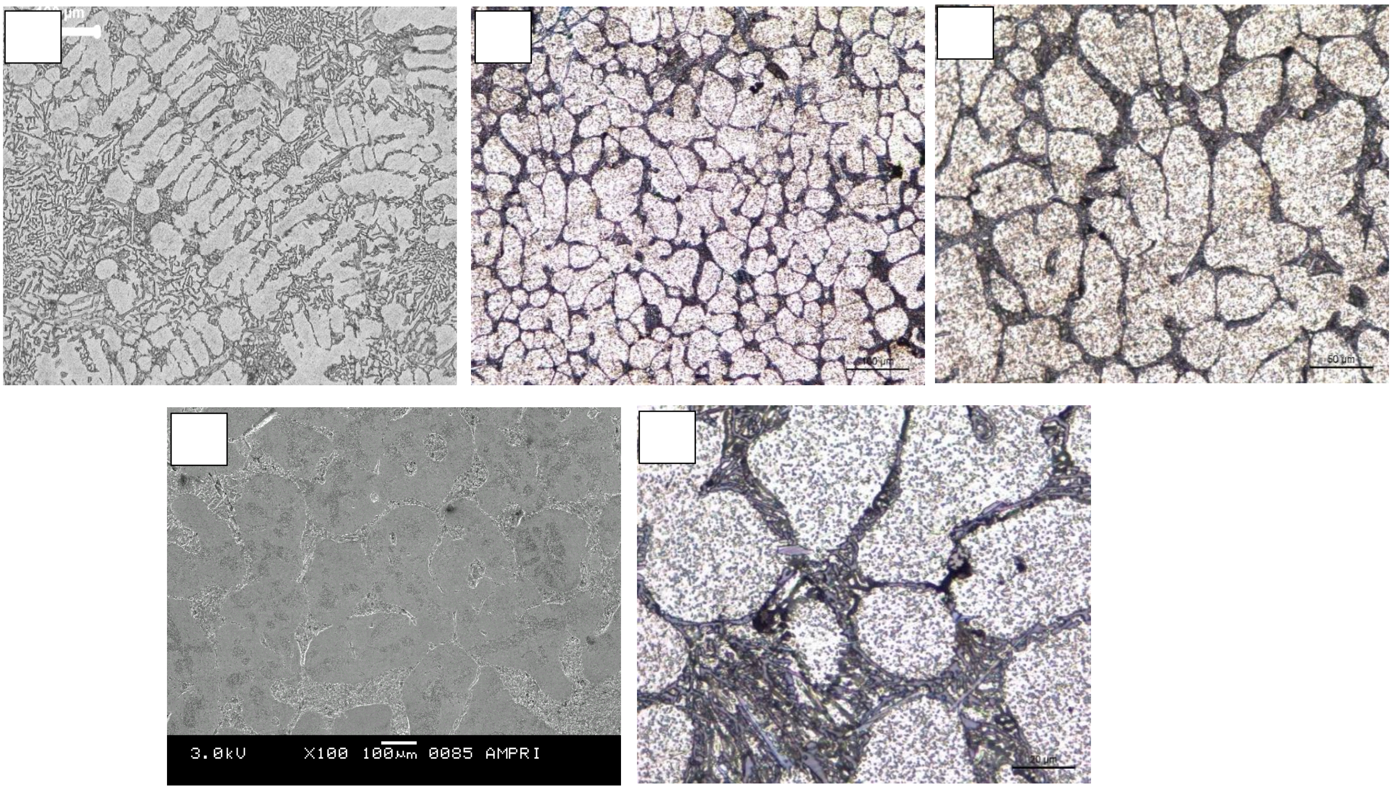

Fig. 4 Microstructures - Gravity Cast and Thixocast LM25 Alloy: (a) Gravity Cast, (b) Thixocast at 590°C, (c) Thixocast at 600°C, (d) Thixocast at 610°C and (e) Nondendritic microstructure with finer α–Al

