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Weldability Study of LM25/ZrO_2 Composites by Using Friction Welding

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ABSTRACT

In this paper aluminum (LM25) alloy was chosen as a base matrix metal, and it was reinforced with 0, 3, 6, 9, 12% of Zirconium dioxide (ZrO_2) particulates based on weight fraction method. Stir casting method was used to cast LM25/ZrO_2 composite material. The cast samples were subjected to physical and mechanical test viz, density, hardness, tensile, compression and impact test. The feasibility trial weld was carried out on the developed composite (similar metals) using Friction welding process (FSW) and then welded sample were prepared for the various test. The welded samples were subjected to various mechanical tests such as tensile, hardness and bend test to evaluate the strength of the friction welded joints. Then welded samples were also subjected to optical microscopy analysis to evaluate microstructures of the base and the weld regions. The tensile, hardness, compression and impact strength increases with increase in the percentage of ZrO_2 in LM25 alloy. The tensile, hardness and bending strength were high in the welded zone. The microstructures of the welded tensile tested specimen were analyzed using the Scanning Electron Microscopy (SEM) in a different region of the welded area. From the above results shows weldability of LM25/ZrO_2 composites was improved with the increase in weight percentage of ZrO_2 reinforcement.

Keywords: Aluminium LM25, Stir casting, friction welding, tensile test, compression test, bend test.

1. INTRODUCTION

Metal matrix composites have been studied for some year, and their potential advantages over conventional monolithic alloys are increasingly being appreciated. Aluminium alloy matrix composites reinforced with ceramic particles exhibit better mechanical properties than unreinforced aluminium alloy [1]. Metal matrix composites are normally fabricated by the addition of a reinforcement phase to the matrix by the use of several techniques such as powder metallurgy and liquid metallurgy [2]. Generally, the composites are produced by liquid casting technique, which is one of the economic and commonly used methods in liquid metallurgy [3]. Stir casting technique is the conventional and economical way of producing AMC. It is difficult to produce a particulate reinforced composite. In this, present method suitable modifications were carried on conventional stir casting method to take care of the molten aluminium with atmosphere, segregation of reinforcing particles and wettability [4]. The addition of a ceramic reinforcement phase in monolithic metal alloys significantly alters their mechanical and physical properties, as well as their deformation behavior [5]. They are usually reinforced by Al_2O_3, SiC, C in addition SiO_2, B, BN, B_4 C may also be considered in the last few decades [6]. But very works are concentrated in ZrO_2 reinforced with aluminium alloy. No works are identified ZrO_2 with LM25 alloy. Metal matrix composites exhibit the ability to withstand high tensile and compressive stresses by the transfer and distribution of the applied load from the ductile matrix to the reinforcement phase [7, 12].

The joining of AMC is still a challenging task to meet the demands. Many researchers attempted to join AMCs using established fusion welding processes. They reported the presence of porosity, coarse microstructure, segregation and decomposition of ceramic particle and formation of several brittle intermetallic compounds [8]. No works have been reported on the friction welding of LM25/ZrO_2

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composites. In the present study, mechanical and microstructure analysis was carried out for joining of LM25/ZrO_2 composites by rotational friction is investigated.

2. MATERIALS AND METHODS

2.1 Materials selection

In this work LM25 was selected as matrix materials for this investigation and it was reinforced with various weight percentages of ZrO_2, in order to overcome failure due to wear for the wide application in automobile and aircraft industries. The corresponding chemical compositions and mechanical properties of LM25 and ZrO_2 are given in Tables 1 and 2 respectively.

Table 1: Chemical composition of LM25 Aluminium alloy and ZrO_2 particles (wt %)

Chemical composition	Cu	Mg	Si	Fe	Mn	Ni	Zn	Pb	Sn	Ti	Al
LM25 alloy	0.1	0.2-0.6	6.5 – 7.5	0.5	0.3	0.1	**0.1**	**0**	**0.1**	**0.2**	**Bal**
Chemical composition of ZrO_2	SiO_2		TiO_2	Fe_2O_3			Y_2O_3			Zr	
	0.25%		0.16%	0.07%			3 to 5%			Bal	

Table 2: Mechanical properties of LM25 Aluminium alloy and ZrO_2 particles

Mechanical properties	Density Test (gm/cm^3)	Tensile test (MPa)	Compression Test (MPa)	Impact Test (Joules)	Hardness Test (VHN)
LM25 alloy	2.68	144.7	193	2	58.21
ZrO_2	6.04	248	2500	1.85	10.7

2.2 Stir Casting Procedure:

The stir casting technique was used to fabricate the composite specimen as it ensures a more uniform distribution of the reinforcing particles. This method is most economical to fabricate composites with discontinuous fibers or particulates as shown in Figure 1. The small ingots of Aluminum LM25 alloy were weighed and loaded in graphite crucible using an electric resistance furnace in which aluminum alloy was melted at 850ºC. To improve the weldability and to achieve a strong bonding by decreasing the surface energy between the matrix alloy and the reinforcement particles, Zirconium dioxide was added during the stirring with the molten aluminum. Before mixing the ZrO_2 reinforcement with liquid melt, ZrO_2 particles was preheated at 900ºC for two hours. Now, the molten metal was mechanically stirred at a constant speed of 400 rpm for 15 minutes by graphite impeller. Then the different amount of preheated Zirconia particles (0%, 3%, 6%, 9% and 12%) were added into the molten alloy and stirred for few more minutes for homogeneous distribution. Then molten metal's were poured into the cast iron permanent moulds. The dies were allowed for cooling to get required specimen shape. After that, the cast specimens were removed and used for different testing by machined in a lathe machine. The cast samples are as shown in Figure 2. Then the rod was cut by power hacksaw machine as per ASTM standards (Length: 100 mm, Diameter: 25 mm).

