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Influence of Stir Casting Process Parameters on Properties of Aluminium Composites

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Abstract : The need of advanced engineering materials for various engineering applications goes on increasing. The global need for materials ranges from reduced weight, low cost, quality and high performance in different environmental conditions. To meet the demands and requirements for advanced materials, metal matrix composite is one of the best solutions. In this paper, an attempt has been made to investigate properties of the unreinforced Aluminium Die Casting-12 (ADC-12) and hybrid aluminium metal matrix composite with the hard ceramic (10% wt. of SiC). Aluminium metal matrix composite (AMC) is fabricated using stir casting process by varying process parameters like stirring speed, stirring time and process temperature. The compressive strength and wear resistance tests were conducted to examine the behaviour of the aluminium alloy and its composites. Taguchi's approach along with Principal Component Analysis is used to find out the most significant process parameter which affects the required properties of the composite. From the experimental results, it is evident that compressive strength and wear resistance increases with increasing processing temperature and decrease with increasing stirring speed and stirring time.
Keywords : Aluminium metal matrix composite, compression strength, wear resistance, stir casting, principal component analysis.

Introduction

Metal matrix composites (MMCs) are a class of materials with the ability to blend the properties of ceramics such as high strength and high modulus with those of metals or alloys like ductility and toughness to produce significant improvements in the mechanical properties of the composite over those of the monolithic metal or alloys. In composites, the materials are combined to make better use of their parent material while reducing the effects of their deficiencies. Aluminium based reinforced metal matrix composite has emerged as a high performance material for use in aerospace, automobile, chemical and transportation industries.

Aluminium forms the matrix phase. The other constituent embedded in aluminium serves as reinforcement which is non-metallic and ceramic such as SiC, Al_2O_3 etc. The reinforcements are preferred according to the requirement of the specific properties. An appropriate reinforcement of SiCp in aluminium matrix in suitable volume fractions alters the physical properties. Aluminium metal matrix composites are fabricated by three methods namely liquid state methods, semisolid methods and powder metallurgy methods. In liquid state methods, the ceramic particulates are mixed in a molten metallic matrix and casting of MMC is done. Stir Casting is a liquid state method of composite materials fabrication, in which a ceramic particle is mixed with a molten matrix metal by means of mechanical stirring. Aluminium metal matrix composites having wide applications in automotive and aerospace industries have to undergo heavier compressive load and wear. There is a need to optimize the process parameters of stir casting method which will greatly influence the mechanical properties of the composites.

Extensive works have been made by many researchers in fabricating and analyzing the properties of AMC's. Having tried with different kinds of reinforcements, it is found that except SiCp and Al_2O_3, others have not shown any commercial potential. The effect of elemental metal such as Cu-Zn-Mg in aluminium matrix was investigated on mechanical properties of stir casting of aluminium composite materials[1]. A significant increase in hardness of the alloy matrix reinforced with aluminium nitride is found[2]. The simulation of the effect of potential parameters such as stirrer height and stirrer speed influencing the particle distribution and the effect of material properties is prescribed[3]. Hardness increases with increase in weight percentage of ceramic materials[4]. The influence of stirrer speed and stirrer time on microstructure of the produced composite is investigated[5]. The effect of Al_2O_3 on wear resistance properties of AA7075 metal matrix composites was analyzed and the results were optimized by Taguchi's technique and response surface methodology[6]. Machinability characteristics of Al/SiC MMC was investigated to optimize metal removal rate, tool wear rate, surface roughness, Circularity simultaneously[7].The process of in-situ multi-component reinforced aluminium metal matrix composite was carried out and optimized for higher density, lower porosity and higher hardness through Taguchi method[8]. The influence of processing temperature and stirrer time on mechanical properties of the produced composite was studied[9]. The effect of process parameters on tensile shear strength of resistance spot weld joint of austenitic stainless steel AISI 304 using Taguchi method have been studied[10]. The experimental investigation for optimization of Tensile Shear (T-S) strength of RSW for galvanized steel has been done by using Taguchi method[11]. The optimal combination of squeeze cast process parameters was dealt[12]. Experiments were conducted by varying squeeze pressure, die pre-heat temperature and pressure duration using L9 orthogonal array of Taguchi method and GA to improve the tensile strength and hardness of LM24[12].