Hardness & Tensile Properties

The hardness of alloy increased after thixocasting. This is due to strain hardening effect during deformation caused by thixocasting. Low porosity level and increased dislocation density is obtained with the application of pressure during solidification, resulting in the improved tensile properties and increased primary α phase hardness. The findings obtained indicate that for the thixocast alloy, the tensile strength, yield strength and elongation to fracture were greater than many of gravity cast samples. The standard dendritic form of the primary alpha phase was identified in gravity cast samples. The enhancement in mechanical characteristics is due to the non-dendritic structure generated by the silicon process and morphological aspects. Especially in comparison to gravity cast samples, the effect of applied pressure on thixocast samples is more important. As a result of applied pressure the tensile property is improved due to low porosity level and increased dislocation density. Increase in applied pressure results in reduction of globular dendrite size which promotes the improvement in mechanical properties. Furthermore, casting under applied pressure leads to finer fibrous type silicon needle, which also lead to improvement in strength. At higher thixocasting temperature the sphericity of globular dendrite may be almost same, but the volume fraction of dendrite decreases and eutectic silicon increases. This is understood from the phase diagram of Al-Si alloy. But at higher temperature the dendrites are found to be coarser in size and the fibrous silicon size also become coarser. This lead to reduction in strength of thixocast samples with higher casting temperature. But the ductility remains almost same and the alloy exhibits around 8% ductility.

Table 3 - Tensile Deformation Behaviour of LM25 Alloy

Type of Processing	True Stress at Yield (MPa)	True Strain at Yield (%)	UTS (MPa)	Young's Modulus (GPa)
Gravity Cast	100	4.87	123	70
Thixocast at 590°C	145	5.90	170	73
Thixocast at 600°C	130	5.08	152	72
Thixocast at 610°C	125	5.08	142	70

