Optimization of Process Parameters on Properties of Aluminium Metal Matrix Composites Using Taguchi's Analysis

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Abstract

Requirement of better mechanical properties, quality, improved wear resistance, lower coefficient of thermal expansion leads to the development of aluminum composites of lighter weight. The properties of the aluminium metal matrix composites are greatly influenced by the process parameters of the production methods. In this paper, stir casting method and powder metallurgy are chosen for preparing composites consisting of aluminium die casting-12 alloy and reinforcement of 10% by weight proportion of silicon carbide. Experimental investigations are carried to optimize the process parameters of the production methods for the improvement of properties such as sliding wear resistance, compressive strength, micro abrasive wear and coefficient of thermal expansion of aluminum metal matrix composite. In stir casting process, stirring speed, stirring time and processing temperature are the process parameters considered. In powder metallurgy route, the process parameters considered are compaction pressure, sintering temperature and sintering time. Taguchi's experimental design is adopted for laying out the experimental conditions and Principal component analysis approach is used to identify the optimum and significant parameters, which provide the preferable properties of the composite. By Principal Component Analysis, it is identified that process temperature is significant parameter in stir casting process and sintering temperature is significant parameter in powder metallurgy on the measured properties.

Keywords:

Principal Component Analysis, Taguchi, Stir casting Process, powder metallurgy

1. Introduction

Aluminium metal matrix composites are highly preferred for its features like high strength, wear resistance and low coefficient of thermal expansion compared to the unreinforced base metal. These additional features made it suitable for aeronautical, automotive industries and medical field. The mechanical properties of AMC produced by stir casting technique are investigated for various compositions of boron carbide and silicon carbide reinforced with aluminium alloy 6061[1]. The changes in mechanical properties of aluminium composites with Cu-Zn-Mg prepared by stir casting process is studied [2]. The influence of aluminium nitride in aluminium matrix is identified to increase hardness. The microstructure of the composite prepared by stir casting process shows proper distribution of the reinforcement particles [3]. Aluminium composite is prepared by infiltration with AlSi12Mg alloy as the matrix material and open cell metallic foam, metal matrix syntactic foam and carbon fiber as reinforcements. Inert argon gas was used for infiltration. Scanning Electron Microscopic analysis and testing of compression strength of the composite were carried out [4]. Aluminium composite is prepared with Al2O3 and SiC reinforcements in aluminum by pressure infiltration pressure. It was observed that the bending strength can be improved by controlling the process conditions [5]. The matrix and reinforcements were interwoven and integrated interface was formed. There was a noticeable improvement in the mechanical properties of magnesium matrix composites interpenetrated by stainless steel reinforcement [6]. Aluminum matrix composite prepared with coal/lignite fly ash by pressure infiltration technique and this composite was proved to be suitable material for wear resistance [7]. The results showed that the composites AlSi7Mg with SiC particles and liquid AlSi9Mg alloy infiltrated in Al2O3 were best suited for automobile components like brake disks and piston heads [8]. Aluminium fabricated with 4 wt. % Cu /Alumina and rice husk composite by in-situ powder metallurgy process and studied the hardness of the composites [9]. The effect of silicon carbide on the particle cracking and ductility is studied on the composite prepared by powder metallurgy process [10]. The effect of weight percentage of ceramic materials like silicon carbide and graphite in the properties of aluminium composite was studied [11].

The influence of stirrer speed and stirrer time is investigated on microstructure of the produced composite and studied the properties such as tensile strength and hardness. Water modeling was used as the tool and simulations were carried out [12]. The effect of process temperature and stirring time is observed in the mechanical properties of the produced composite by genetic algorithm [13]. The influence of stirrer height and stirrer speed of the mechanical stirrer on the particle dispersion and properties were prescribed with neural networks [14]. Computational and experimental analysis were carried out for Al-SiC composite for the process parameters like stirrer speed, processing period and reinforcement size for two different viscosity levels to produce uniform distributions [15].Addition of carbon fibers increase tensile strength and Young's modulus of aluminium composite prepared by High pressure die casting process [16].Micro hardness, macro hardness and tensile strength of Aluminium Matrix Composite Reinforced with Silicon Nitride (AA6061/Si3N4) Synthesized by the Stir Casting Route [17].The measured hardness values and the UTS of the hybrid composites fabricated by 4% CSFA and varying 2, 4, 6, 8, and 10wt. %SiC micro particles into the melt of Al6061 matrix increased by 32.6% and 22.53% respectively[18].The microstructural characteristics and mechanical behavior of aluminium matrix composites reinforced with Si-based refractory compounds derived from rice husk were investigated and observed thatthe composites A1650, C1650 and A1600 grades have superior elongation [19].