1. **Preheating Furnace**
2. **Control Unit**
3. **Main Furnace**
4. **Stirrer**

Figure 1: Stir Casting Machine

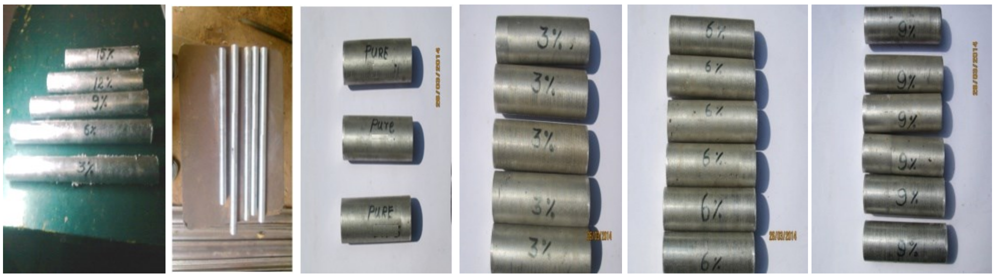


Figure 2: Cast samples of LM25-ZrO_2 composites

2.3 Friction Welding

Friction welding is a solid-state welding process. It makes use of frictional heat generated at the rubbing surfaces to raise the temperature of the interface higher enough to cause the surfaces to be forged together under high pressure. Continuous drive friction welding in which the energy required to make the weld is supplied by the welding machine through a direct motor connection for a preset of the welding cycle. In continuous drive friction welding, one of the workpieces is attached to a motor-driven unit while the other is restrained from rotation. The motor- driven workpieces are rotated at a predetermined constant speed. The workpieces to be welded are forced together and then a friction force is applied heat is generated as the laying surfaces rub together this continues for a predetermined time or until a preset amount of axial shortening takes place. The rotational driving force is discontinued, and the rotating workpiece is stopped by the application of a breaking force. The friction force is maintained or increased, for a predetermined time after rotation. The input variables that control the joints are heating pressure (HP), heating time (HT), upsetting pressure (UP) and upsetting time (UT). The output variables are the flash width (FW), flash height (FH) and flash thickness (FT). In this machine heating pressure, upsetting pressure, speed, heating time, upset time given to the machine as per the Table 3.

Table 3: Friction Welding Process Parameters

Upsetting Pr (bar)	Heating Time (sec)	Upset Time (sec)	Speed (rpm)	Bdt/Udt (sec)	Mode	Feed Rate (mm/sec)	Final Length (mm)	Material Loss (mm)
25	4	3	1500	.8/.3	Fkt	0.5	158	8.1

After friction welding, the material loss is (burn off length) 8.1 mm. The loss of the composite material is will not affect the tensile strength. The welded samples are shown in Figures. 3.

Figure 3: Friction Welded Samples

3. RESULTS AND DISCUSSION

The results obtained from the various mechanical, metallurgical tests for the cast and welded samples are as discussed in detail below.

3.1 Mechanical test results for LM25-ZrO_2 composites

This section mainly illustrates and discusses in details about the various results obtained from mechanical testing of the developed composites

3.1.1 Effect of Density:

The density of a material plays a vital role in Al MMCs. It was estimated by theoretically and experimentally in order to find its accurate density value. Rule of the mixture is a method of approach to find out theoretical estimation of composite material, based on the assumption that a composite property is the volume weighted average of the matrix and reinforcement phase properties. Then, the density of fabricated Aluminium LM25/ZrO_2 metal matrix composite was measured by Archimedes principle for experimental calculation. The density measurement involved weighing the polished sample specimen in air and when immersed in distilled water. The experimentally evaluated densities are derived from the recorded weights and then compared to the theoretical rule of a mixture of densities, which is almost relevant to experimental values. The comparisons of densities by the rule of mixture and Archimede's principle are shown in Figure 4. From the Figure 4, it is clearly identified that the density was gradually increased by the addition of ZrO_2 particle with aluminium LM25 alloy. Similar trends have been observed by many other researchers [5].

