# EFFECT OF SYNTHESIS METHOD ON THE MECHANICAL BEHAVIOUR OF NEAR NET SHAPED ALUMINIUM METAL MATRIX HYBRID COMPOSITES

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*The aim of this work was to develop and characterize the near net shaped aluminium metal matrix hybrid composites. Three different synthesizing methods such as two step stir casting, squeeze casting and modified squeeze casting were employed to fabricate the composites. Three different materials such as Al alloy LM 25 – 10 wt% fly ash (FA) composite, LM 25–10wt% steel particles (SP) composite and LM 25 – 5wt% FA and 5wt% SP hybrid composites were chosen. Tests were performed based on Taguchi's three level L9 orthogonal array to choose the best fabricating method and the material in enhancing the mechanical properties of the composites. Anova was used to investigate the influence of the synthesis method and materials on the mechanical behaviors of the material.*

**Keywords**: near net shaped aluminium metal matrix hybrid composites; synthesizing method; two steps stir casting; squeeze casting; modified squeeze casting; Taguchi

## 1. Introduction

The potential of MMC materials for significant improvements in performance over conventional alloys has been widely recognized because of increased mechanical and physical properties, i.e. strength, stiffness, hardness with respect to the base material. The major advantage of composites lies in the tailorability of their properties to meet specific design criteria [1-2].

Research on production of metal matrix composite has started in the international arena since early 1960s. Composites development began with the use of ceramics and graphite. Both theoretical and experimental work on the synthesis of composites employing the stir casting method is reported in the literature [3].

According to a metals and minerals analyst (Mahitha Mallishetty), Technavio research reported that, "The world wide MMCs market is likely to attain 10.8 kTons by 2021"[4]. Manufacturing of MMCs has become inexpensive

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as a result of the considerable progress in the synthesis of production method. Surappa and Rohatgi were originally developed vortex mixing method to fabricate the ceramic particle reinforced MMC [5-6]. Consequently, some non ferrous metal production industries modified the vortex mixing method to synthesis the MMCs on business scale. Various laboratories and institutions are investing in R&D related activities for composites and advanced materials. In India Defense Metallurgical Research Laboratory at DRDO, DMRL, Hyderabad, IIT, Bombay and Council of Scientific and Industrial Research (CSIR) Trivandrum work in the areas of MMCs, CMCs, PMCS and carbon-carbon composites. Among various synthesizing methods, stir casting seems to be the simplest way for manufacturing of MMCs on account of the capability to manufacture the composites on industrial mass production [7-8]. Dispersion of ceramic particulates in cast composites could be a difficulty on account of interaction between floating solid reinforcement particles and moving solid to liquid interface during the solidification phase [9-10].Various issues still impede the large-scale manufacture of MMCs employing stir casting. Exhaustive analysis and relevance of existing literature could offer needed solutions. Porosity and uneven sharing of reinforcement particulates into the matrix are the most important issues coupled with a stir casting. Adverse effects of poor wettability and higher porosity can be nullified by optimizing the method and parameters concurrently for synthesizing the MMCs [10-11]. A major obscurity in the conventional stir casting is in adequate wetting which leads to non homogeneous dispersion. With the aim of achieving the enhanced characteristics of the MMCs, several parameters are required to consider. It includes getting a consistent sharing of the reinforcement material in the matrix by enhancing the wettability and to minimize the porosity. Hence, engineers require the sound academic and practical knowledge for the composite preparation.