From the literature, it is evident that different compositions of aluminium composites have been prepared by using various fabrication methods and analyzed to obtain the required mechanical properties. Still, there is a plethora of articles addressing the analysis of wear resistance and compressive strength of aluminium composites relating the process parameters of stir casting method. Determination of optimal combination of process parameters by Taguchi's approach with Principal Component analysis method is yet to be carried out.

The objective of the paper is to study the influence of stir casting process parameters such as process temperature, stirring speed and stirring time on the properties like compressive strength and wear resistance of the composite using Taguchi's approach along with Principal Component Analysis method.

Experimental

Preparation of Aluminium Metal Matrix Composite

Major die castings produced for the industrial and commercial applications are made of aluminium alloy. It is due to its lower specific gravity of about 2.7 g/cm³ and its improved strength, hardness, toughness, wear resistance and so on.

The alloy ADC-12 has been selected to be the base matrix material because of its wide applications. Some of the applications of the alloy include automotive components, engine brackets, transmission and gear cases, appliances, lawn mower housings, furniture components and power tools. The mechanical properties of aluminium alloy ADC-12 is shown in Table 1.(Table 1)

Table 1.Chemical Composition of ADC-12(Laboratory Report from Indus Rite Metals, 2015)

Element	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ni**	**Sn**	**Al**
Weight (%)	12	1.3	3.5	0.5	0.3	1	0.5	0.2	80.7

Table 2.Properties of Silicon Carbide (Laboratory Report from Madras Metallurgical Services Pvt. Ltd., 2015)

Density	3.22 g/cm³
Melting point	2973 ºC
Coefficient of thermal expansion	4 µm/mºC
Thermal conductivity	126 W/mK
Young's modulus	410 GPa

Introduction of SiC to the aluminium matrix enhances the strength, modulus, abrasive wear resistance and thermal stability of the composite. The resistance of SiC to acids, alkalis or molten salts up to 800ºC makes it a good reinforcement material for aluminium based MMC. SiC is easily available and has good wettability with aluminium alloys. Addition of alumina particle results in good wear properties and compatibility. Addition of silicon carbide particle results in excellent mechanical properties and produces a very hard and strong material. Particles of SiC of mesh size 320 grid are used as reinforcement (Table 2).

The reinforcing phases are distributed into the metal matrix by mechanical stirring process. Mechanical stirring in the furnace is a key element of this process. The resultant molten alloy, with ceramic particles, can then be used for die casting, permanent mould casting, or sand casting. A major concern associated with the stir casting process is the segregation of reinforcing particles which is caused by the surfacing or settling of the reinforcement particles during the melting and casting processes.

The final distribution of the particles in the solid depends on material properties and process parameters like stirring time, stirring speed, process temperature, reinforcement preheat temperature, preheat temperature of mould, powder feed rate, addition of Mg and so on.

Bala Sivanandhaprabu et al[5]investigated the influence of stirrer speed and stirrer time on microstructure of the produced composite and studied the properties such as tensile strength and hardness. Process temperature plays a vital role in the stir casting process. The following process parameters are considered for the composite preparation.

- Stirring Speed
- Stirring Time
- Process Temperature

Taguchi method involves laying out the experimental condition using orthogonal array. By adopting this method, number of analytical exploration needed to get the required design is significantly reduced and thus reducing the testing time and experimental cost.

Three experimental factors namely stirring speed, stirring time, processing temperature is considered. Three levels for each factor are considered. Experiments are conducted using Taguchi's orthogonal array (OA9) experimental design which consist of 9 combinations of stirrer speed, stirring time and processing temperature. According to the design catalogue prepared by Taguchi, three parameters (without interaction) are varied in three finite levels.

