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Investigation on Mechanical Properties of Diffusion Bonded AZ-91 Magnesium Alloy Reinforced with Sic Particles

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***Abstract* - AZ-91 magnesium alloy plate were placed one above the other and joined by diffusion bonding technique. Hard silicon carbide particles are placed between the plates and bonded at the optimum value of temperature, holding time and load. Mechanical properties are determined by double shear test. The shear strength of the material joined with reinforcement is greater than the specimen joined without reinforcement. The strength of the material declined when the reinforcement percentage is raised to six. The fractured surface is observed under scanning electron microscope. EDS and XRD analysis were made on the sheared surface for elemental distribution and phase identification.**

Keywords: Silicon Carbide, Shear Test, Diffusion Bonding, EDS, XRD

I. INTRODUCTION

Die-cast magnesium alloys offering good combination of castability, corrosion resistance and mechanical properties are widely used for structural applications including automotive, industrial, materials-handling, commercial, and aerospace equipment. The disadvantages of these materials are the poor workability, limited ductility and low stiffness because of their hexagonal structure and the degradation of mechanical properties at elevated temperatures. As a general means of materials manufacturing, welding can be used to optimize product design and minimize the cost of production. Information published on welding of magnesium alloys were still limited. Welding methods such as TIG, LBW, electron beam welding, friction welding and diffusion welding have already been applied to join magnesium alloys [1]. Diffusion bonding is a solid state joining technique and has widely used in titanium alloys, aluminum alloys, steels, and iron aluminides. During diffusion bonding two clean surfaces are brought into contact under vacuum or atmosphere at low pressure and elevated temperature less than 0.7 Tm. Many factors affect the quality of diffusion bonds, including temperature, pressure, time, metallurgical effects and interlayer. By using vacuum diffusion bonding the development of solidification cracking and high distortion stresses can be avoided, compared to conventional welding technique. The optimal conditions to produce high quality diffusion bonds have already been reported for aluminum alloys, titanium alloys and steels. Recently, the use of interlayers has been investigated for the bonding of magnesium alloys [2]. The crack, distortion and segregation produced using fusion welding can be avoided using diffusion bonding technology [3]. Joining Mg and Al would meet the requirements of special properties for some applications, particularly in the field of aerospace, such as aircraft engine, which requires meeting different requirements of temperature and mechanical performance at both sides. In order to fully utilize the superiority of Mg and Al, to achieve weight and cost reduction, few researchers have used dissimilar bonding technique to join Mg and Al such as brazing, friction stir bonding and vacuum diffusion bonding, etc [4]. The difficulty when joining Mg and Al is the formation of high hardness and brittle intermetallic compounds (IMCs) [5]. Formation of intermetallic compounds were encountered during the diffusion bonding of Al 7075 and Mg AZ31 alloys at higher temperature and pressure [6]. Many long and broad voids were witnessed at the bonding interface of diffusion bonded Ti-17 titanium alloy. As the ridges of bonding surfaces contact together, void size decreases in length and the height hardly changes [7]. Minimum bonding strength is achieved at low bonding pressure while joining Mg-Cu alloys [8]. Tensile test on hot rolled diffusion bonded AZ31 magnesium alloy revealed that the material behaved in a superplastic manner at 523 K and the grain size was confined to 8.5 microns. Various prediction methods are applied to define the desired output variables through developing mathematical models to specify the relationship between the input parameters and output variables [10]. Various researches were made so far by joining similar and dissimilar materials by diffusion bonding technique. However no extensive works were carried out in diffusion bonding by adding reinforcement materials between the surfaces of two bonding materials. The introduction of hard ceramic particles could play a decisive role between the two faying surfaces and is greatly expected to create a better impact on the mechanical properties of the bonded material. In this work SiC carbide particles are suspended freely between the three layered specimen at various sizes and percentages and diffusion bonded. The mechanical properties and distribution of hard SiC particles were investigated. XRD analysis were done to determine the impact of formation of intermetallic compounds at the interface.