No of baffles, impeller size and shape on the dispersion of SiC in the matrix was studied by Rohatgi et al [12]. The impeller should be designed in such a manner that it has to create a vortex in the molten composite melt. Hence, knowledge of impeller parameter is necessary. Our earlier study reveals that the impeller model (radial flow) with 0.7 $I_{OD}/C_{ID}$ ratio (Outer diameter of impeller outer to Inner diameter of crucible) had a noteworthy effect on dispersion of the reinforcement in the molten metal. Two step stir casting was employed to manufacture quality composites [13]. Apart from stir casting, squeeze casting is gaining importance as the applied pressure during solidification of composite melt enhances the wettability and reduces the porosity in fabricating MMCs. Various researchers have investigated the mechanical and the tribological behavior of squeeze casted MMCs. Application of high-pressure during solidification of composite melt, partially reduces the porosity and partially to attain enhanced properties and productivity [14]. Mechanical behavior of magnesium alloys was valuated with respect to squeeze casting parameters [15]. Mechanical behavior of AL alloy A356 was valuated with respect to squeeze casting parameters [16]. Squeeze casting process parameters were optimized for alloy castings. Squeeze pressure was the key parameter which has a significant factor in deciding the defect free quality castings [17].

Even sharing of reinforcement in the matrix material is a major problem in the manufacture of metal matrix composites as it directly affects the properties and quality of the composite. The aim of this work is to develop and characterize the net shaped aluminium metal matrix hybrid composites. The term near net shape is used in metal casting sector that aims to manufacture the desired quality components which are close to the final shape of the components in lesser production time and costs.

It is to be achieved by combining the two step stir and squeeze casting methods. Initially MMCs melt was prepared by two step stir casting technique to facilitate even sharing of reinforcement particulates in the molten metal. Then composite melt is introduced into a squeeze casting set up to get a net shaped quality component. By applying high pressure during the solidification of the melt, gas and shrinkage could be prevented.

## 2. Materials and Methodology

### 2.1 Matrix Material

LM 25 aluminium ingot was used as the matrix material. LM 25 alloy is mostly employed where enhanced mechanical properties and resistance to corrosion are the main considerations. It offers excellent castability and machinability. Table 1 provides the chemical composition of LM25 Al alloy.

*Table 1*

**Chemical Composition of LM25 Aluminium Alloy**

| **Element** | **Si** | **Fe** | **Cu** | **Mn** | **Mg** | **Ni** | **Zn** | **Ti** | **Sn** | **Pb** | **Al** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wt %** | 6.5 | 0.4 | 0.1 | 0.2 | 0.05 | 0.09 | 0.06 | 0.012 | 0.01 | 0.1 | 92.478 |

### 2.2 Reinforcement Materials

Particles of fly ash (FA) and steel (SP) with size of 100 μm were used as the reinforcements. Fly ash (class F) was received from Mettur thermal power plant and its chemical composition is provided in Table 2. Composition of steel powder is provided in Table 3. Both the reinforcement particles were cleaned by magnetic separation and then shifted to the size of 100 μm. SEM illustration of FA particulates and steel particles are portrayed in Fig.1 and Fig.2 respectively.

*Table.2*

**Chemical composition of Fly ash**

| Compound | CaO | MgO | $Fe_2O_3$ | $SiO_2$ | $Al_2O_3$ |
|---|---|---|---|---|---|
| % | 2.4 | 2.1 | 6.1 | 54.27 | 34.73 |

*Table.3*

**Chemical composition of Steel Powder**

| Element | Composition (%) | Element | Composition (%) |
|---|---|---|---|
| C | 0.27588 | Cu | 0.19824 |
| Si | 0.21646 | W | 0.01037 |
| S | 0.06229 | Ti | 0.00132 |
| P | 0.08671 | Sn | 0.2547 |
| Mn | 0.52829 | Co | 0.00789 |
| Ni | 0.09356 | Al | 0.00022 |
| Cr | 0.07784 | Nb | 0.00078 |
| Mo | 0.00932 | Fe | 98.4063 |