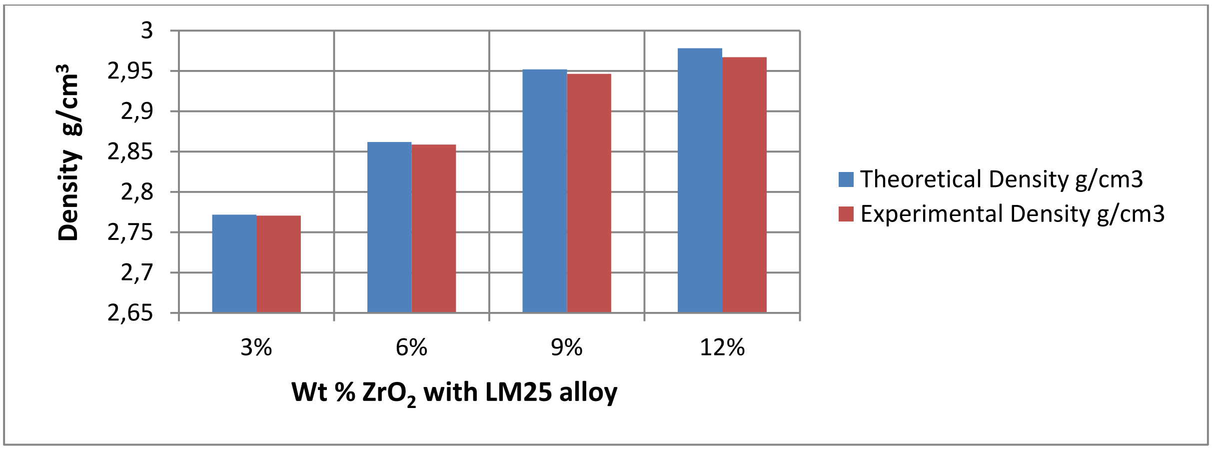


Figure 4: Comparisons of Theoretical and Experimental density

3.1.2 Effect of Tensile strength

The fifteen tensile test sample specimens were prepared as per the ASTM standard (ASTM B-557-M-94), and it was tested in a Universal Testing Machine (FIE Pvt.Ltd., model: unitek 94100) . Before measuring the tensile strength, the fifteen samples were machined into cylindrical shape. Three samples were tested for each composition to obtain the best tensile test result. The tensile test results indicating yield, ultimate tensile strength, and percentage of elongation of the six specimens LM25 reinforced with 0%, 3%, 6%, 9% and 12% respectively are given in Figure 5. From the Figure 5, it is clearly identified that the maximum ultimate tensile strength is obtained for the sample 5 that contains 12 % of ZrO_2. Therefore, this clearly reveals that the ultimate tensile strength increases with increasing percentage of ZrO_2 as shown in Figure 5. Similar trends have been observed by many other researchers [5,10].

3.1.3 Effect of Compression Strength

The compression test sample specimens were prepared as per the ASTM standard (ASTM D695), and it was tested in a Universal Testing Machine (FIE Pvt.Ltd., model: unitek 94100). In general, an aluminium alloy shows an apparently higher strength in compression than in tension. For this test, three different sample specimens were prepared for the different weight fractions of ZrO_2 particles with Aluminium LM25 based MMCs. The results are shown in Figure 6. From this Figure 6, it was observed that with the increase in the weight fraction of ZrO_2 particle increases the compressive strength.

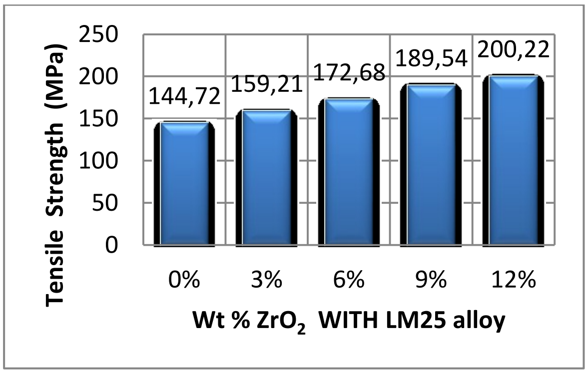


Figure 5: Effect of Tensile strength

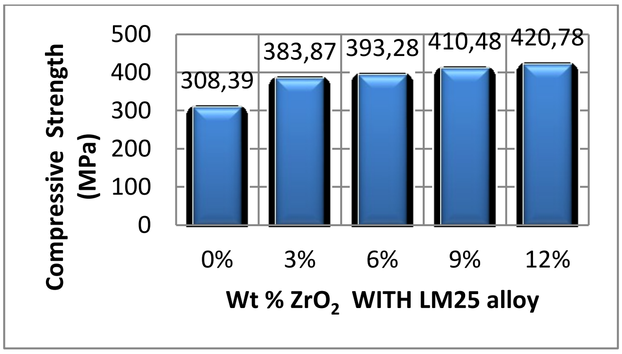


Figure 6: Effect of compressive Strength

3.1.4 Effect of Impact strength:

The eighteen impact test sample specimens were prepared as per the ASTM standard (ASTM A370), According to this standard, the standard specimen size for Charpy impact testing is 10 mm × 10mm × 55mm. The impact test of the material can be obtained by Charpy or Izod test. The results of the Charpy impact tests for Aluminium LM25 composites fabricated with the different weight fractions of the ZrO_2 particle are shown in Figure 7. The test results revealed that the impact energy of Aluminium LM25/ZrO_2 based metal matrix composite mainly depends on the distribution of the particles in the matrix. It was interesting to note that there was no variation in the value of the Base Metal and 3% Volume fraction of ZrO_2 particles with Aluminium LM25 was shown in Figure. 7. The impact values were slightly increased with increasing volume fraction of ZrO_2 of the particle after 3% of ZrO_2.