II. EXPERIMENTAL

A diffusion bonding machine with capacity to operate at wide range of temperatures and different loading conditions were chosen to carry out the experiments. Mg AZ91 alloy with dimensions 50mmx50mmx4mm were chosen for the study. The chemical composition of Mg AZ91 is given in Table 1. Three specimens of same dimensions were stacked one above the other as shown in fig. 1 and trial experiments were carried out by varying the parameters. Load (tonnes), Temperature (°C) and Holding time (hr) are the three parameters chosen for the study. Pilot experiments are carried out initially to determine the optimum operating conditions by observing the formation of bonded layer between the specimens. The optimum values at which the study is to be carried out is given in Table 2. Firstly, pure magnesium specimens are placed one above the other and bonded at the predetermined optimum values of chosen parameters. Subsequently, silicon carbide particles at various sizes and percentage are placed between the layers and diffusion bonded to study the effect of reinforcement particles over the formation of layers and its influence on mechanical properties of the material. Taguchi L_9 design shown in Table 3 is used to carry out the experiments to find out the effect of adding SiC particles of various sizes and percentage on mechanical properties of the bonded specimens. The specimens are subjected to shear test and the shear strength values and ductility attained were tabulated. ANOVA is carried out to determine the significance of individual factors on the mechanical properties. SEM analysis is carried out on the sheared surfaces of the specimen to determine the surface texture and deposition of SiC particles. EDS and XRD analysis were carried out on the fracture surface of all the specimens to investigate the distribution and adherence of the reinforcement particles over the surface of the substrate.

TABLE 1 CHEMICAL COMPOSITION OF MG AZ91 ALLOY (wt %)

Mg	Al	Zn	Mn	Si	Fe	Cu	Be
90.8	8.25	0.63	0.22	0.035	0.014	0.003	0.002

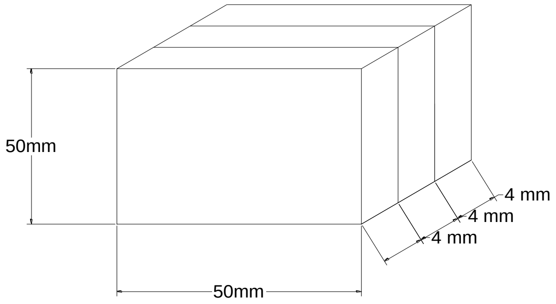


Fig. 1 Dimension of the three layered specimen

TABLE 2 OPTIMIZED PROCESS PARAMETERS FOR DIFFUSION BONDING PROCESS

Temperature (°C)	Load (tonnes)	Time (hrs)
420	2.5 tonnes	1 hr holding time

TABLE 3 TAGUCHI L_9 DESIGN

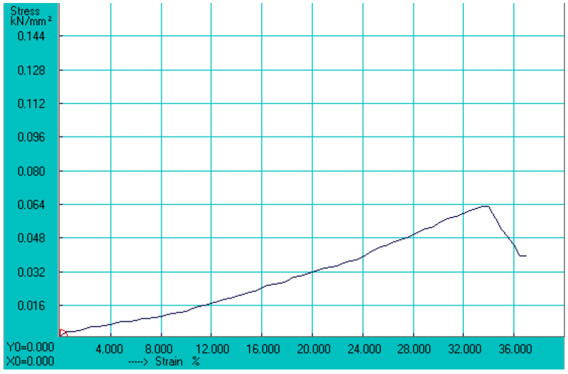
S.no	Size of particles	% of reinforcement
1	10	2
2	10	4
3	10	6
4	25	2
5	25	4
6	25	6
7	45	2
8	45	4
9	45	6