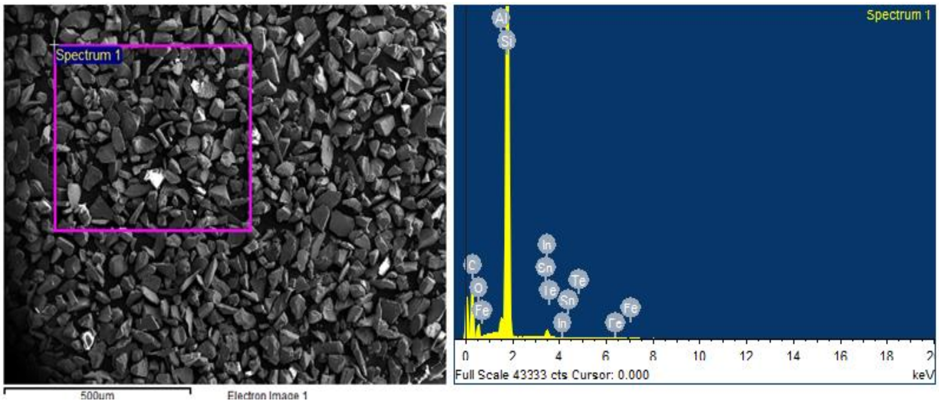

Fig. 1. SEM image of fly ash particles

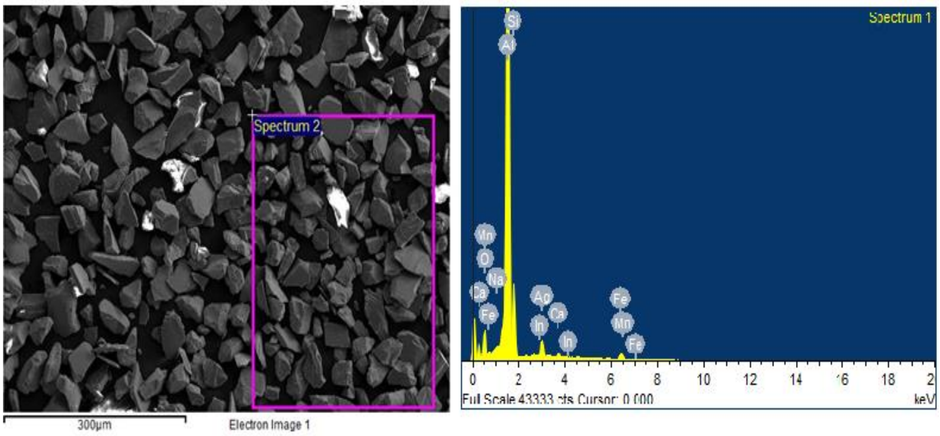

Fig. 2. SEM image of steel particles

### 2.3 Preparation of Composites

An attempt was made to synthesize the MMCs through the three different manufacturing methods which are discussed in the following sections. In all the three manufacturing methods, both the fly ash and steel particles were pre heated to 500°C to remove the moisture content. Stirring was performed at 300 rpm. The size of the specimen is 1000X600mmX50mm.An electrical resistive furnace (2kW-1kg capacity) was employed. Argon gas was blown in the melt zone to prevent the oxidation. Thermocouple with an accuracy of +/-3K was used to measure the temperature.

#### 2.3.1 Method I: Two step Stir Casting Method

In this method, melt stirring is performed in two steps. Stirring is done in a liquid state of composite melt followed by semi solid state. Schematic of two step stir casting furnace is portrayed in Fig.3. Al alloy was allowed to melt in the furnace where the liquidus temperature (660°C) was maintained. The temperature was reduced to 575˚C to attain the semi- solid condition and stirred for 5 minutes.

