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Microstructure and Bending Behaviour of Thixocast LM25 Alloy: Effect of Processing Temperature

A. K. Tuli*

S.V. Polytechnic College, Shyamla Hills, Bhopal-462002

***Abstract** – In the present work, microstructure and mechanical properties of thixocast LM25 alloy were correlated and compared with gravity cast LM25 alloy having the same composition. Thixocasting of samples was done at 590°C,600°Cand 610°C within a cylindrical die. Microstructures and mechanical properties were observed, correlated and compared with those of gravity cast samples. The tensile strength, yield strength, hardness and percentage elongation of the thixocast samples 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.*

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INTRODUCTION

Massachusetts Institute of Technology is the inventor of semisolid metal processing before 30 years ago [1]. In this metal forming process, metal is heated up to the temperature where mixture of globular solid particles and liquid is formed and filled in the mould to obtain desired shape. In 1972, a paper was published on the thixocast process with the advantage of thixocast sample on the conventional processed sample. The experiment was performed on the tin-lead alloy by heating it in the range of semisolidous state. It was found that thixocast product has very good mechanical properties as compared to the product synthesized through conventional liquid metallurgy route. Therefore, this process becomes the centre of attention for the researchers. The main advantage of the semisolid process is that it contains lower heat comparing with the liquid metallurgy route, causing the minimization of cost of processing. In semisolid processing, semisolid mixture has higher viscosity than liquid metals and lower flow stress than the solid processing technique. Therefore, advantage of liquid metallurgy route and forming route can be achieved in the thixocasting process [2, 3]. Therefore, final product processed through thixocast route has less defects in the form of porosity, gas entrapment and the shrinkage [4]. Porosity of the product plays an important role to enhance the mechanical properties like yield strength and elastic modulus [5]. In the thixocast process porosity of the product can be minimized which increase the mechanical properties of the product. Also, thin walled complex shaped product with high precision can be manufactured through this technique [6, 7]. Lot of research work has been done by the researchers to investigate the potential of this route in the automotive industry [2]. However, controlling the shape and size of the solid particles in the liquid phase, fraction of the solid in the liquid phase, the viscosity of the solid liquid mixture etc. are difficult and research is going on to obtain the uniform microstructure of the final product [8, 9]. As a semi solid slurry an alloy has a much higher viscosity than when fully liquid, thereby retaining laminar flow and filling the die more evenly, facilitating the near-net shape forming with a single step process [10]. It is also investigated that the most uniform microstructure can be found for the slurry having 50 % solid particles and 50% liquid [11]. From the experiments, it was found that Al alloys are the most suitable materials for the synthesization of product through this route. As Al is a light metal, it is more effective for the purpose of weight reduction, especially in automobile sector. However, to be successfully thixoformed, these materials must exhibit a non-dendritic microstructure, more precisely, one which is formed by an 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 [12]. The intension of the researchers is to obtain the globular shaped solid particles in the slurry, so that slurry can flow easily in the mould and minimize the defects. Die design is also a problem to eliminate the possible defects present in the product [13]. The production of thick products is difficult by this method, because so much heat needs to be transferred from the die which causes shorten the die life and reduce the productivity. Therefore, high pressure die casting technique is preferred to obtain much superior properties as compared to the gravity casting semi solid metal [14]. 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 [15].

Today, efforts for the development and implementation of thixocasting done on entire world because these offers many advantages as compared to the conventional processing methods (casting in liquid state and forging, die-forging, stamping in solid state), advantages that come out of the behaviour and characteristics of the materials in semisolid state. So, due to the heat content, lower than that of the liquid metal, high processing speeds can be applied, the wear of the deformation tools being lower. Thixocasting represents a paradigm change in casting. The flow behaviour enables the use of hot runners making casting more competitive with the plastics industry [16].

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 – 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. The chemical composition of LM-25 alloy is given in Table-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

Fig. 1 LM25 alloy Finger Castings

Thixocasting

The billets of alloy 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 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 phases formed were identified by X- Ray diffraction (Model : Bruker-D8 with Cuα radiation). 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 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.

XRD Analysis

The physical and chemical changes in phase constituents in the alloy were examined by X- ray diffraction (Model: Bruker-D8 with Cuα radiation) at a scan rate of 0.02°per Second. The 2ϴ angle was varied from 10° to 90° and the scanning rate used was 1.2° per minute. D-values obtained from XRD patterns were compared with the characteristic d-spacing of all possible values from JCPDS cards to obtain the various X-ray peaks.