III. RESULTS &DISCUSSIONS

A. Mechanical properties

The experiemnts are carried out at different levels as per taguchi design and the formation of layers are observed under macroscope. The specimens are nailed according to dimension using Wire-EDM and subjected to double shear test and the corrsponding values are tabulated. The yield strength, shear strength and ductility of the specimes were recorded. The fractured specimen of the bonded base material without reinforcement is shown in fig 2. The result shows that the shear strength is higher when SiC carbide particles are added and declines when the percentage of reinforcement increases to six. The stress strain curve attained by the bonded specimens were shown in fig. 3(a)-(i). Table 4 and Table 5 represents the measured mechanical properties of the non-reinforced and reinforced diffusion bonded specimens. The mechanical properties of all the specimens are depicted graphically in fig. 4 to highlight the variation in attained values . The presence of more number of SiC hard particles that has diffused into the surface to a particular depth would have acted as the barrier in preventing the diffusion of the free loose particles. This could lead to more number of improperly bonded SiC particles between the layers that leads to fracture at earlier stage when sheared. The ductility was also low when the percentage of reinforcement is more. The diffusion of reinforcement particles into the subsrate and the penetration depth determines the bonding between the particles and the substrate.

Fig. 2 Sheared base material



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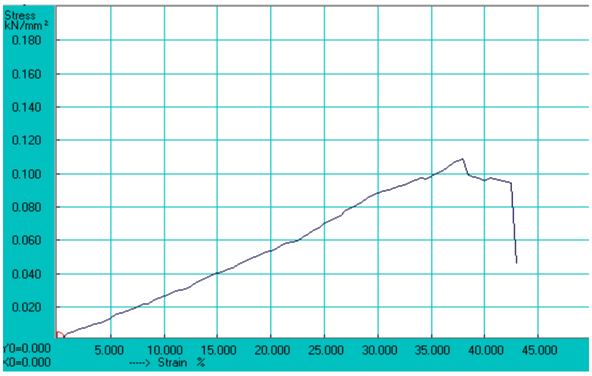

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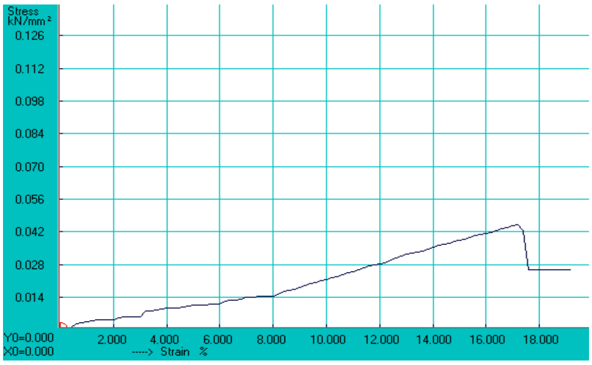

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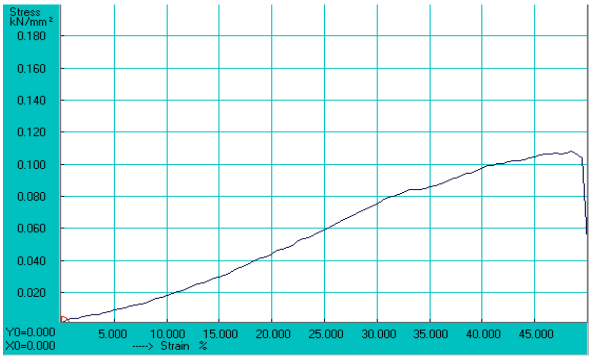

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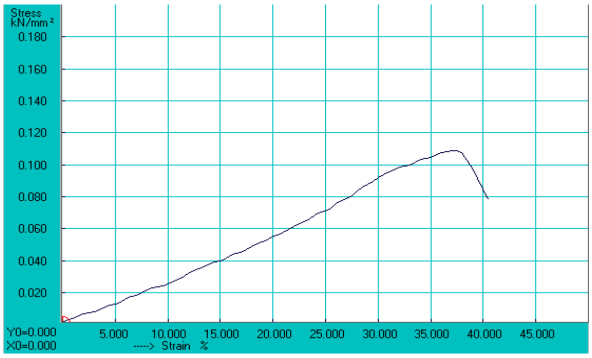