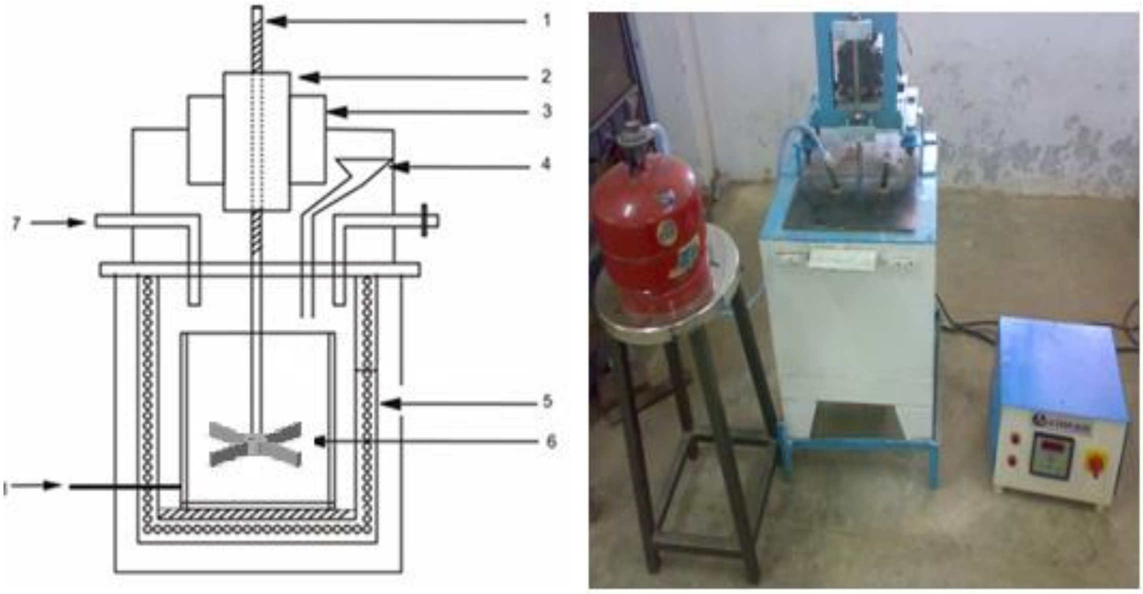


Fig. 3. Two step stir casting setup
1.Stirrer spindle 2. Impeller position control unit 3. Electric motor 4. Sprue 5. Electric furnace 6. Radial impeller 7. Argon gas inlet 8. Thermocouple

A radial type four blade impeller with 0.7 $I_{OD}/C_{ID}$ ratio (Impeller outer dia / Crucible inner dia ratio) was used for stirring. Impeller blade which has 30 mm height and 10 mm thickness is made up of stainless steel. The impeller could rotate and move vertically within the melt using control unit. The melt was again heated till it attains the liquid condition and stirred for 5 minutes at 300 rpm. Finally, the melt was poured into the mold.

#### 2.3.2 Method II: Squeeze casting setup

In this method stirring is done only in liquid state. After the stirring, slurry is poured into the mold cavity and pressure applied by the punch on the melt to produce composites. It is a simple and an economical process and used to manufacture near-net parts. It is found wide spread usage in the industry.

Al alloy was allowed to melt in the furnace where the temperature is maintained at 660˚C. FA and steel particles were incorporated and the stirring was initiated at 300 rpm for 10 minutes. In this method, stirring is done only in liquid state. A 50MPa pressure was exerted on the melt for 40 seconds by a punch. After the solidification, punch was withdrawn and the specimen was removed from the mold assembly.

#### 2.3.3 Method III: Modified Squeeze casting

A new method is proposed, and it is a combination of two step stir and squeeze casting methods. In the modified squeeze casting, stirring is performed in two steps. Stirring is done in liquid state of composite melt followed by semi solid state. Stirring is carried out similar to the two steps stir casting. After the stirring, slurry is poured into the mold cavity and pressure applied by the punch on the melt to produce composite.

Schematic of modified squeeze casting method is shown in Fig.4. Specifications are given in Table 4. In a modified squeeze casting, the same procedure is adopted as that of squeeze casting. But the impeller could rotate and move vertically within the melt using control unit. Finally, the melt was poured into the mold. A radial four blade impeller with 0.7 $I_{OD}/C_{ID}$ ratio (Impeller outer dia / Crucible inner dia ratio) was employed for stirring the melt. After stirring, 50MPa pressure was exerted on the melt for 40s by a punch. After the solidification, punch was withdrawn, and the specimen was removed from the mold assembly.