Therefore, nine specimens are prepared using the given experimental conditions. Table 3 shows the experimental conditions for the preparation of composites. (Table 3)

Table 3.Experimental Conditions of Composite Preparation

Experimental factors	Level 1	Level 2	Level 3
Stirring speed (Rpm)	400	500	600
Stirring time (min)	5	10	15
Processing temperature (°C)	700	750	800

Stir casting process starts with placing the crucible in the electrical induction furnace which is set to an initial temperature of 500ºC. One kg of aluminium ADC-12 is placed in the crucible. The heater temperature is raised to the experimental temperature slowly. Silicon carbide powder is preheated in the muffle furnace to 800ºC.Flux and degasser of 5 gm each are added to the molten aluminium alloy and the impurities are removed. The stirrer is brought to 2/3rd of the total height from the base of the crucible and its speed is raised to the experimental speed. Preheated SiC is poured into the molten aluminium alloy. The alloy is allowed to mix with the SiC powder for the experimental time period. The stirrer speed is reduced to zero and the molten alloy is poured into the die of diameter 50mm and length 250mm and squeezed under the pressure of 127 MPa. The stir casting apparatus at Government college of Engineering, Coimbatore is utilized for specimen preparation.

Testing of wear resistance and compression strength

The wear tests are conducted as per ASTM G99. The specimen dimensions are of diameter 10mm and length of 32mm. The wear rate is measured with the help of pin on disc wear testing machine (DUCUM) as dry test at 400 rpm, 39.24 N for 478 seconds. The compression strength is measured using compression testing machine. The machine has data acquisition system auto instrument series 2005 to acquire data from the load cell and the displacement measuring device. The compressive strength tests are conducted on these samples according to the ASTM – E9-95. The specimen dimensions are of diameter 15mm and length 20mm. The test results are shown in Table 4. (Table 4)

Table 4.Results of Wear Rate and Compressive Strength

Specimen No.	Composition	Operating Condition			Wear Rate (mm^3/min)	Compression Strength (MPa)
		Speed (rpm)	Time (min)	Temp (º C)		
S0	ADC-12	-	-	-	0.001071	254
S1	ADC-12+ 10%SiC	400	5	700	0.000113	292
S2		400	10	750	0.000299	312
S3		400	15	800	0.000382	294
S4		500	5	750	0.000376	292
S5		500	10	800	0.000226	277
S6		500	15	700	0.000238	206
S7		600	5	800	0.000151	297
S8		600	10	700	0.000459	250
S9		600	15	750	0.000254	224

Analysis of Test results

To solve a multi response optimization problem with uncorrelated or independent quality attributes, Principal Component Analysis(PCA) is applied to eliminate response correlation that exist between the responses to evaluate uncorrelated quality indices called principal components. Principal component analysis is a way to identify the correlated data patterns and expressing the data with their similarities and differences. The main advantage of PCA is that the data can be compressed by reducing the number of dimensions without much loss of information.

The steps involved in PCA are
Step 1: Getting data
Step 2: Normalization of data

The normalization of data provides fair information for determining the optimal levels of parameters. The original data are converted to a range of 0 and 1 with 1 counting the best performance and 0 the worst. The normalization procedure for higher the better for compressive strength and lower the better for wear rate characteristics is given in the equation 1 and 2.