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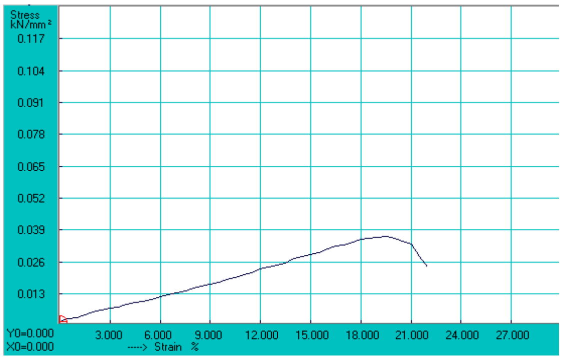

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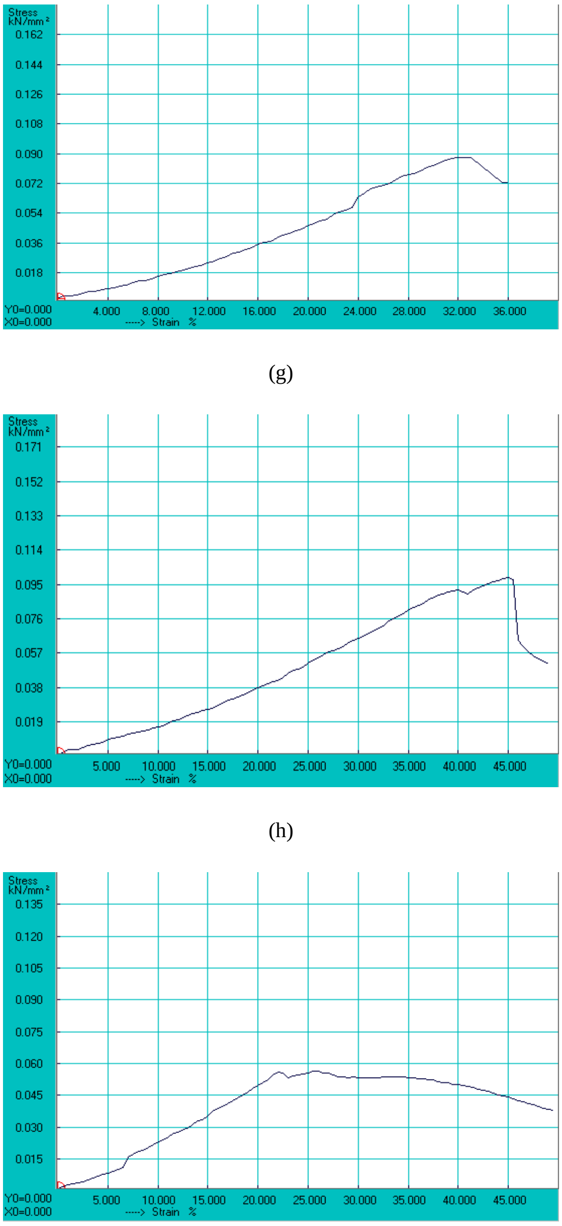


(g)

(h)

(i)

Fig. 3 Stress vs strain curves of bonded specimen (a), base material, (b) 10 microns 4%, (c) 10 microns 6%, (d) 25 microns 2%, (e) 25 microns 4%, (f) 25 microns 6%, (g) 45 microns 2%, (h) 45 microns 4%, (i) 45 microns 6%

TABLE 4 PROPERTIES OF NON-REINFORCED BONDED SPECIMEN

Yield strength KN/mm^2	Ultimate shear strength KN/mm^2	Ductility %
0.052	0.063	37