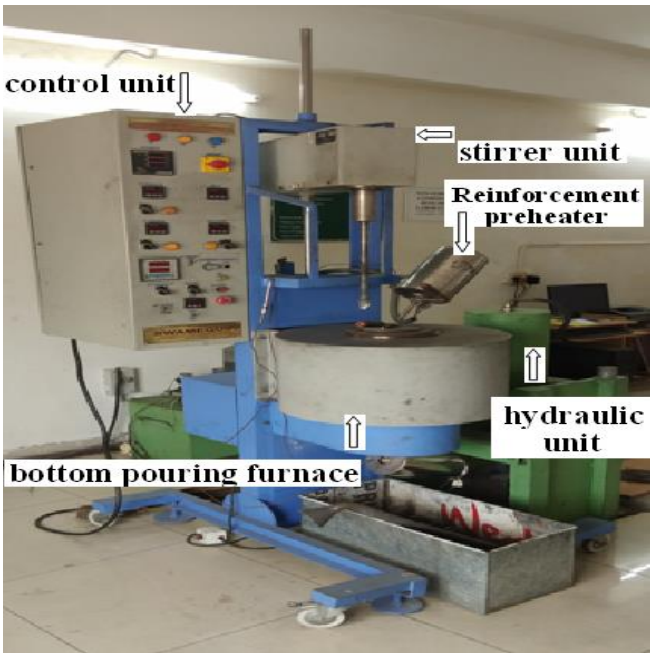

Fig. 4. Modified Squeeze casting setup

*Table 4*

**Specification of Squeeze casting furnace**

| | |
|---|---|
| Melt capacity range | 0.5 to 2 kg |
| Maximum melting temperature | 1000˚C |
| Stirrer speed | 100-1500 rpm |
| Maximum preheating temperature | 500˚C |
| Thermocouple | K type |
| Maximum hydraulic load | 50 tons |
| Power | 440 V, 50 Hz, 3 phase |

### 2.3.4 Mechanical properties

Hardness test was conducted by Rockwell testing system according to the ASTM E18 which is the most commonly used hardness test method. It is determined by measuring the permanent depth of the indentation. Conical diamond with a round tip intender was used. 10 kgf test load was employed.

. Tensile test was conducted on composites employing a computerized UTM machine (Instron 3366) in line with the ASTM E08/2017 which is one of the most common test methods. Solid round specimens which have 12.5 mm of diameter and 50 mm of gauge length were used.

### 2.3.5 Taguchi Method

Optimal levels of parameters are identified using Taguchi method. It reduces test runs, duration and the cost. In Taguchi designs, a measure of robustness used to identify control parameters that reduce variability in a process by minimizing the effects of uncontrollable factors (noise factors). The signal to noise ratio provides a measure of the impact of noise factors on the outcome and performance of the process. Since the highest hardness and tensile strength are enviable, "Larger is better" S/N (Signal to Noise) ratio was selected.

It is represented by the succeeding mathematical equation 1.

$$S/N = -10\log_{10} 1/n\sum\left(\frac{1}{Y_i^2}\right) \tag{1}$$

Where, $y_i$ is the observed data and n is the number of observations.

In this investigation materials type and synthesis method were selected as parameters. Since two control factors were considered, eight degrees of freedom was calculated. A Taguchi based, three levels L9 orthogonal array was selected. Total Degrees of Freedom (DoF) = no. of tests– 1= 9 – 1 = 8. In the present investigation, tensile strength and hardness tests were accomplished in line with the L9 orthogonal array. In view of that, nine tests were conducted.

## 3. Results and Discussion

Three different synthesizing methods were considered such as two step stir casting, Squeeze casting, modified squeeze casting. Materials such as Al alloy LM 25 – 10wt% fly ash (FA) composite, LM 25–10wt% steel particles (SP) composite and LM 25 – 5wt% FA and 5wt% steel particles (SP) hybrid composites were chosen. The chosen parameters and levels are provided in Table 5. Measured values and corresponding S/N ratios are provided in Table 6.