Higher the better for compression strength:

$$Xi * (k) = \frac{Xi(k)}{maxXi(k)} \quad (1)$$

Lower the better for wear rate:

$$Xi * (k) = \frac{minXi(k)}{Xi(k)} \quad (2)$$

where i = 1, 2,………..m
j = 1, 2 …......... n
m = number of experimental runs in Taguchi's OA design
n = number of quality characteristics
Xi (k) is the normalized data of the kth element in the i sequence

Step 3: Determination of correlation coefficient array

The normalized data is utilized to construct a correlation coefficient array R

$$R = \begin{bmatrix} R1,1 & \cdots & R1,n \\ \vdots & \ddots & \vdots \\ R3,1 & \cdots & R3,n \end{bmatrix} \quad (3)$$

where Ri, j = cov X*i (j), X*j (k) /σX*i (j) x σX*j (k)
cov X*i (j), Xj*(k) is the covariance of sequences X*i (j) and Xj*(k)
σX*i (j) and σX*j (k) are the standard deviation of sequences X*i (j) and Xj*(k)

Step 4: Determination of Eigen vectors and Eigen values

The Eigen vectors and Eigen value of the covariance matrix is calculated.

Step 5: Evaluation of principle components

Let X*(1), X*(2), X*(3) . . . X*(n) be a set of variables. Through the PCA, the following uncorrelated linear combinations are derived:

PC1 =a11 X*(1) + a12 X *(2) + ……. +a1n X* (n) (4)
PC2 =a21 X*(1) + a22 X *(2) + ……. +a2n X* (n) (5)
PCk = ak1 X*(1) + ak2 X *(2) + ……. +akn X* (n) (6)

where PC1 is called the first principal component and PC2 is called the second principal component and so on. The coefficient of kth component is the elements of Eigen vector corresponding to largest kth Eigen value.

Orthogonal Arrays (OA) provide a set of well balanced (minimum) experiments and Signal-to-Noise ratios (S/N). Signal-to-Noise ratios are log functions of desired output, serve as objective functions for optimization and help in data analysis and prediction of optimum results. S/N ratio, measures the variation of the observations in run.

The equation for calculating (S/N) ratio is as follows

S/N ratio = -10 log10 (∑ (1/Y2)/n) (7)
where Y is the observed data
n is the number of observations

In this investigation the (S/N) ratio for maximizing Multi Performance Index (MPI) is “larger the better” quality characteristics. The purpose of Analysis of Variance (ANOVA) is to investigate the stir casting parameters which significantly affect the performance characteristics. This is accomplished by separating the total variability, and is measured by the sum of the squared deviations from the total mean of the response value into contributions by each process parameters and the error. In this study general linear model ANOVA is used to determine the percentage of influence of stirrer speed, stirring time and processing temperature. ”Larger the better” is chosen for finding the optimum process parameters. Design-Expert® Software Version 9 is used to create the ANOVA and analyze the results.

Result and Discussion

Wear Rate analysis for the prepared nine specimens are shown as follows. (Figure 1)(Figure 2) (Figure 3) (Figure 4)(Figure 5) (Figure 6) (Figure 7) (Figure 8) (Figure 9).