TABLE 5 PROPERTIES OF BONDED SPECIMENS WITH REINFORCEMENT

Specimen	Size of particles	% of reinforcement	Yield strength KN/mm^2	Ultimate shear strength KN/mm^2	Ductility %
1	10	2	0.054	0.094	47
2	10	4	0.060	0.109	43
3	10	6	0.045	0.015	19.2
4	25	2	0.084	0.108	50
5	25	4	0.098	0.109	40.5
6	25	6	0.033	0.036	22
7	45	2	0.073	0.088	36
8	45	4	0.042	0.099	49
9	45	6	0.007	0.056	49.5

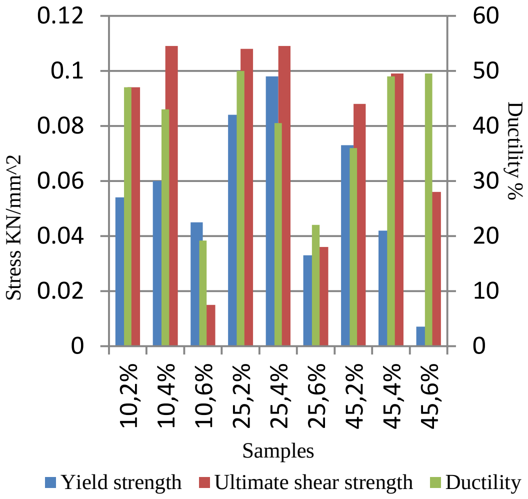
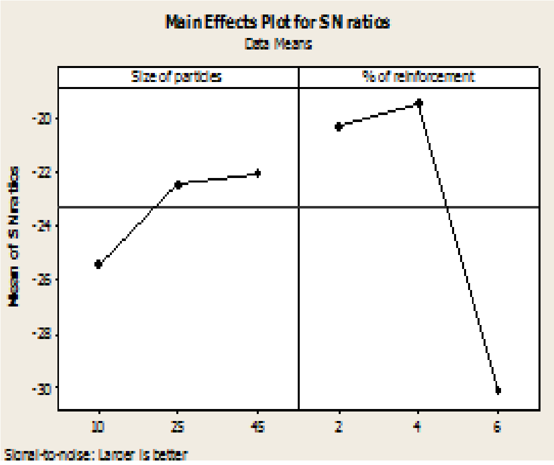


Fig. 4 Mechanical properties of joined specimens

Table 6 shows the anova for SN ratio and Table 7 presents the anova for means of the shear strength values. Table 8 and Table 9 represents the response table for SN ratio and means of shear strength. ANOVA result shows that the contribution of reinforcement is more than the size of the particles which is in concurrence with the results of shear test. Similarly Fig. 5 shows the main effect plots and interaction plots for SN ratio and means of shear strength. Similarly Fig. 6 shows the main effect plots and interaction plots for SN ratio and means of ductility. Table 10 shows the anova for SN ratio and Table 11 represents the anova for means of ductility. Table 12 and Table 13 represent the response table for SN ratio and means of ductility.



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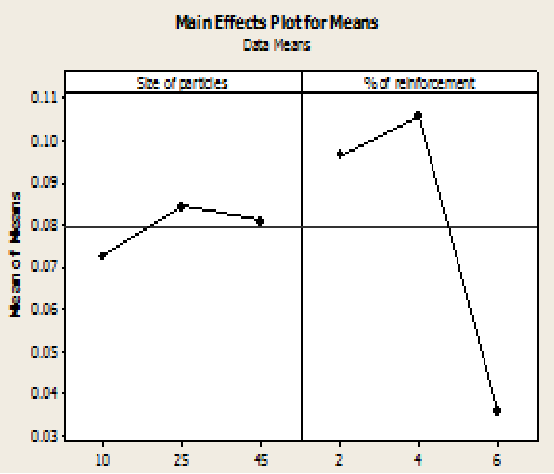