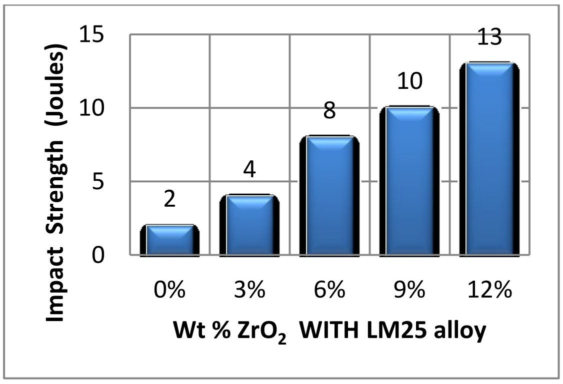


Figure 7: Impact strength of LM25 with various Wt % ZrO_2

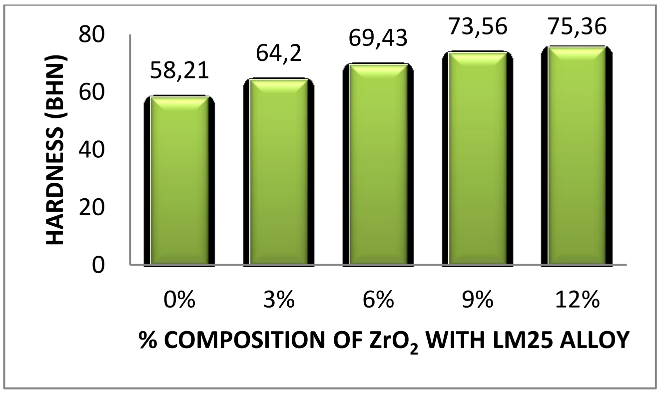


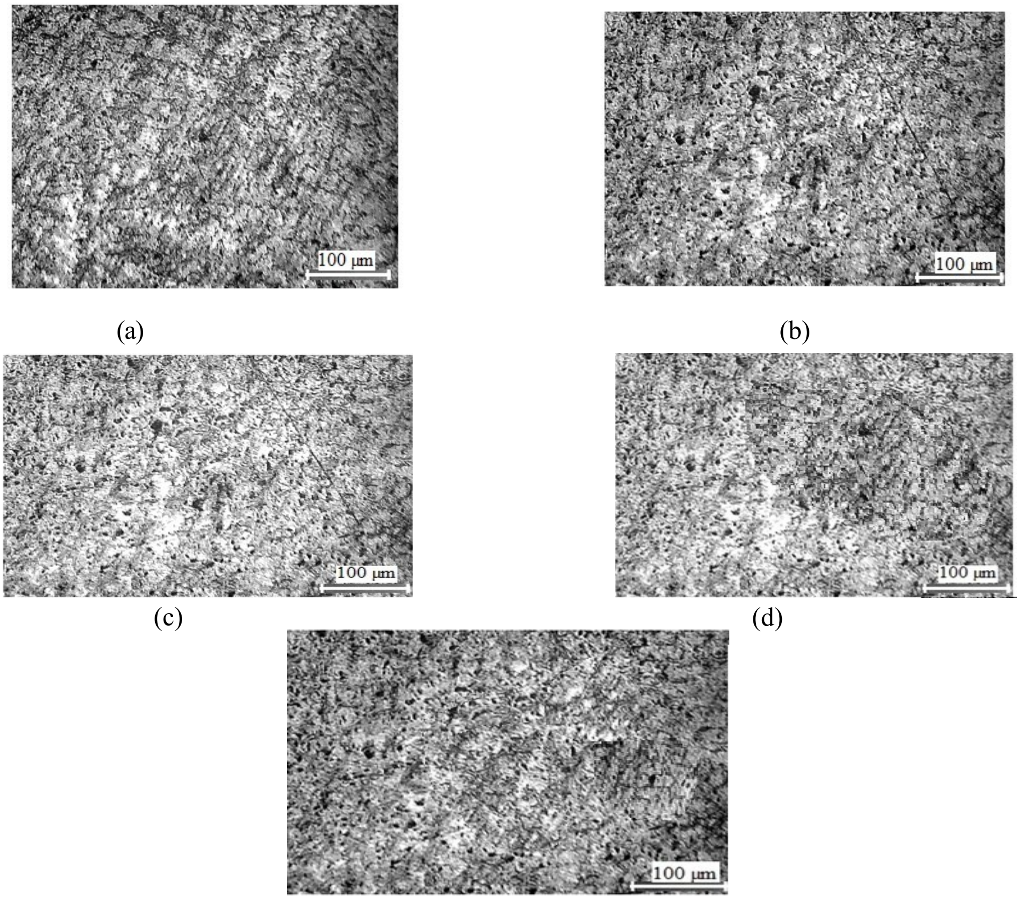
Figure 8: Hardness value with varying wt% of ZrO_2

3.1.5 Effect of hardness:

The hardness of the composite depends on the reinforcement of matrix material. As the coefficient of thermal expansion of Zirconia is less than the aluminium alloy, an enormous amount of dislocations is generated at the particle-matrix interface during the solidification process. This makes a further increase in hardness of the matrix. The hardness test was conducted using Brinell hardness equipment for a load of 1 kg. The results are graphically represented in Figure 8. It is observed that the hardness values of the material are directly proportional to the presence of ZrO_2 and with the increase in ZrO_2, the hardness value of the composites increase**s .**The above graph shows the variation of Brinell hardness value for different compositions of ZrO_2 in LM25/ZrO_2 composites. Similar trends have been observed by many other researchers [11,13].

3.1.6 Microstructure evaluation of the developed composites:

In this work, ZrO_2 is added as reinforcement for aluminium alloy LM25 series to analyze the change in the properties of the matrix metal. As a part of it, the wider effort is taken to improve the performance of LM25/ZrO_2 composites. This research sets out to investigate the effect of minor elements (Zirconia) on castability. This is clear from the Figure 9 (a-e), which shows optical microscopy images. The LM25/ZrO_2 composites show fine grains of Al-Zr eutectic in aluminium solid solution. The constituents of phases present in the matrix are Mg_2Si and some Cu-Al_2 phases which are randomly distributed. The Al-Si eutectic forms an interdendritic pattern due to rapid cooling. As it is chilled, the cast shows that the dendritic pattern of the grains is cured towards the direction of the chilled plate. No directional orientation could be seen in castings. The presence of ZrO_2 in the aluminium matrix alloy is uniform and present as dark particles.



(a) (b)

(c) (d)

(e)

Figures 9 (a-e): Optical Microscopic image of various composite specimens a) LM25 alloy (b) LM25–3% of ZrO_2 (c) LM25–6% of ZrO_2 (d) LM25–9% of ZrO_2 (e) LM25–12% of ZrO_2

3.2 Mechanical and metallurgical evaluation of the welded specimens:

This section mainly illustrates and discusses in details about the various results obtained from mechanical and metallurgical testing of the welded LM25-ZrO_2 composite specimens.

3.2.1 Effect of Tensile Strength for Welded Specimen:

The tensile test of the LM25/ZrO_2 based composites was carried out in accordance with ASTM UTN 40: SR No: 11/ 98 – 2450 on the universal testing machine at room temperature [9]. Four samples specimen were prepared for repeat tensile tests, which were cut from each fabricated various weight fractions of the composite ingot, and the tensile properties reported in this paper was averaged. The ultimate tensile strengths obtained for different compositions are shown in Figure 10. From the Figure 10, it is clearly identified that addition of ZrO_2 increases the tensile properties of the LM25 composite also increases. Similar trends have been observed by many other researchers [14].