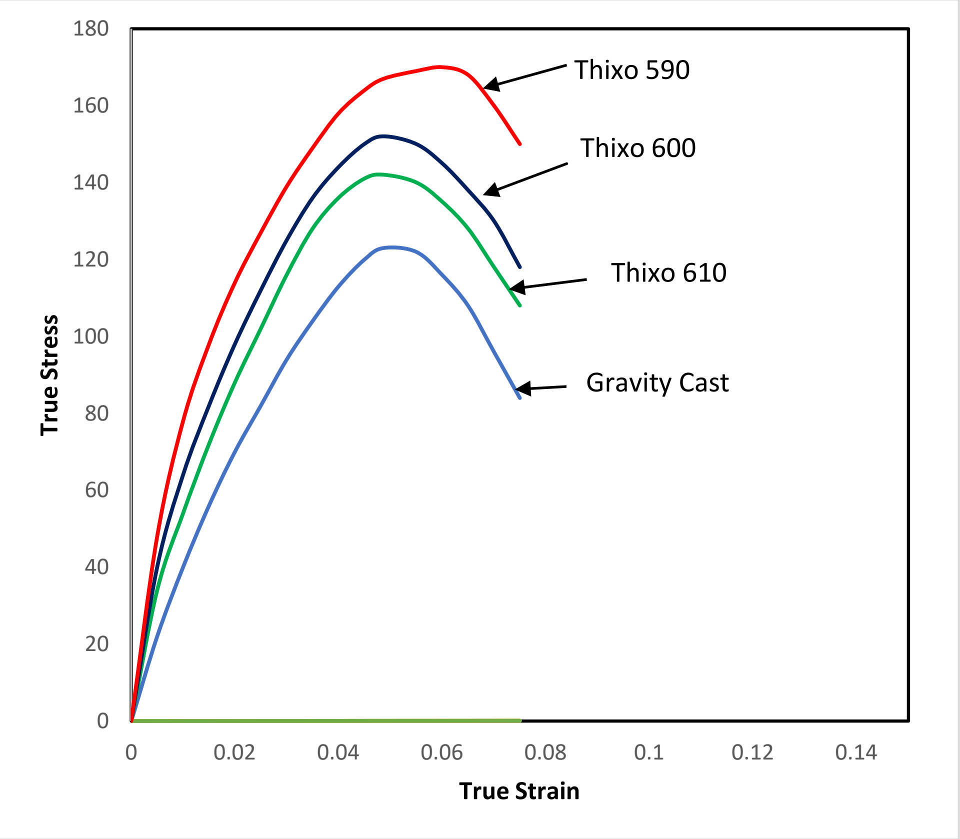

Fig. 5 Stress Strain Curves

Fractography

In gravity cast samples, the eutectic phase between the secondary dendrites is the preferred region for crack initiation and growth and cause of decreased ductility. When subjected to tensile deformation dislocations are generated at the interface with silicon particles. Tensile cracks initially formed in the eutectic area where silicon particles are coarser and large needle type and then propagated either through shear of primary α phase or around the silicon particles. This could be clear from the fractured surface of gravity cast sample as shown in (Fig. 5(a)) (marked 'P') and exposed α dendrites (marked 'O') are clearly visible. At much higher magnification, ridges formed around the dendrites are also examined (marked 'R') (Fig. 5(b)).This demonstrates that a fraction of dendrites gets shared. The presence of porosity act as fracture initiation points in gravity cast samples. It results in very low level of ductility and strength. The possibilities of fracture increases in the presence of long and elongated silicon particles as compared to spherical particles. Morphological properties shows that aspect ratio of secondary dendrites in thixocast samples is near to unity in finer silicon particles or silicon particles with lower aspect ratio outcomes in improved mechanical properties. The probability of silicon cracking depends upon the characteristic ratio. Thixocasting process results in decreased aspect ratio of silicon particles as compared to gravity casting. Also, porosity level gets lowered. Thixocast samples of low processing temperatures shows improved tensile properties due to the low aspect ratio of silicon particles along with low porosity level. Fracture in thixocast samples found mostly in dimple fracture mode when cast at 590°C (Fig. 5(c)). There is no evidence of a tensile direction following the clusters of eutectic silicon particles in the Thixocast samples. As a result the secondary dendrites did not expose after fracture. At higher magnifications (Fig. 5(d)), it may be noted that the dendrites (marked 'D') get shared. But sharing take place in random direction which causes delay in crack propagation. This become more clear when view at much higher magnification (Fig. 5(e)), which clearly depicts the shearing of dendrites and ridges along the sides of dendrites (marked 'R'). As a result, this thixocast alloy also showed less ductility. The fractograph of samples thixocast at 600°C (Fig. 5(e)) shows shearing of spherical dendrites (marked 'D') and ridges along the boundary of these sheared dendrites (marked 'R'). This becomes clearer at higher magnification fractograph (Fig. 5(f)). It clearly depicts shearing of dendrites and ridges along the surrounding area of dendrites. The extent of shearing of dendrites increases in samples thixocast at 610°C because of coarser dendrites (Fig.5(g)) and the ridges. Furthermore, more number of microcracks (marked 'arrow') are observed at the fracture surface (Fig. 5 (h)) in the sample thixocast at 610°C. The presence of microcracks or microcavities is due to difficulty in flow of large size dendrites. This also causes reduction in strength as well as ductility when samples are thixocast at higher temperature. Elongated particles break more frequently than the spherical ones. Particles fracture because of stress concentration given by dislocation accumulation. By fractographic analysis , it is evident that perhaps the globular form is beneficial in enhancing ductility and tensile strength, though it reveals a ductile fracture mode for the thixocast samples with smaller dimples, while a mixed ductile brittle fracture for the gravity cast samples of greater dimples.