*Table 5*

**Process parameters with their values at three levels**

| Level | Material (A) | Synthesis Method (B) |
|---|---|---|
| I | Al – 10% FA (1) | Two step Stir casting (1) |
| II | Al – 10% SP (2) | Squeeze casting (2) |
| III | Al – 5% SP-5%FA (3) | Modified Squeeze casting (3) |

*Table 6*

**Measured values and corresponding S/N ratios**

| Sl No | Materials (A) | Synthesis method (B) | Measured values | | S/N ratios | |
|---|---|---|---|---|---|---|
| | | | Hardness (HRC) | Tensile strength (MPa) | Hardness | Tensile strength |
| 1 | Al – 10% FA | Two step Stir casting | 78 | 155.35 | 37.84 | 43.82 |
| 2 | Al – 10% FA | Squeeze casting | 86 | 178.72 | 38.68 | 45.04 |
| 3 | Al – 10% FA | Modified Squeeze casting | 90 | 186.43 | 39.08 | 45.41 |
| 4 | Al – 10% SP | Two step Stir casting | 87 | 169.30 | 38.79 | 44.57 |
| 5 | Al – 10% SP | Squeeze casting | 91 | 184.2 | 39.18 | 45.30 |
| 6 | Al – 10% SP | Modified Squeeze casting | 96 | 191.83 | 39.64 | 45.58 |
| 7 | Al – 5% FA-5%SP | Two step Stir casting | 95 | 178.39 | 39.55 | 45.02 |
| 8 | Al – 5% FA-5%SP | Squeeze casting | 102 | 193.63 | 40.17 | 45.73 |
| 9 | Al – 5% FA-5%SP | Modified Squeeze casting | 107 | 197.60 | 40.58 | 45.91 |