MECHANICAL PROPERTIES

3-Point Bending Test

This test was carried out for 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.

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.

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 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 2.70 gm/cc and that of gravity cast samples was 2.68 gm/cc. This signifies that thixocast alloy samples are more dense 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.

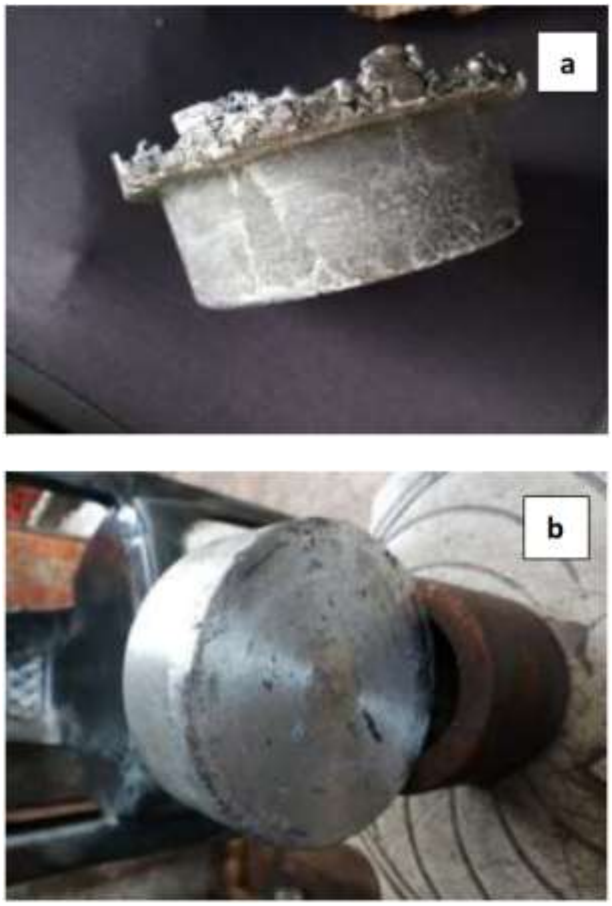

Fig. 3 Thixocast Alloy : (a) Before Machining (b) After Machining

Fig. 3 (c) Thixocast Alloy after Machining (at diff. processing temperatures)

Microstructures: Gravity Cast and Thixocast LM 25 Alloy

In gravity cast samples a typical dendritic shape of the α-Al phase was observed, whereas in thixocast samples a non-dendritic (spherical) primary α-Al phase was observed. The samples thixocast at 590°C shows a very small level of porosity. Samples thixocast at 600°c showed little more globular α-Al particles. At 600°C the primary α-Al phase was more continuous as compared to 610°C processing. 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 concentration of α-Al phase decreases with 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. 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 0.95 to 1.02, 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). Excellent mechanical properties of thixocast specimens are not only due to nondendritic microstructure but also due to the small size of the primary α- Al, which specially results in enhanced elongation to fracture. When the shape factor increases (more rounded primary globules), tensile and elongation properties also increases. However, because of the microstructural variation, there is a possibility of optimum temperature of thixocasting for getting maximum strength and hardness.

Table 2 – LM 25 Alloy

Type of Processing	Grain Size (µm)	Aspect Ratio	Hardness HV	Volume Fraction Eutectic	α – Al
Gravity Cast	210	0.7	72	48	52
Thixocast at 590°C	42	1.02	81	48	52
Thixocast at 600°C	82	0.99	84	50	50
Thixocast at 610°C	130	0.95	88	60	40