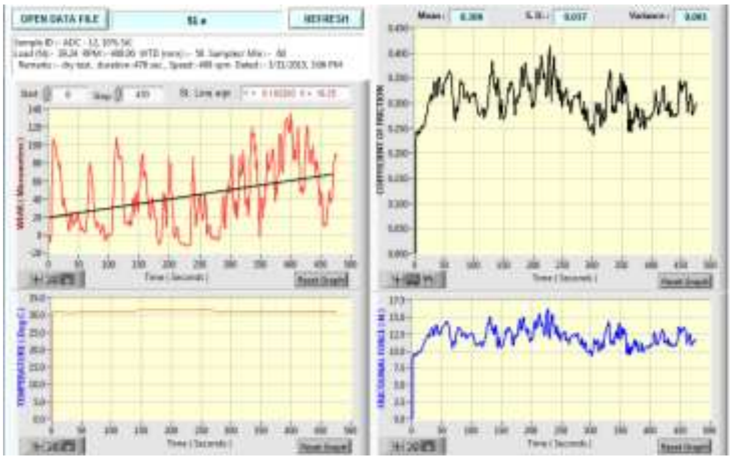

Figure 1.Wear rate analysis for Specimen 1

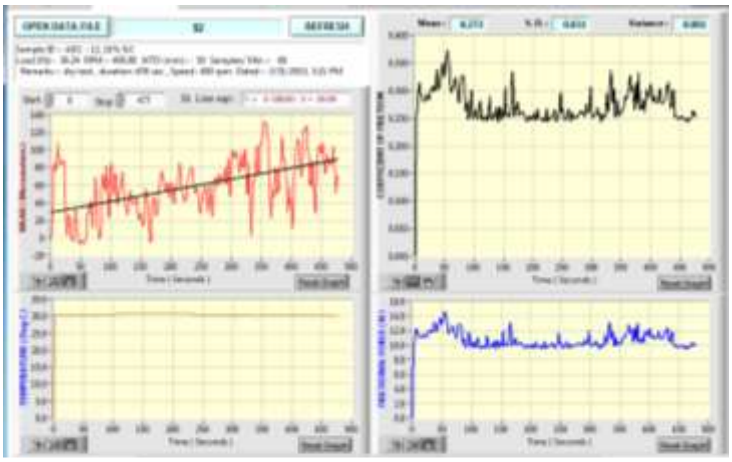

Figure 2 Wear rate analysis for Specimen 2

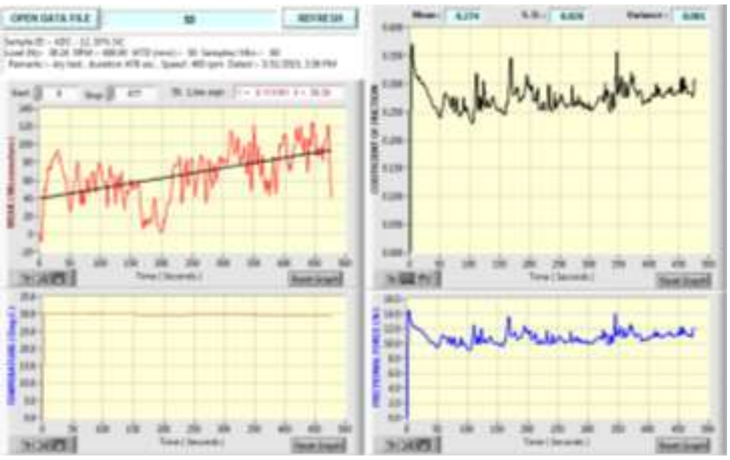

Figure 3.Wear rate analysis for Specimen 3

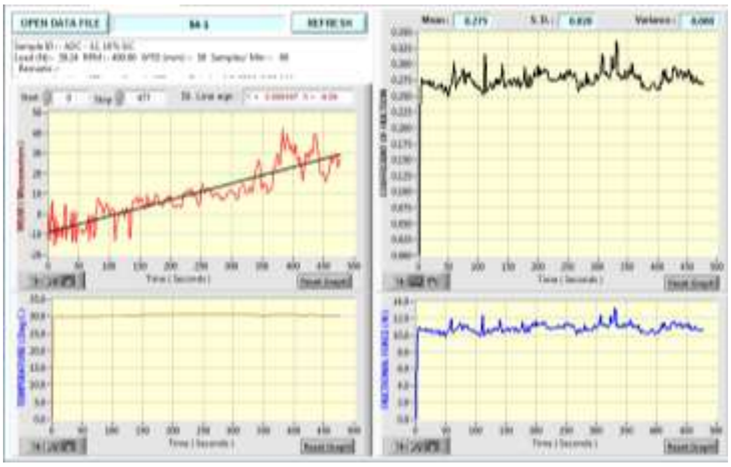

Figure 4.Wear rate analysis for Specimen 4

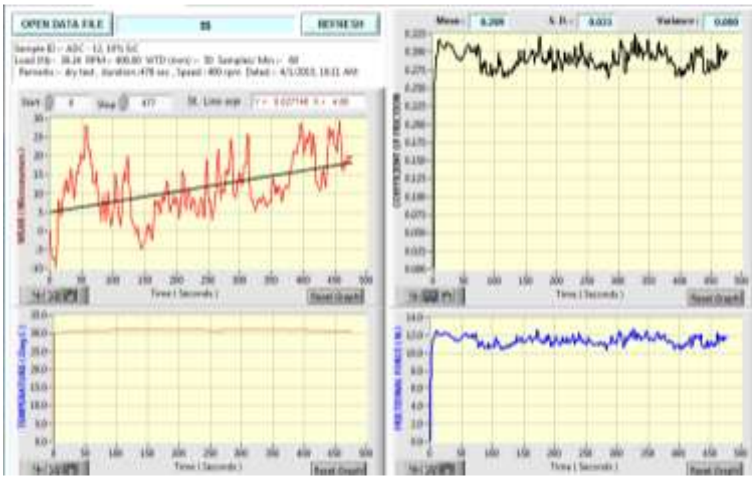

Figure 5.Wear rate analysis for Specimen 5

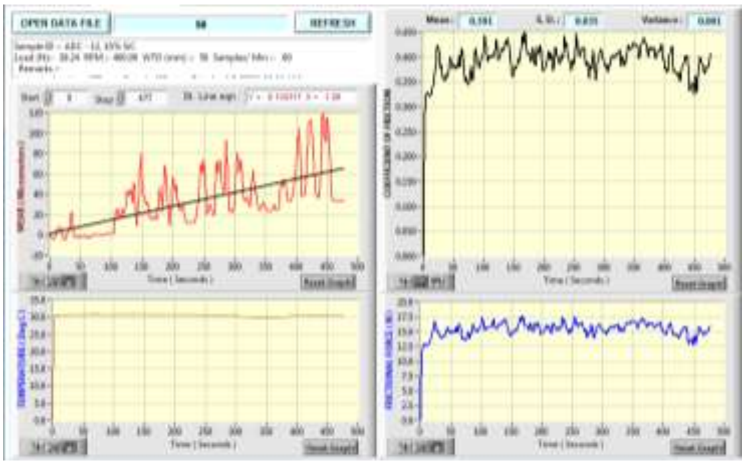