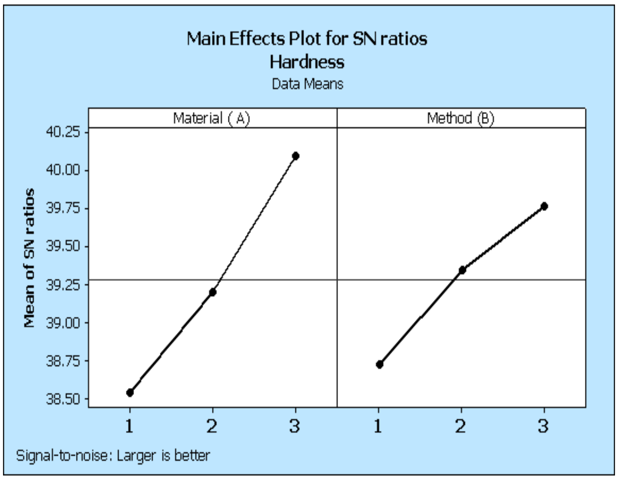


Fig. 5. Main Effects plot for SN ratios – Hardness

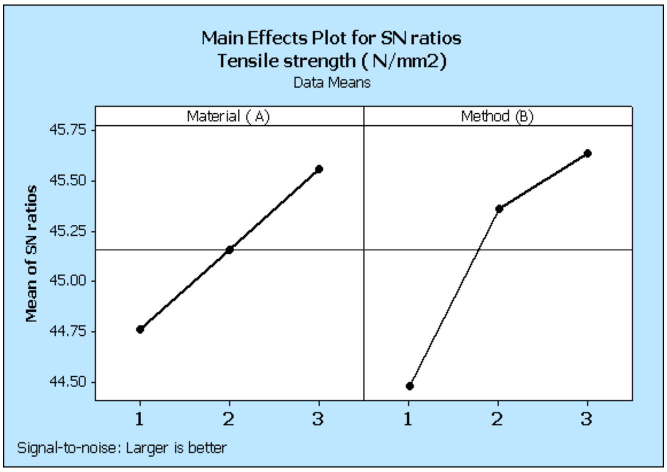


Fig. 6. Main Effects plot for SN ratios – Tensile strength

Fig.5 and 6 infer that LM25/FA/SP hybrid composite and modified squeeze casting synthesis method was found to be optimum level of parameters in enhancing the mechanical properties of the composites. ANOVA determines the optimum combination of process parameters more accurately by investigating the relative importance among the parameters. ANOVA was performed with the help of the software package MINITAB15 for a level of significance of 5% to study the contribution of various factors. ANOVA analysis for hardness and tensile strength is presented in the Table 7. In the ANOVA Table 7, there is a P-value for each independent parameter in the model. When the P-value is less than 0.05, then the parameter can be considered as statistically significant. It is observed that, all the two factors have P value less than 0.05, which means that they are highly significant at 95% confidence level. The last column of the Table 7 shows the percentage contribution (Pc %) of each variable in the total variation, indicating their degree of influence on the mechanical properties. The material (69.19%) was the major factor subsequently synthesis method (29.97%) in obtaining the preferred hardness of the composites. Synthesis method (67.236%) was the major factor subsequently material (29.47%) in obtaining the preferred tensile strength of the composites.

***Table 7***

**ANOVA analysis for Hardness and Tensile strength**

| Factors | DoF | Hardness (HRC) | | | Tensile strength (MPa) | | |
|---|---|---|---|---|---|---|---|
| | | F | P value | Pc% | F | P value | Pc% |
| Material (A) | 2 | 165.22 | 0.00 | 69.19 | 17.90 | 0.01 | 29.47 |
| Synthesis method (B) | 2 | 71.57 | 0.00 | 29.97 | 40.85 | 0.00 | 67.24 |
| Error | 4 | | | 0.84 | | | 3.29 |
| Total | 8 | | | 100 | | | 100 |

Hardness of the composites produced through three processing routes is presented in Fig.7. The hardness of the modified squeeze cast samples showed higher values than those obtained in the two-step casting and squeeze cast samples. Hardness of the Al/10% fly ash is increased to 90HRC when the composites manufactured through modified squeeze casting.


Fig. 7. Hardness of the composites produced through different processing routes

The hardness of the modified squeeze casted Al/FA/SP samples showed 12.63 % higher than those obtained in the two step stir casting and 4.90% higher compared to squeeze casted samples. Modified squeeze casting distributes the fly ash and steel particulates evenly in the Al alloy without any agglomeration. The hardness of the modified squeeze casted Al/SP samples showed 6.67% higher than those obtained in Al/FA samples because of higher hardness of steel particles.

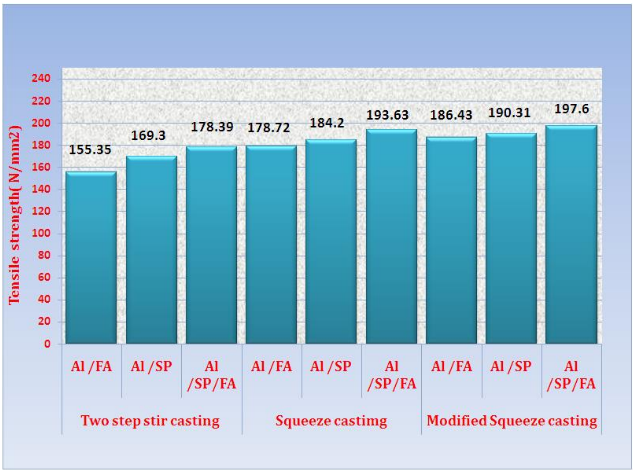


Fig. 8. Tensile strength of composites produced through different processing routes

Fig.8 shows the tensile strength of the composite produced using different processing routes. Compared to two step stir casting and squeeze casting methods, composites prepared through modified squeeze casting method had higher strength. Tensile strength of the modified squeeze casted Al/FA/SP samples showed 10.76 % higher than those obtained in the two step stir casting and 2.05 % higher compared to squeeze casted samples. It can also be observed that Al/SP/FA hybrid metal matrix composite exhibits better hardness and tensile strength compared to single reinforcement composites such as Al/SP and Al/FA composites. It can be concluded that the incorporation of dual particulates such as FA and SP in the matrix enhances the mechanical properties instead of incorporation of single particulate reinforcement.