Similarly, the elongation of composite's increases gradually with increasing the weight fraction of the ZrO_2 particle as shown in Figure 11. These results indicate that the ZrO_2 addition leads to improvement in the ultimate tensile strength and elongation of LM25/ZrO_2 MMC.

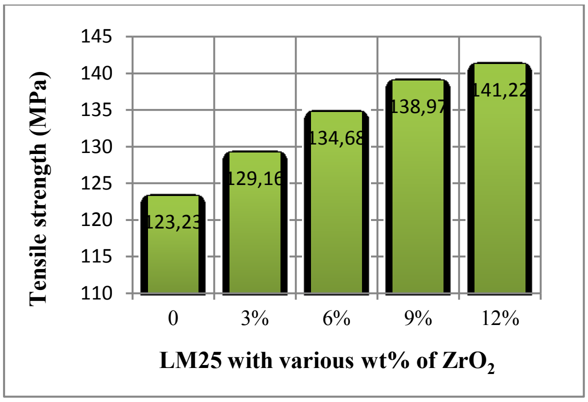


Figure 10: Material Vs Tensile Strength

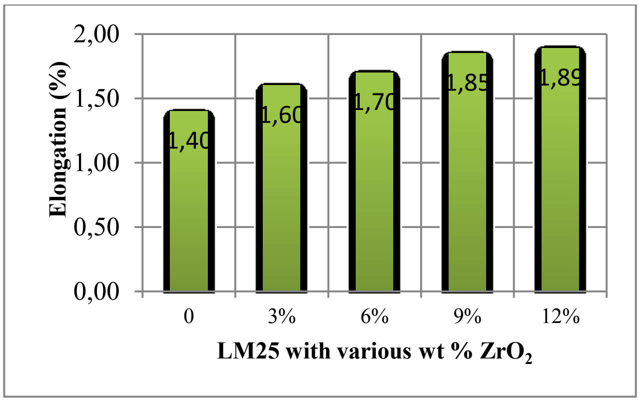
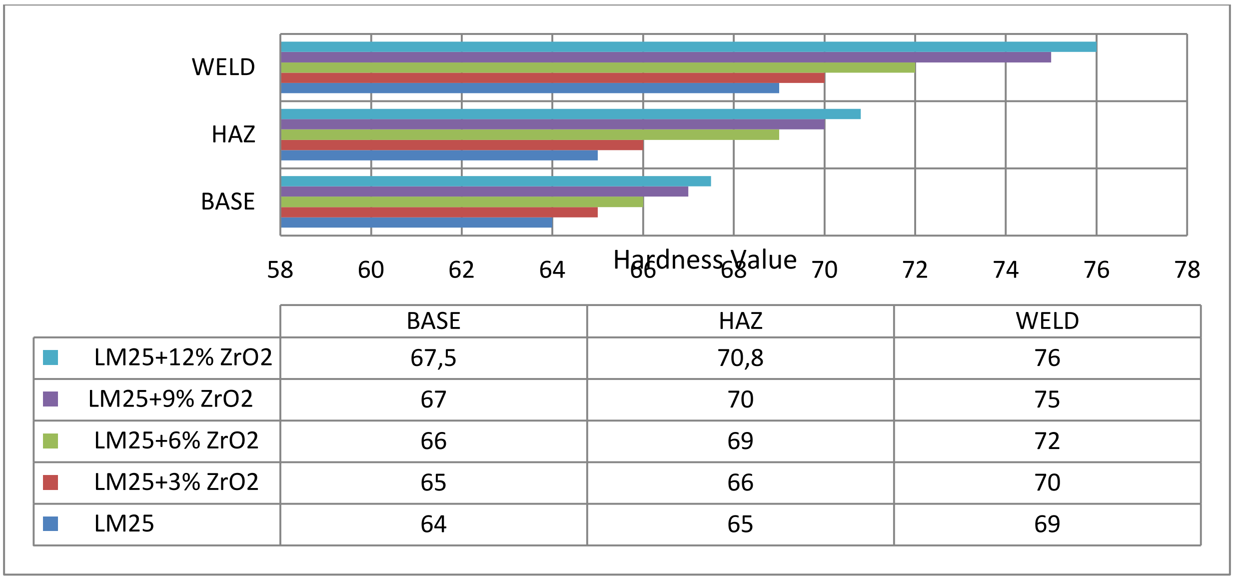


Figure 11: Material vs % of elongation

3.2.2 Effect of Brinell Hardness of the Welded Specimen:

The hardness of the composite depends on upon the reinforcement and matrix material. As the coefficient of thermal expansion of zirconia is less than the aluminium alloy, an enormous amount of dislocations is generated at the particle-matrix interface during the solidification process. This makes the further increases the hardness of the matrix. The hardness test was conducted on brinell hardness equipment for a force in 100 N, and the magnification is 200X then the dwell time is varied with respect to the material. Thus the obtained results are shown in Figure 12. From the graph reinforcement of ZrO_2 particle increases the correspondingly hardness of the material also increases for three regions like base, HAZ, and welds zone.



	BASE	HAZ	WELD
🟦 LM25+12% ZrO2	67,5	70,8	76
🟪 LM25+9% ZrO2	67	70	75
🟩 LM25+6% ZrO2	66	69	72
🟥 LM25+3% ZrO2	65	66	70
🟦 LM25	64	65	69

Figure 12: Hardness for three different welded region

3.2.3 Effect of bend Test of the welded specimen.

In generally, an aluminum alloy shows apparently lower strength than tension. Bending is extremely high commercial importance because it helps to determine material properties [10]. The bend tests were carried out according to ASTM standard, which was conducted on a universal testing machine. For this test, five sample specimen was prepared for a different weight fraction of a ZrO_2 particle with Al LM25 based MMC. The results were shown in Figure 13. The bending test like a three- point load test. From these results , it was observed that the increasing the weight fraction of the ZrO_2 particle, which increases the bending strength up to 12 % .But in 15 %, the bending strength decreases from that of pure material.