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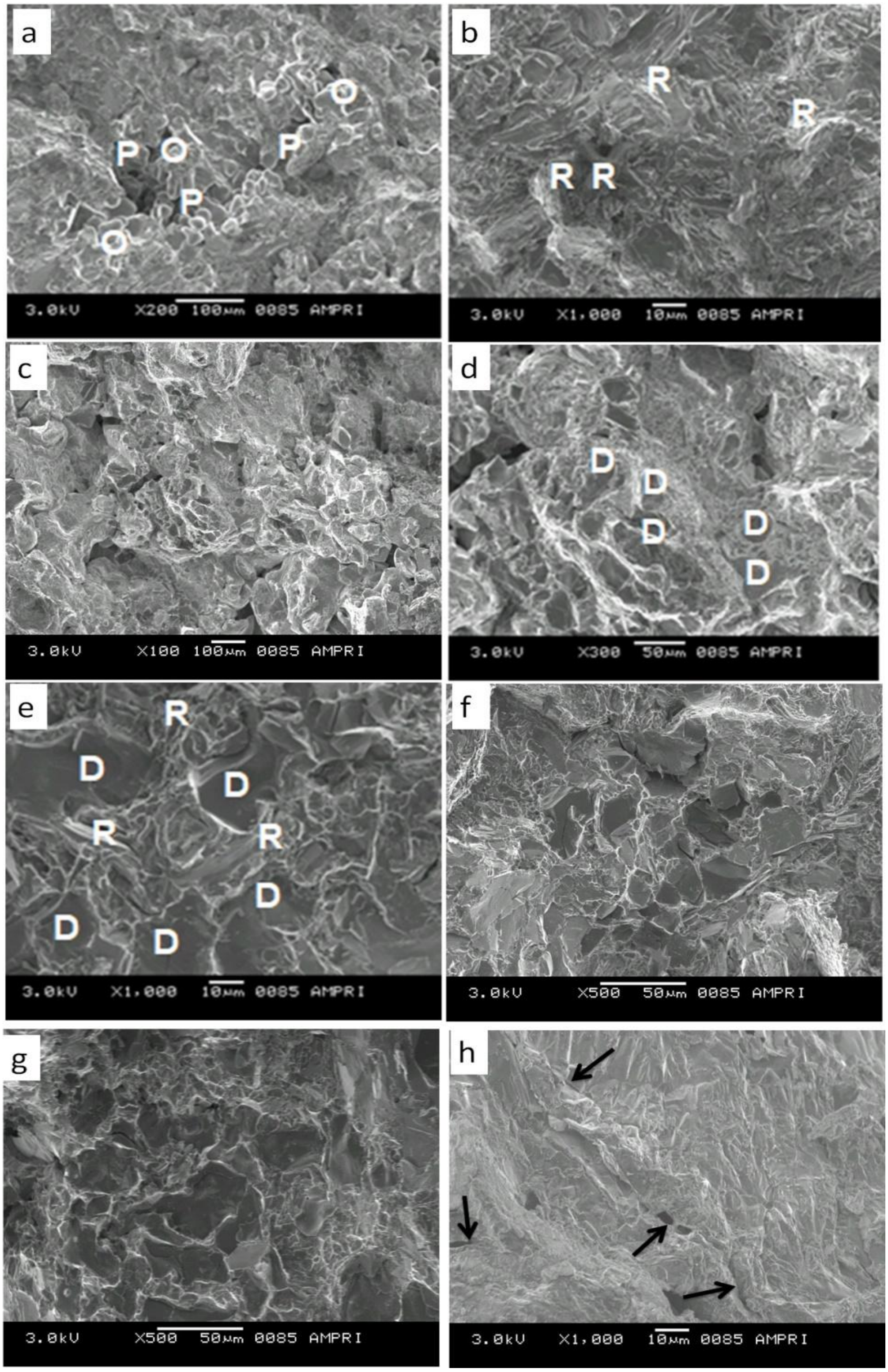

Fig. 5 Fractographs : (a)&(b) Gravity Cast, (c)&(d) Thixocast at 590°C, (e)&(f) Thixocast at 600°C, (g)&(h) Thixocast at 610°C

Conclusion

Thixocast LM25 alloy samples were found with significant improvement in tensile properties as compared to the gravity cast samples. The enhancement in mechanical characteristics is responsible for non-dendritic structure generated by the silicon process and morphological factors. The variation in tensile fracture paths is caused by microstructural changes and morphological features of the silicon process. The possibility of fracture increases with long and elongated silicon particles as compared to spherical α-Al dendrites. The existence of shrinkage porosity in gravity cast materials serves as fracture initiation points. This leads in very poor ductility and strength levels. Thixocast samples with a low degree of porosity and greater dislocation density were found compared to gravity cast samples. The size of dendrite and volume fraction of eutectic phases changes with thixocasting temperatures which also causes changes in tensile properties and hardness. In samples thixocast at 590°C, a very small level of porosity was observed which is responsible for better tensile properties especially tensile elongation. Thixocast samples of low processing temperatures shows improved tensile properties due to the low aspect ratio of silicon particles along with low porosity level. Coarsened silicon particles provides sources for stress concentration in thixocast samples processed at 600°C & 610°C due to higher aspect ratio of silicon particles as compared to thixocast samples processed at 590°c. Thixocasting process can be very helpful in improving mechanical properties of LM25 alloy as compared with gravity casting. Thixocasting at lower temperature is expected to give even better microstructure and mechanical properties.

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