### 3.1 Micro structural analysis of composites

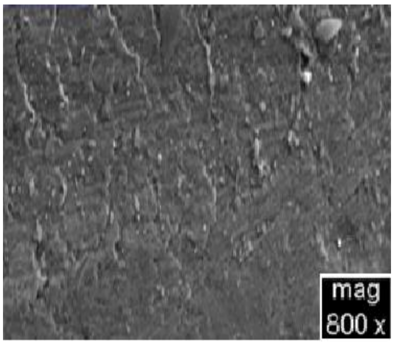


Fig 9(a). SEM image Of the Al – 10 wt% Fly ash composite

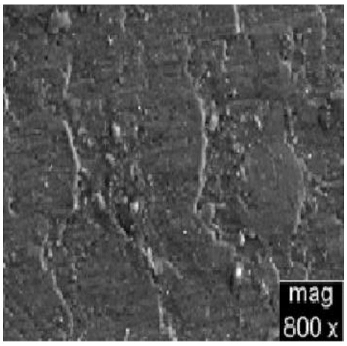


Fig. 9(b). SEM image of the Al – 10wt% steel powder composite

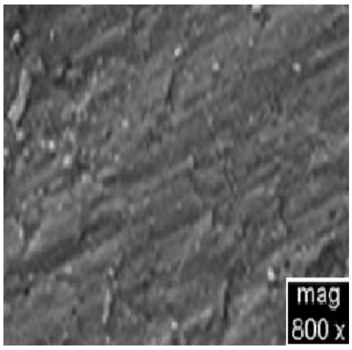


Fig.9(c). SEM image of the Al – 5 wt% fly ash / 5 wt% steel powder composite

It can be observed from the SEM images Fig.9 (a), (b) and (c) that the no clustering of particulates was seen. The composites produced with the modified squeeze casting resulted in a much more homogeneous microstructure and the fly ash and steel particles are being distributed more uniformly throughout the specimen. SEM images of the composites which are produced through the two step stir casting method and conventional squeeze casting showed that clustering of reinforcement particles was seen and some sections were identified without particles. Thus, it can be concluded that the modified squeeze casting method is certainly advantageous compared to two step stir casting and conventional squeeze casting at it enhances the uniform sharing of particulates in the Al alloy.

## 4. Conclusions

LM25/FA/SP hybrid composite and modified squeeze casting synthesis method was found to be optimum level of parameters in enhancing the mechanical properties of the composites. The hardness of the modified squeeze casted Al/FA/SP samples showed 12.63 % higher than those obtained in the two steps stir casting and 4.90% higher compared to squeeze casted samples. Tensile strength of the modified squeeze casted Al/FA/SP samples showed 10.76 % higher than those obtained in the two steps stir casting. Composites produced through the two steps stir casting method and conventional squeeze casting showed that clustering of particles and some sections were identified without particles.

It leads to poor interfacial bonding and a consequent reduction in properties of composites. Modified squeeze casting distributes the fly ash and steel particulates evenly in the Al alloy without any agglomeration. Thus, it can be concluded the modified squeeze casting method is certainly advantageous since it helps in achieving a more uniform distribution of particles in the matrix.

It can also be observed that Al/SP/FA hybrid metal matrix composite exhibits better hardness and tensile strength compared to single reinforcement composites such as Al/SP and Al/FA composites. It can be concluded that the incorporation of dual particulates such as FA and SP in the matrix enhances the mechanical properties instead of incorporation of single particulate reinforcement. Thus, this proposed modified squeeze casting method can be employed to attain the even distribution of particles and to develop pore free near net shaped industry ready MMC components.

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