Figure 6.Wear rate analysis for Specimen 6

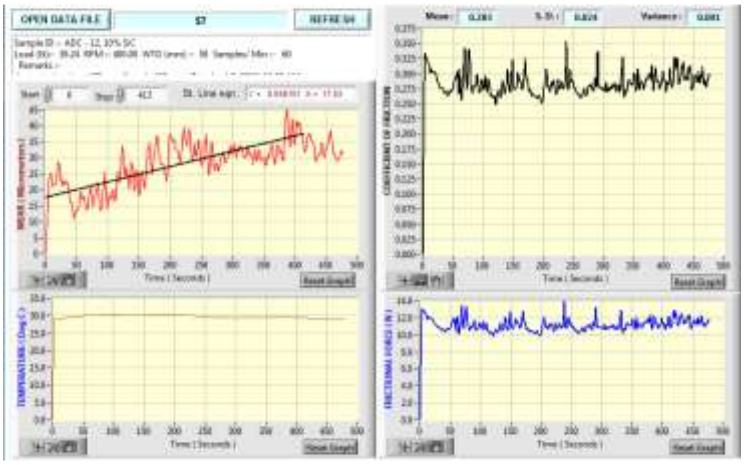

Figure 7.Wear rate analysis for Specimen 7

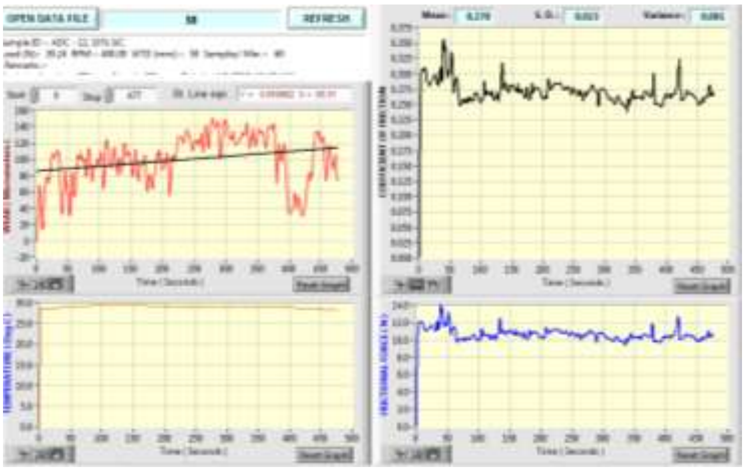

Figure 8.Wear rate analysis for Specimen 8

Figure 9.Wear rate analysis for Specimen 9

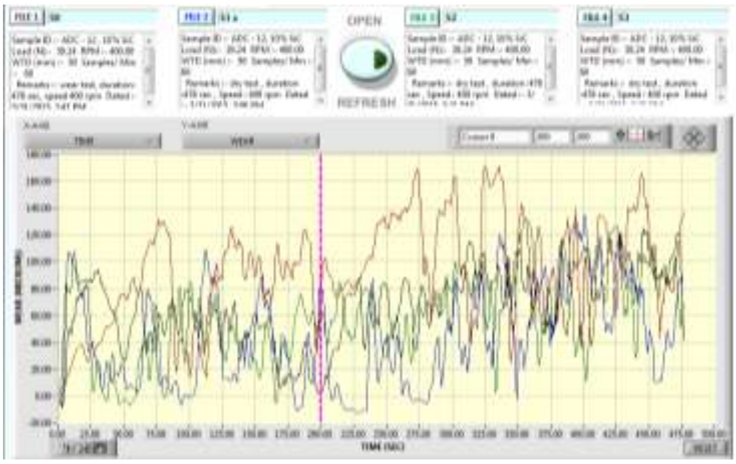

Figure 10.Compressive Strength analysis for Specimens 0,1,2,3

Figure 11.Compressive Strength analysis for Specimens 4,5,6,7