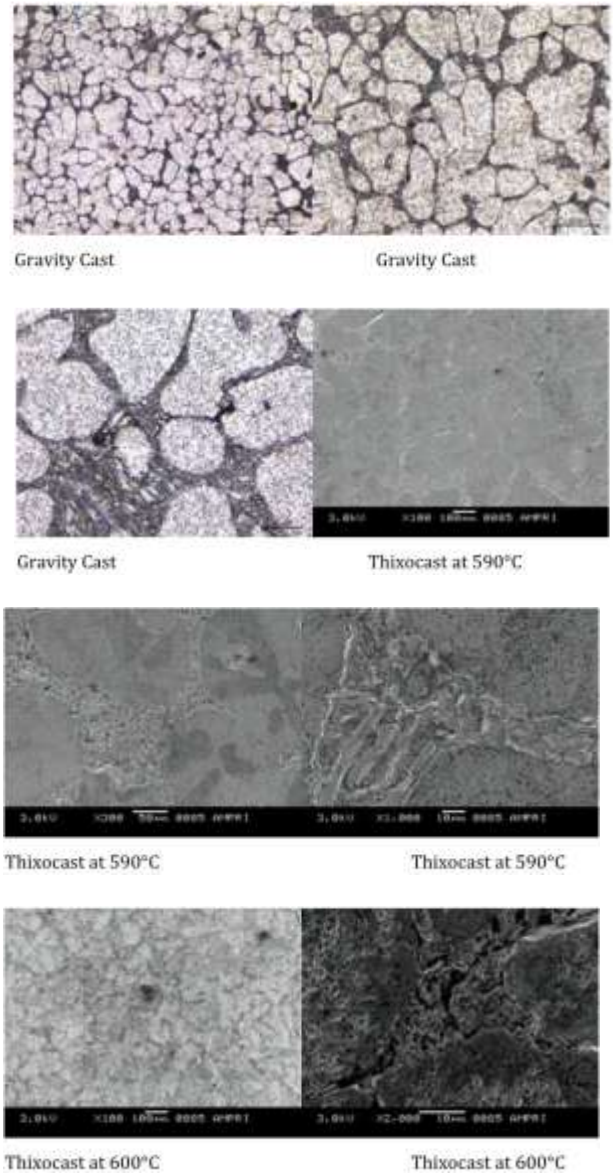

Fig. 4. Microstructures: Gravity Cast and Thixocast LM 25 Alloy

Hardness

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.

Flexural Deformation Behaviour of Thixocast LM25 Alloy

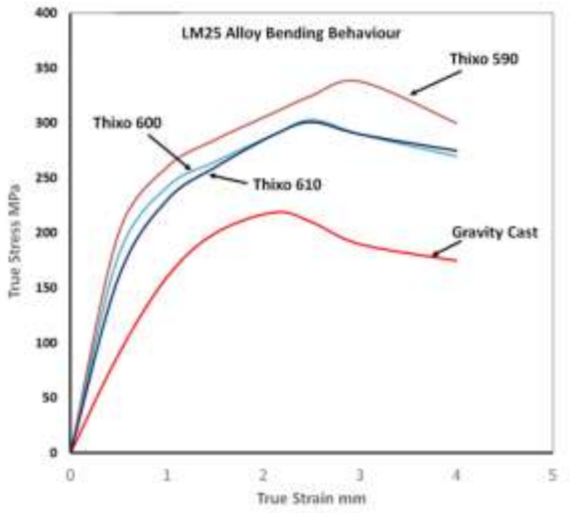

Fig. 5. LM25 Alloy: Flexural Stress-Strain Curves

Table 3. Three Point Bending Behaviour of LM 25 Alloy

Type of Processing	Flexural Strength (σ_b) (MPa)	Max^m flexure extension (δ_b) (mm)	Flexural Modulus (E_b) (GPa)
Gravity Cast	219 ± 10.95	2.12 ± 0.10	84 ± 4.20
Thixocast at 590°C	338 ± 16.90	2.35 ± 0.11	100 ± 5.00
Thixocast at 600°C	303 ± 15.50	3.84 ± 0.19	98 ± 4.90
Thixocast at 610°C	301 ± 15.05	2.68 ± 0.13	95 ± 4.75