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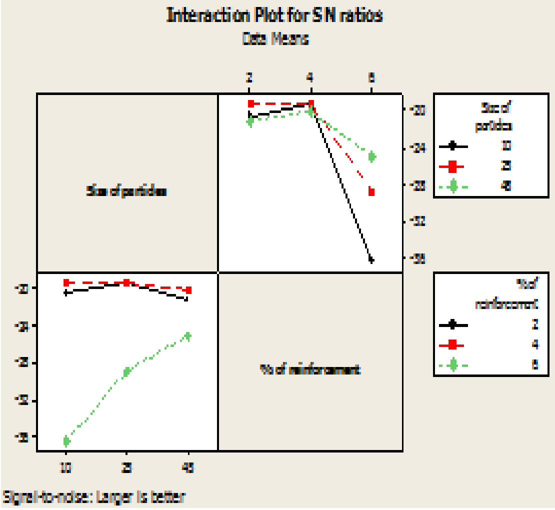

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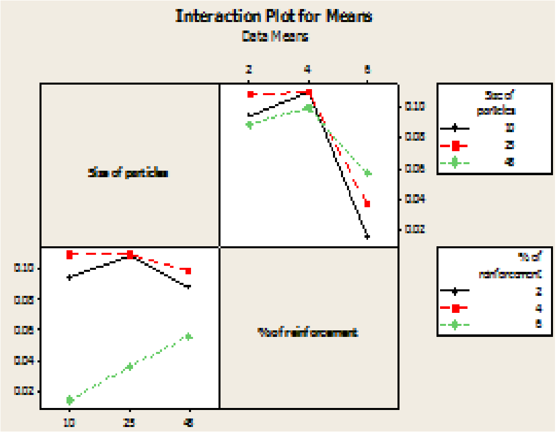

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Fig. 5 shear strength (a) Main effect plot for SN ratio, (b) Main effect plots for means, (c) interaction plots for SN ratio, (d) interaction plots for means

TABLE 6 ANALYSIS OF VARIANCE FOR SN RATIO

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Size of particles	2	19.98	19.98	9.988	0.80	0.510
% of reinforcement	2	209.08	209.08	104.540	8.37	0.037
Residual Error	4	49.96	49.96	12.491		
Total	8	279.02				

TABLE 7 ANALYSIS OF VARIANCE FOR MEANS

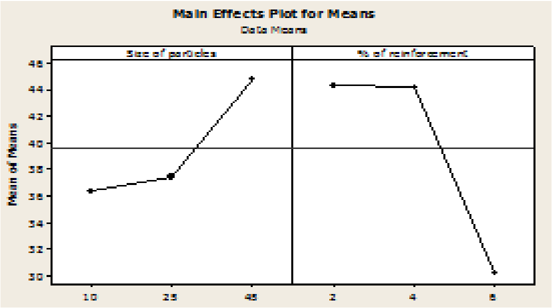
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Size of particles	2	0.000217	0.000217	0.000108	0.48	0.650
% of reinforcement	2	0.008702	0.008702	0.004351	19.31	0.009
Residual Error	4	0.000901	0.000901	0.000225		
Total	8	0.009820				

TABLE 8 RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (LARGER IS BETTER)

Level	Size of particles	% of reinforcement
1	-25.42	-20.33
2	-22.49	-19.53
3	-22.08	-30.13
Delta	3.34	10.60
Rank	2	1

TABLE 9 RESPONSE TABLE FOR MEANS

Level	Size of particles	% of reinforcement
1	0.07267	0.09667
2	0.08433	0.10567
3	0.08100	0.03567
Delta	0.01167	0.07000
Rank	2	1



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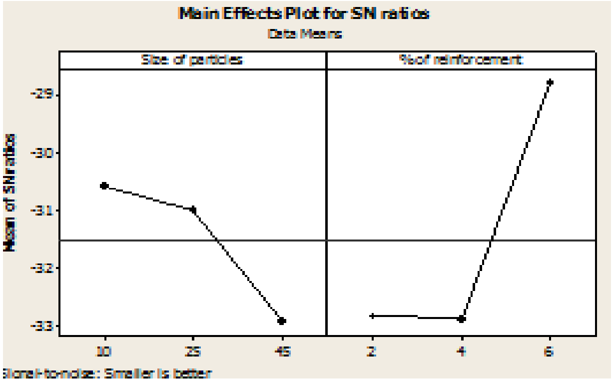