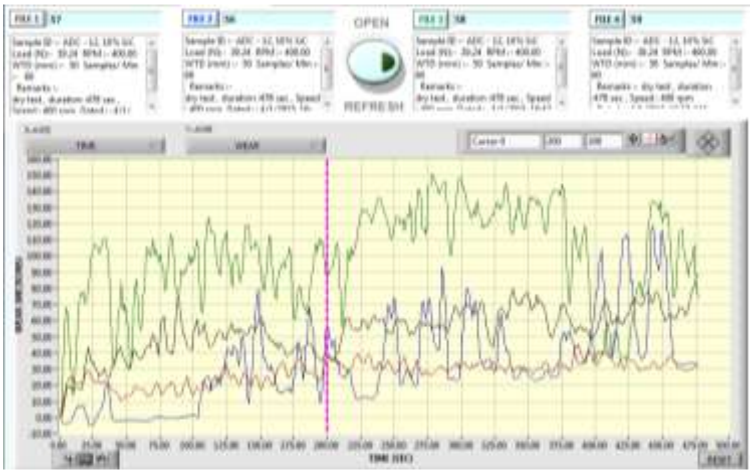

Figure 12.Compressive Strength analysis for Specimens 6,7,8,9

Compressive Strength analysis for the prepared nine specimens is shown as follows (Figure 10)(Figure 11) (Figure 12).

The calculated values of MPI and S/N ratio are given in Table 5. (Table 5)

ANOVA is carried out to identify the process parameters that significantly affect the responses. The results of ANOVA using Minitab 16 software is shown in Table 6.