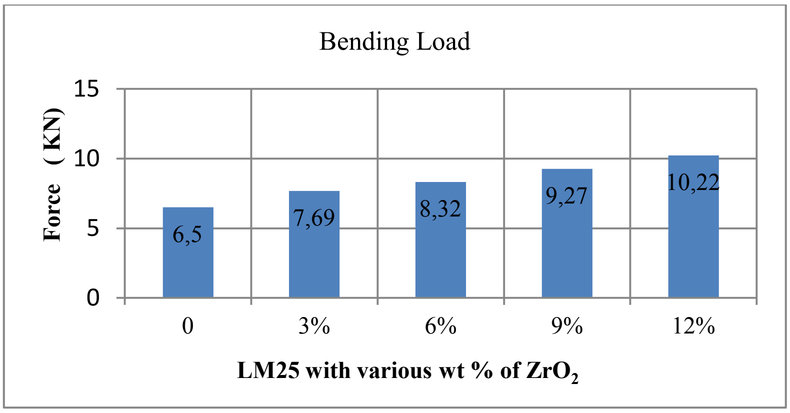
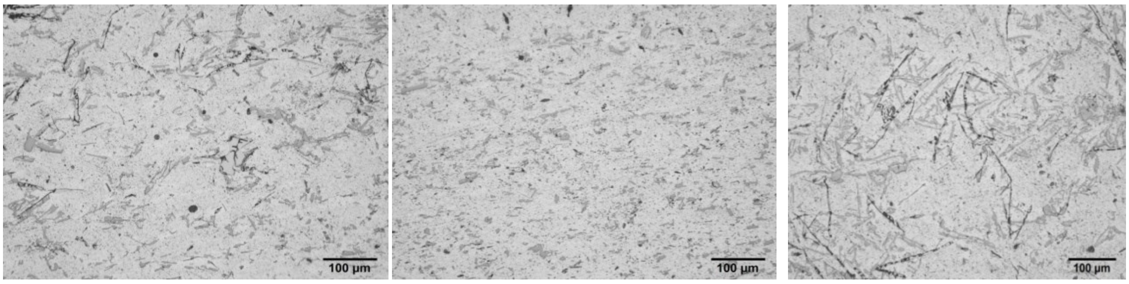


Figure 13: Bending strength of LM25 with various Wt % ZrO_2

In this result the three point bending m/c the 12 % of the ZrO_2 Composite material withstand the high load than other materials.

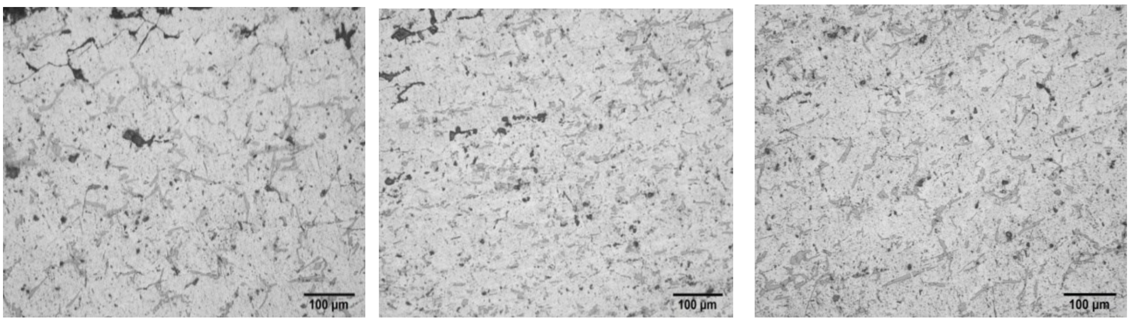
3.2.4 Microstructure evaluation of the welded specimens:

The metallographic analysis offers a powerful quality control as well as an important investigative tool. The grain structure and reinforced particle's size, shape and their distribution were observed in a micrograph. The more important use of the optical microscope in microstructure examination was in the analysis of reinforced particles in an aluminum matrix. Metallographic specimens were prepared using standard hand polishing using 240, 600, 800, and 1000 grit silicon carbide paper. The finished specimens were polished using 1µm diamond paste suspended in distilled water to obtain a mirror-like surface finish. To expose the microstructural features, the polished specimens were etched with a killer etching solution. The etch polish procedures were used to attain good microstructure.