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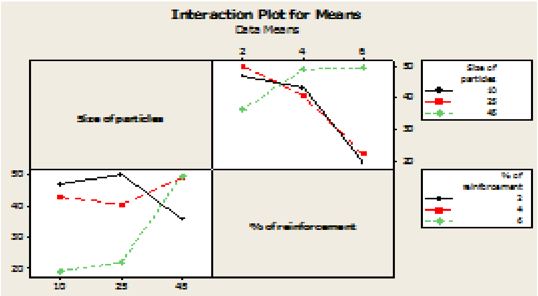

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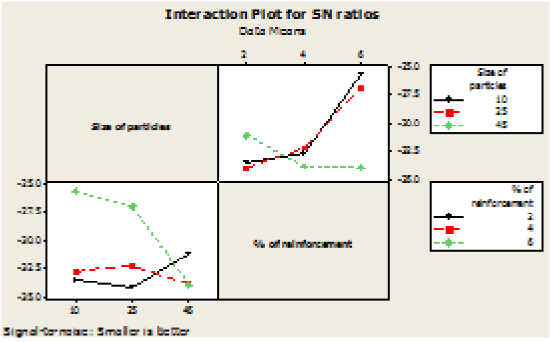


(d)

Fig. 6 Ductility (a) Main effect plot for SN ratio, (b) Main effect plots for means, (c) interaction plots for SN ratio, (d) interaction plots for means

TABLE 10 ANALYSIS OF VARIANCE FOR SN RATIOS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Size of particles	2	9.470	9.470	4.735	0.52	0.628
% of reinforcement	2	32.959	32.959	16.480	1.82	0.273
Residual Error	4	36.120	36.120	9.030		
Total	8	78.549				

TABLE 11 ANALYSIS OF VARIANCE FOR MEANS

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Size of particles	2	126.1	126.1	63.05	0.43	0.675
% of reinforcement	2	393.0	393.0	196.49	1.35	0.356
Residual Error	4	581.5	581.5	145.36		
Total	8	1100.5				

TABLE 12 RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS (SMALLER IS BETTER)

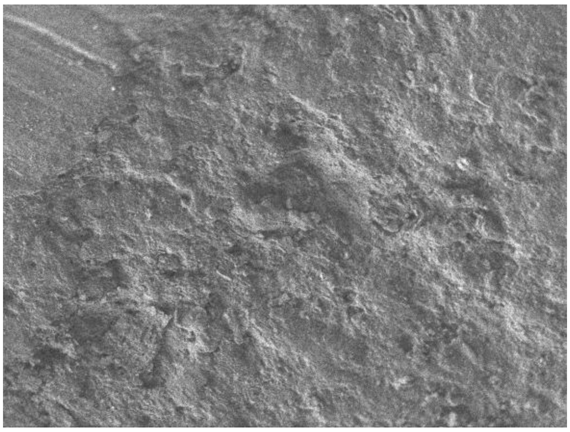
Level	Size of particles	% of reinforcement
1	-30.59	-32.85
2	-30.99	-32.87
3	-32.94	-28.80
Delta	2.35	4.07
Rank	2	1

TABLE 13 RESPONSE TABLE FOR MEANS

Level	Size of particles	% of reinforcement
1	36.40	44.33
2	37.50	44.17
3	44.83	30.23
Delta	8.43	14.10
Rank	2	1