The microstructure and mechanical properties are studied for aluminium matrix nanocomposites reinforced with reduced graphene oxide and graphene nanosheets. The process parameters such as compaction pressure, density and sintering temperature were optimized and proved to be the low cost technique for better properties [20]. The influence of reinforcement particles is studied on the mechanical properties of the composites prepared by powder metallurgy process [21]. The contribution of ceramic reinforcements is observed to reduce the coefficient of thermal expansion and to increase the mechanical properties like hardness, stiffness and specific strength of the composites [22]. An in-situ process was developed for the preparation of multi-component reinforced composite and Taguchi's analysis was used for optimizing the properties like density, porosity and hardness [23]. The mechanical and tribological properties of the aluminium MMC'S like 6061, 7075, 5058 series by using stir casting, squeeze casting, compo casting, powder metallurgy and in situ synthesis methods depend upon the distribution of the reinforcements [24]. Differences in the type, size, and amount of reinforcement produce various hybrid compositeproperties, especially in the physical properties, mechanical properties, and tribological behavior ofHybrid Aluminium Matrix Composite[25].Al-10 % SiC- X% Kaoline (X = 0, 2, 4, 6, 8) composite samples were fabricated through powder metallurgy technique by applying a compaction pressure of 350 MPa and it is observed that The best suitable combination of mechanical properties was obtained at Al-10 % SiC-4 % Kaoline hybrid composite[26].

Wear resistance properties of aluminium alloy 7075 metal matrix composites is studied by response surface methodology and Taguchi's analysis [27]. Experiments using L9 orthogonal array of Taguchi method is conducted by varying die squeezing pressure, mould temperature and duration of pressure application. Tensile strength and hardness of the alloy is analyzed using genetic algorithm [28]. Influence of stir casting process parameters on compressive strength and wear resistance of aluminium composites are studied and Taguchi's method along with Principal component analysis method is used to determine the optimal process conditions [29].

Numerous research works have been carried out in the preparation of aluminium metal matrix composites reinforced with different materials at different proportions by various production methods. The microstructures, mechanical, tribological and thermal properties of the aluminium metal matrix composites were measured. Of the various liquid state production methods, stir casting process is found to be the most promising production method, since it allows the proper distribution of reinforcement particles and is economical [30]. From the studies, it is observed that the poor distribution of the reinforcement particles can be eliminated by adopting proper process parameters of the stir casting process. Still there is a need for research to study the influence of stir casting process parameters on the properties like compression strength, sliding wear resistance, micro abrasion wear and coefficient of thermal expansion. There is rarity of articles addressing the determination of optimal process parameters affecting the above properties.

In solid state production methods, powder metallurgy process is the most efficient process because it ensures the net shape formation and provides better mechanical properties [31]. Even a lot of researches have been carried out in the preparation of aluminium composites by varying the composition and weight percentage of reinforcements, the analysis of the process parameters involved in the stir casting process and powder metallurgy technique has not been addressed so far. Principal Component Analysis method has not been employed so far for the optimization of process parameters on properties of aluminum metal matrix composites.

The main objective of this paper is to investigate the effect of process parameters on properties of aluminium metal matrix composites based on stir casting process and powder metallurgy by Taguchi's analysis.

2. Experimentation and Testing

In this paper, Aluminium Die Casting – 12 (ADC-12) is used to prepare the composites with ADC-12 matrix using 10% of Silicon carbide by weight as reinforcement. Stir casting process and powder metallurgy technique are considered for the preparation of aluminium metal matrix composites. The chemical composition of ADC-12 is shown in Table 1.Properties of silicon carbide are exhibited in Table 2.

The process parameters considered are stirring speed, stirring time and process temperature. In powder metallurgy technique, the process parameters considered are compaction pressure, sintering temperature and sintering time.

The properties of the composite materials such as compression strength, sliding wear, micro abrasive wear and coefficient of thermal expansion are taken into account, since these are the properties required for the automobile applications considered in this paper.

2.1 Preparation of Aluminium Metal Matrix Composites

2.1.1 Stir Casting Process

In this process, the reinforcement is heated to a temperature of 800ºC and the same temperature is maintained for 30 minutes. The processing temperature, stirring speed and the stirring time are predetermined by Taguchi's OA9 orthogonal array.The stirring speed is raised to the required value to create a vortex on the molten metal. After mixing the reinforcement for the specified time period, the stirrer is brought back to ideal condition and the composite slurry is poured into the die of dimension 50 mm diameter and 250 mm length and compressed at pressure of 127 MPa. The composite slurry is then allowed to solidify. The composite casting is removedfrom the mold and cleaned.

Table 1. Chemical Composition of ADC-12

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

Properties	Values
Density	3220 kg/m^3
Melting point	2973 ºC
Coefficient of thermal expansion	4 µm/mºC
Thermal conductivity	126 W/mK
Young's modulus	410 GPa

According to the Taguchi's design methodology, three factors without interaction are considered in three levels. Nine Specimens are prepared using Taguchi's OA9 orthogonal array design consisting of 9 combinations of process parameters by stir casting process. Table 3 shows the experimental conditions for the preparation of composites by stir casting process.