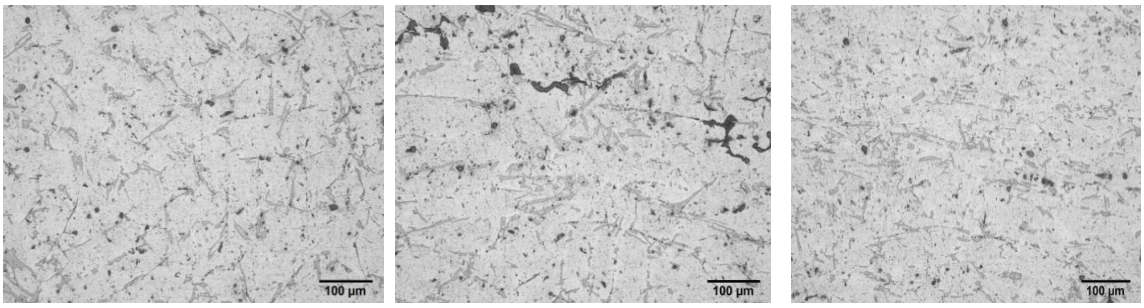
(a) TOP 100X (b) MID 100X (c) BOT 100X

Figure 14 (a, b, c): Optical Microstructure of Pure LM25



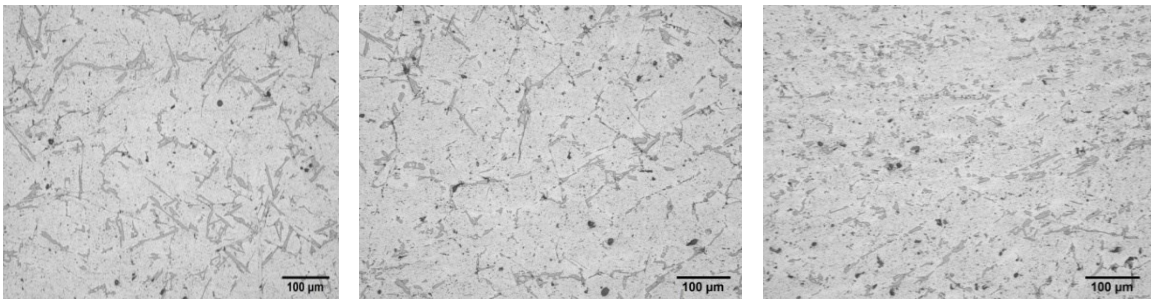
(a) TOP 100X (b) MID 100X (c) BOT 100X

Figure 15 (a ,b ,c): Optical Microstructure of LM25 with 3 % ZrO_2



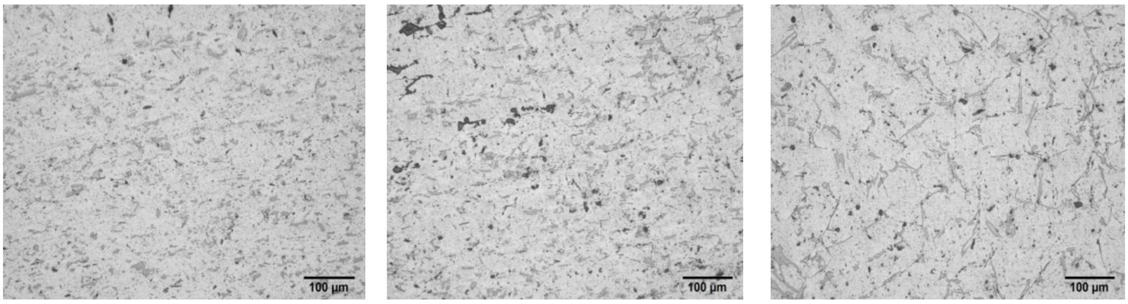
(a) TOP 100X (b) MID 100X (c) BOT 100X

Figure 16 (a, b, c): Optical Microstructure of LM25 with 6 % ZrO_2



(a) TOP 100X (b) MID 100X (c) BOT 100X

Figure 17 (a ,b ,c): Optical Microstructure of LM25 with 9 % ZrO_2



(a) TOP 100X (b) MID 100X (c) BOT 100X

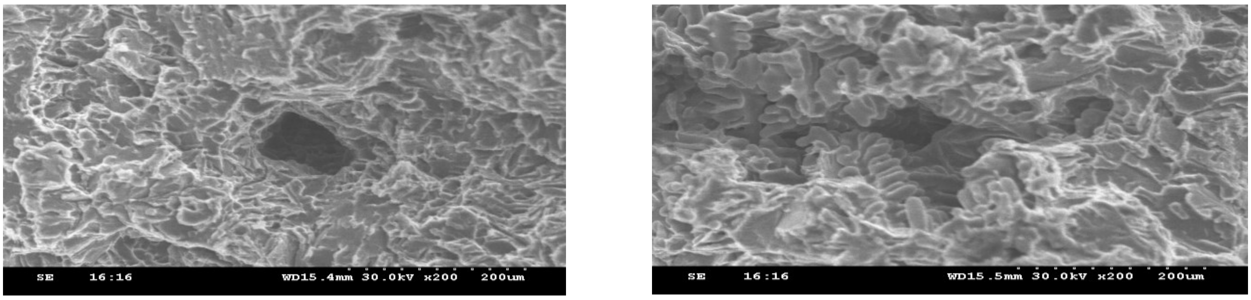
Figure 18 (a ,b ,c): Optical Microstructure of LM25 with 12 % ZrO_2

The microstructure was taken three different areas like a top, middle and bottom portion. The mid portion of the friction welding after testing of microstructure the black point of ZrO_2 in 12% is superior binding of cast structure. So the weldability is good in the proportion. On viewing the figures it was found that the particle size of the Zirconia is very fine. This is why, at 100µm, the particles look very small, and it can be easily detected that the distribution of the particles is almost uniform. Scanning Electron Microscope test too reveals this Scanning Electron micrographs (SEM) of the different volume fraction of ZrO_2 particles with LM25 are shown in the Figures 14 to 18. The distribution of particles throughout the matrix was found to be fairly uniform. Scanning Electron micrographs at lower magnification show that the distribution of ZrO_2 particle throughout the MMCs and at higher magnification scanning electron microscopes show that the particle-matrix interfaces. From these figures, is revealed the homogeneous distribution of ZrO_2 reinforced particle with aluminium alloy. Further, these figures reveal the homogeneity of the cast composites. The relationship between the distribution of particles and weight fraction of Zirconia is studied from scanning electron micrographs. In either case, no pores have been observed this indicates better wettability between the matrix and reinforcement particles. So the interfacial bonding was obtained in the case of rapid cooling. It is observed that as the percentage of reinforcement increases the area fraction also increases as shown in the micrographs. Similar trends have been observed by many other researchers [11].