True stress-strain curve for the LM25 ally is shown in Fig 5. From the figure, it is clear that the true stress strain curve has three specific parts. In the first part, material elastically deformed causing the linear stress strain curve. At the lower load, the upper layer of the specimen material that was in contact with the indenter, got elastically deformed. In this region, there is no deformation effect observed below the neutral layer of the specimen. After a certain stress point, strain of the material increases considerably in comparison to the stress. It is caused due to the deflection of the specimen between the two supports. In this region material got deformed plastically and bending occurs. In the stress-strain curve, an inflection point was observed for the each material specimen. At the inflection point, the fracture or cracks in the material start. After the inflection point, stress of the material reduces, while strain increases rapidly. It is caused due to the propagation of the cracks in the material that increase the plastic deformation of the material at reduced load. The trend of the stress strain curve is similar for each specimen. After performing three point bend test the flexural strength and flexural modulus for thixocast LM25 alloy was found to be more than those of gravity cast samples. In gravity cast samples, typical dendritic shape of primary α phase was observed. The improvement in flexural properties is due to the non-dendritic structure produced and morphological aspects of the silicon phase during thixocasting. Due to dendritic microstructure, the relative density of the material reduces because of the insufficient fluidity of the material, causing higher number of pores in the gravity cast samples than the thixocast one. The pores in the material plays an important role in the crack initiation and propagation. The pores has sharp corner points with high residual stresses. These points are more susceptible to crack generation at lower stress or load. On the other hand, in thixocast sample, the globular microstructure of the materials improves the relative density. Hence, smaller number of pores are generated which reduces the chance of crack propagation and improves the flexural property of the material. Additionally, the presence of fine fibres like Si particles improve the bonding among the globular particles that resist the deformation of the material. With the increment of thixocasting temperature, flexural properties of the thixocast material reduces. It is caused due to the compositional as well as microstructural changes occur in the material. The volume fraction of the fibrous Si particles increases, while volume fraction of α-Al reduces with the increment of thixocasting temperature. However, the thickness of the Si particles as well as size of the globular particles increases without significant change in sphericity. Therefore, the bonding among the particles reduces, causing reduction in the flexural properties of the thixocast material. The values of flexural strength (σ_b), maximum flexure extension (δ_b) and flexural modulus (E_b) were calculated from the flexural stress strain curve of the each specimen material. The values of each property are shown in the Table 3 and Fig 5. From the Table, it is clear that σ_b of Thixo 590 sample is higher than the other tested samples. It is 40% higher than the gravity cast and around 10% and 30% higher than the Thixo 600 and Thixo 610 samples respectively. There was very marginal difference of σ_b was detected between the Thixo600 and Thixo 610. Similarly, $\sigma_{b\delta}$ for Thixo 590 is considerably higher than the gravity cast. In the group of thixocast material, $\sigma_{b\delta}$ of Thixocast 590 is marginally higher than the Thixo 600 and Thixo 610. The value of E_b for the gravity cast, Thixo 590, Thixo 600 and Thixo 610 were analysed as 84 GPa, 100 GPa, 98 GPa and 95 GPa respectively.