B. Elemental analysis and XRD analysis

Fractured Surface of the specimen bonded with SiC particles at a size of 10 microns at 6% is observed under scanning electron microscope. Mountain shaped structure is observed on the surface with more number of irregularities created by the penetration of hard particles. The microstructure also shows the presence of SiC particles homogeneously distributed over the surface. EDS analysis shown in fig. 8 depicts the presence of more number of SiC particles being deposited on the surface with some of the alloying elements of the substrate. XRD results also shows the higher intensity of SiC particles on the fractures surface. XRD analysis of fractured surface of bonded specimen at 10 microns, 6% reinforcement is shown in fig. 9



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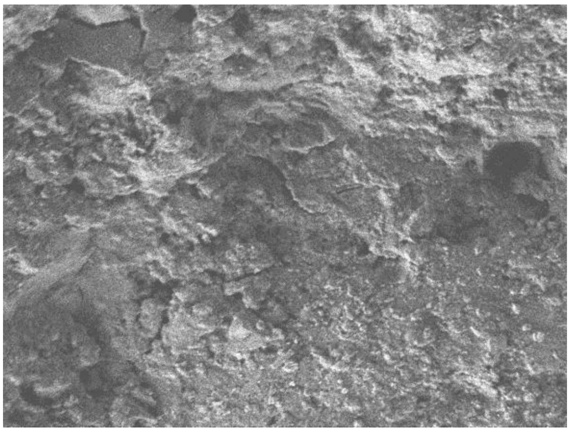

(b)

Fig. 7 (a), (b) SEM image of fractured specimen sheared at SiC of 10 microns at 6%

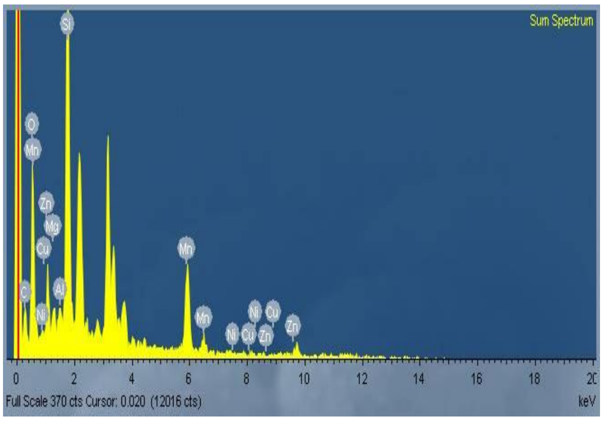

Fig. 8 EDS analysis of fractured surface of bonded specimen at 10 microns, 6% reinforcement

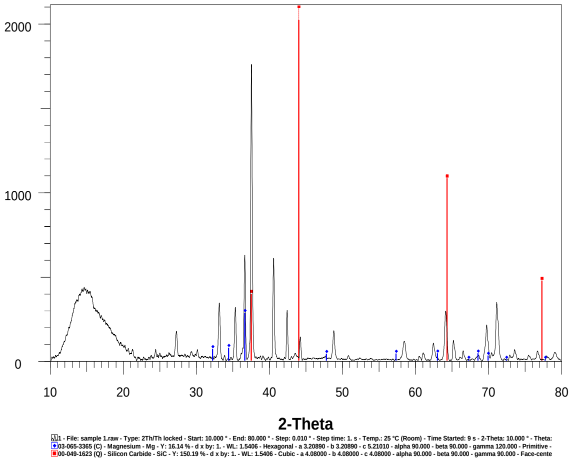

Fig. 9 XRD analysis of fractured surface of bonded specimen at 10 microns, 10% reinforcement

IV. CONCLUSION

Form the above results the following conclusions are derived

i) Shear strength of the diffusion bonded specimen reinforced with SiC particles is greater than the diffusion bonded base material.
ii) ANOVA result shows that the reinforcement particles plays a predominant role in deciding the mechanical properties of the material.
iii) SEM image analysis shows the variation in microstructure over the fractured surface
iv) EDS analysis shows the dominance of harder SiC particles on the substrate compared with other alloying elements.

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