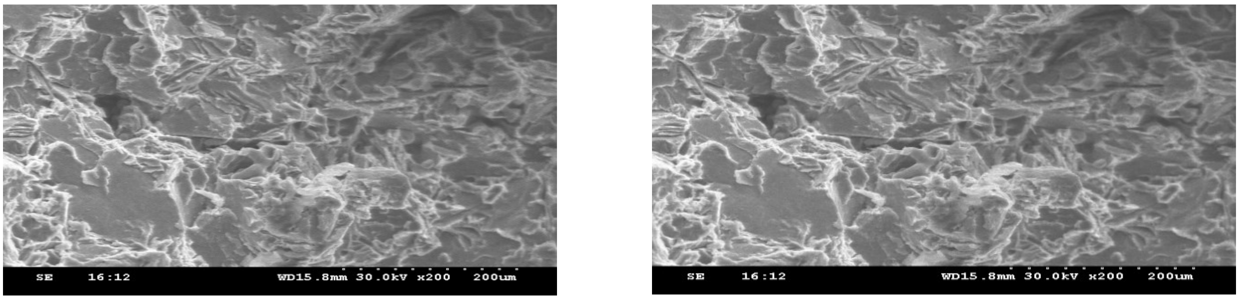
3.2.5 Fractography analysis of the tensile tested weld specimen:

Fracture surface analysis revealed different topographies for the composites containing different weight percentages of zirconium particles. Results of the fracture surface analysis conducted on fracture toughness specimens of FCC structured LM25 alloy samples revealed large dimples along with a large amount of plastic deformation indicating a ductile fracture. The fracture surfaces also exhibit fine and shallow dimples indicating that the fracture is ductile as shown in Figure 19 (a).

Scanning electron microscopy of the fracture surface of the MMCs tested is shown in Figures from 19 (a) to (e). Examination of these fracture surface features in SEM at high magnification is to identify the fatigue and final fracture region, to identify areas of micro-crack initiation and early crack growth, and the over-loaded region to identify the fine-scale fracture features.

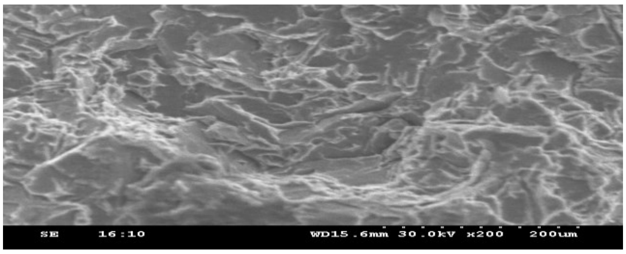


(a) LM 25 Alloys (b) LM25 with 3 % of ZrO_2



(c) LM25 with 6% of ZrO_2

(d) LM25 with 9% of ZrO_2



(e) LM25 with 12% of ZrO_2

Figures 19 (a-e): Fractography analysis LM25 with various Percentages of ZrO_2

Fracture surfaces revealed different topographies for the composites containing a different weight percentage of zirconium particles. Fracture surface in the case of MMCs containing 3 wt.% (Figure 19 (b)) reinforcement reveals mixed mode fracture and MMCs containing 12 wt.% reinforcement revealed cleavage type of fracture (Figure 19 (e)) due to the presence of excessive zirconium particulates. It can also be seen that regions of clustered particles for reinforcement above 9 wt.%,(Figure 19 (d)) are sensitive to premature damage in the composites, and the large particles seem to be prone to fracture and hence registered a reduction in the fracture toughness value. Fracture mode of the matrix alloy which changed from ductile to cleavage type (in the case of MMCs) was dominated with microcrack nucleation and propagation as shown in Figure 19 (a-e). Scanning electron microscope observations of MMCs suggest that, at higher reinforcement content (12 wt.%, Figure 19 (d)), void nucleation may also take place at large participates in addition to the matrix/particle interface, while at lower reinforcement (0,3, 6, 9 wt.%, Figures 19 (a-d)) rates the fracture seems to occur by breakage of the particles.

Fracture surface analysis of MMCs containing 12 wt.% dispersoid (Figure 19 (e)) exhibit, predominantly that fractured particles (dispersoid) and the matrix material with coarse dimples, suggests that fracture is of mixed mode type. Close examination of the fractured surface indicates that most dimples were associated with the matrix material (Figure 19 (e)). Massive separations of the particle indicate that failure of the material is initiated by fracture of the particles rather debonding between the matrix and reinforcements. Finally composite containing 12 wt% dispersoid showed cleavage indicating that the fracture is towards brittle.

4. CONCLUSIONS

The Development of aluminium LM25/ZrO_2 composites and feasibility welding of LM25/ZrO_2 composites for different weight proporations are experimentally studied. Then the following conclusions are made from experimental results.

- The Densities of the fabricated composites were slightly increases for different compositions, while compared to the theoretical and experimental analysis.
- There is an improvement in the tensile strength, ultimate tensile strength and % of elongation (ductility) with the addition of ZrO_2 particle.
- The compressive strengths also increase, when an addition of ZrO_2 particle reinforced with Aluminium LM25 alloy.
- The impact strength gradually increased while adding ZrO_2 particle reinforced with Aluminium LM25 alloy.

- The hardness of the reinforced composites was improved compared with unreinforced alloy and 12 % of ZrO_2 combination achieves high hardness value.
- The ultimate tensile strength of the welded specimen was improved by adding of ZrO_2 particle with LM25 and attains high tensile strength at 12% of ZrO_2 Particle. In this test welded area is not the fracture. So weldability is good.
- In the Result of Three-Point Bending Machine, the 12% Of the ZrO_2 composite material is withstanding the high load than other Materials. So the weldability of the aluminium metal matrix composite was improved by adding of ZrO_2 with LM25.
- The hardness of the welded specimen of the reinforced composites was improved comparing with unreinforced Alloy and 12% Of ZrO_2 Combination Achieves High Hardness Value. The hardness of the welded area was greater than that of other regions.
- The mid portion of the friction welding area after testing of microstructure the black point of ZrO_2 in 12 % is superior binding of cast structure. So the weldability is good in this proportion.

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