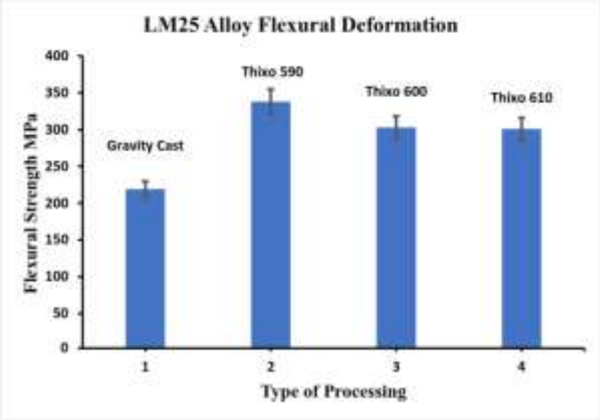

Fig. 6. Bar Chart: Flexural Strength of LM25 Alloy

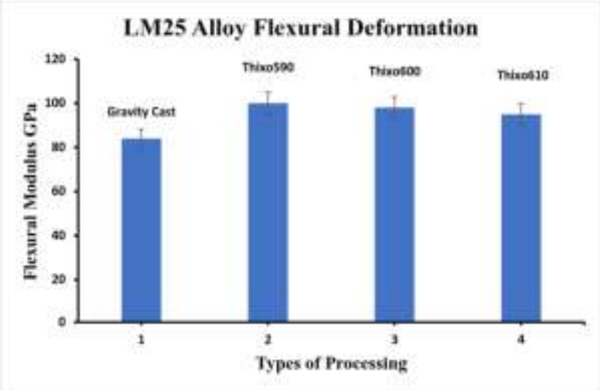

Fig. 7. Bar Chart: Flexural Modulus of LM25 Alloy

Three Point Bending Fracture: Gravity and Thixocast LM25 Alloy

The fracture surface of LM25 alloy after three point bending is shown in Fig. 8 (a). It shows cleavage type fracture with full of ridges. These ridges are through over the dendrites ends and causing sharing of dendrites. Few microcracks are also revealed. At lower magnification fractograph (Fig. 8 (b)) micro voids are also observed indicating that the as cast alloy contains micro porosities. This will also cause lower flexural strength. The fracture surface of thixocast LM25 alloy (at 590°C) after bending indicate relatively less cleavage characteristics (Fig. 8 (c)). The ridges are fever and lower in number. Here, the dendrites also get sheared. Low magnification fractograph does not show any micro voids, but indicate a few dimples (Fig. 8 (d)). However, the overall fracture is cleavage dominated. When the alloy is thixocast at 600°C, its fracture surface becomes quite rough. But it contains a large number of microcracks (Fig.8(e)). Higher magnification micrograph (Fig.8(f)) showed cleavage dominated surface with large number of ridges and shearing of dendrites. Similarly, lower magnification micrographs of thixocast LM25 alloy (at 610°C) after bending (Fig.8(g)) showed rougher surface and it seems that decohesion of dendrites takes place. But at higher magnification, large number of microcracks at the eutectic region and shearing of dendrites are observed (Fig.8(h)). This may be due to larger and coarser eutectic silicon at the intermediate layer of dendrites. Coarser dendrites could not be deformed or reorient easily and hence cracks propagate through dendrites. During Thixocasting also there is a possibility of micro-cracking in the inter-dendritic region. As a result, when crack grows to a critical value, the dendrites get sheared and cause failure.

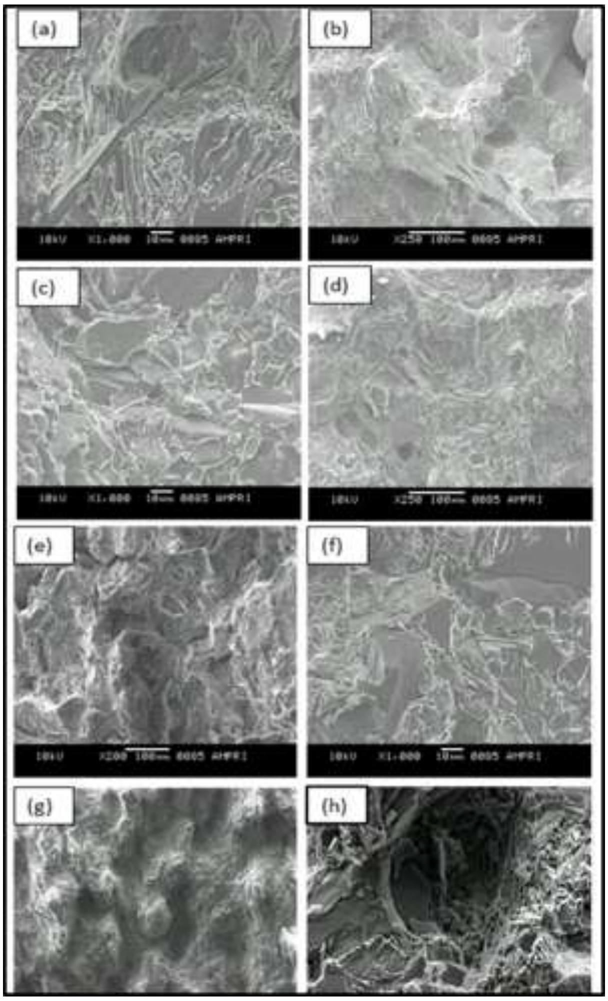

Fig. 8. LM25 Alloy: Bending Fractographs - (a) Gravity Cast, (b),(c)&(d) Thixocast at 590°C, (e)&(f) Thixocast at 600°C, (g)&(h) Thixocast at 610°C

CONCLUSION:

Thixocast LM25 alloy samples were found with significant improvement in mechanical properties as compared to the gravity cast samples. The improvement in mechanical properties is due to the non-dendritic structure produced and morphological aspects of the silicon phase. Microstructural changes and morphological aspects of silicon phase cause the difference in the tensile fracture paths. The possibility of fracture increases with long and elongated silicon particles as compared to spherical α-Al dendrites. The presence of shrinkage porosity act as fracture initiation points in gravity cast samples. It results in very low level of ductility and strength. As compared with gravity cast samples, thixocast samples were found with low porosity level and higher density. The size of dendrite and volume fraction of eutectic phases changes with thixocasting temperatures which also causes changes in properties and hardness with thixocasting temperature. In samples thixocast at 590°C, a very small level of porosity as well with finer and more globular dendrites was observed which is responsible for better properties. Thixocast samples of low processing temperatures shows improved 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 beneficial 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. Irrespective of loading conditions (tensile, compressive or bending) thixocast samples provide higher strength and hardness. Amongst the thixocast samples, the alloy samples thixocast at lower temperature exhibited higher mechanical properties and finer microstructure. Both tensile and bending fractures are brittle type which showed lot of ridges, confirming shearing of dendrites.

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Corresponding Author

A. K. Tuli*

S.V. Polytechnic College, Shyamla Hills, Bhopal-462002