Table 5.Calculation of Normalized Data, Principal Components, MPI and S/N ratio

Speci men No.	**Normalized data**		**Principal component**		**MPI**	**S/N ratio**
	Wear rate (mm^3/ min)	**Compressive strength (MPa)**	**PC 1**	**PC 2**		
1	1	0.9359	-1.3686	0.0453	-0.687	-3.26087
2	0.4496	1	-1.0248	-0.3899	-0.718	-2.87751
3	0.3515	0.9423	-0.9147	-0.4176	-0.675	-3.41392
4	0.3572	0.9359	-0.9142	-0.4091	-0.67	-3.47850
5	0.5953	0.8878	-1.0485	-0.2067	-0.643	-3.83578
6	0.5652	0.6603	-0.8664	-0.0672	-0.481	-6.35710
7	0.8882	0.9519	-1.3009	-0.0450	-0.6955	-3.15406
8	0.2923	0.8013	-0.7732	-0.3598	-0.574	-4.82176
9	0.5989	0.7179	-0.9309	-0.0841	-0.523	-5.62997

Table 6.Analysis of Variance for Principal Component

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Stirrer speed	2	3.7113	3.7113	1.8557	20.95	0.046
Stirring time	2	5.3304	5.3304	2.6652	30.09	0.032
Process temperature	2	2.7570	2.7570	1.3785	15.57	0.060
Error	2	0.1771	0.1771	0.0886		
Total	8	11.9759				

Analysis of Variance for SNRA1, using Adjusted SS for Tests (Table 6)

S = 0.297594 R-Sq. = 98.52% R-Sq. (ad) = 94.08%
where DF – Degrees of Freedom
Sew SS – Sequence Sum of Squared Deviations
Ad SS – Adjusted Sum of Squared Deviations

Ad MS – Adjusted Mean Square
F – F values
P – P values

The result of ANOVA for principal components shows that at significant level of 5% it is found that the process parameters namely stirrer speed and stirring time are significant parameters on wear resistance and compressive strength. Processing temperature is found to be insignificant from ANOVA for wear rate and compressive strength. (Figure 13)

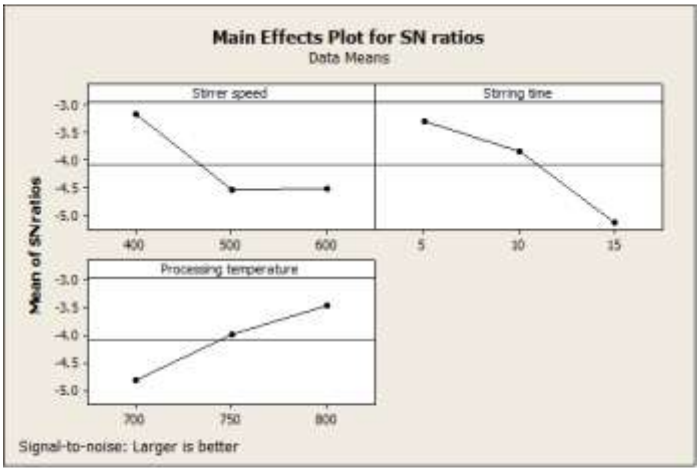

Figure 13.Main Effect plot for S/N ratio

S/N ratio, measures the variation of the observations in run. Figure 13 shows the main effect plot for S/N ratio. From main effect plot for S/N ratio, it is observed that the optimal process parameters are stirrer speed 400rpm, stirring time 5min and processing temperature 800ºC.

Conclusion

Specimens of ADC-12 with 10% of SiC reinforced aluminium metal matrix composite is prepared by stir casting process under various operating conditions and the tests are conducted for wear resistance and compression strength. The test results are analyzed using Taguchi's method with Principal Component Analysis. From the analysis, it is evident that wear resistance and compressive strength increase with increasing processing temperature and decrease with increasing stirring speed and stirring time. This work can be further extended by varying other process parameters like mould preheat temperature, reinforcement preheat temperature, powder feed rate and so on. The other properties of composite can also be optimized by the similar method.

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