2.1.2 Powder Metallurgy Process

In this process, ready to use atomized aluminium powder of 200 mesh size is used as the base metal for composite preparation having the same chemical composition of ADC-12. The powders of aluminium and silicon carbide are weighed using an electronic balance with an accuracy of ± 0.1 mg. The weighed powders are placed in a cylindrical container to get a mixture of Al-10%SiC. Dies to press the blended powders are made from Oil Hardened Non distorting Steel (OHNS). A hydraulic press having a capacity 40T is used for compaction. The filled powder mixture in the die is compressed uniaxially for 60 seconds at the designed compaction pressures. Compaction of the composite material is carried out at room temperature. The green compacts obtained from consolidation process are sintered at high temperature muffle furnace.

Taguchi's orthogonal array (OA16) experimental design consisting of 16 combinations of compaction pressure, sintering temperature and sintering time is considered for this paper. Table 4 shows the experimental conditions for the preparation of composites by powder metallurgy process.

2.2 TESTING OF PROPERTIES

The compression strength is measured using Universal 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 specimen dimensions are of diameter 15 mm and length 20 mm. The tests are conducted on these specimens prepared according to the ASTM – E9-95.The wear test is conducted on a pin on disc machine. The specimen dimensions are of diameter 10 mm and length of 25 mm. The specimen prepared in the form of pin is fixed on a holder, which is provided to apply the load. The wear tests are conducted as per ASTM G99-05. The tests are conducted under dry sliding conditions in ambient air at controlled constant temperature of 30℃ at a speed of 400 rpm, under a load of 20 N for 475 seconds.

Table 3. Experimental design of composite preparation for stir casting process

Experimental Factors	Level 1	Level 2	Level 3
Stirring Speed(rpm)	400	500	600
Stirring time (min)	5	10	15
Processing Temperature (℃)	700	750	800

Micro-abrasion wear volume is measured with a micro-abrasion tester. The specimens are prepared having the size of 24 mm diameter and 12 mm thickness. The testing ball made of high carbon, high chromium steel of 25 mm diameter is used. The size of silicon carbide particles used in the slurry is 4mm. The micro abrasive wear tests are conducted as dry test for 300 seconds with an applied load of 6 N at a speed of 200 rpm.

Hytherm computerized dilatometer is used for measuring the coefficient of thermal expansion on the prepared composite specimens. The dimensions of the specimen are 10mm diameter and 45 mm length. The working temperature range for this dilatometer is maintained between 27℃ to 500℃. High precision measurements are carried out and the relative expansion is measured for the given temperature variation.

Tables 5 and 6 show the designed operating conditions and the measured properties of the specimen prepared by stir casting and powder metallurgy processes respectively.

3. RESULTS AND DISCUSSION

Principal component analysis (PCA) is a mathematical procedure, by which a number of possibly correlated variables are converted into lesser number of uncorrelated variables called principal components. The turning process parameters of copper are optimized by using PCA and Taguchi's method [32]. A combination of Taguchi-General Regression -PCA is employed for optimization of wear behavior of Aluminium composites [33]. PCA with Taguchi's analysis is utilized for optimization of CNC Turning Centre parameters [34].

PCA method is followed for optimizing the stir casting process parameters such as stirring speed, stirring temperature and stirring time for increased compressive strength and reduced wear [35].

The procedure followed in PCA is:

Step 1: Data Collection. Experimental test results are collected by measuring the properties of the composite specimens and shown in Table 5 for stir casting process and Table 6 for powder metallurgy route.

Step 2: Data Normalization.

Higher the better is chosen for compression strength:

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

Table 4. Experimental design of composite preparation for powder metallurgy process

Experimental Factors	Level 1	Level 2	Level 3	Level 4
Compaction Pressure (MPa)	100	110	120	130
Sintering Temperature (℃)	300	400	500	600
Sintering Time (min)	120	180	240	300

Lower the better is chosen for Sliding wear resistance, Micro abrasion wear volume, coefficient of thermal expansion:

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

where i = 1, 2, … m; j = 1, 2, … n; m is the number of experimental runs in Taguchi's OA design; n is the 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

Step 4: Calculation of Eigen vectors and Eigen values

Step 5: Evaluation of principal components (PC).

In order to eliminate response correlations, Principal component analysis has been applied to derive two independent quality indices called principal components. The independent quality indices are denoted as PC1, PC2, PC3 and PC4.

In this paper, the signal to noise (S/N) ratio for maximizing Multi Performance Index (MPI) is the "Larger the better" quality characteristic. The purpose of Analysis of Variance (ANOVA) is to investigate the process parameters, which significantly affect the performance characteristics like properties of the composite material. In this study, general linear model ANOVA is used to determine the percentage of influence of process parameters of the production methods, involved in the preparation of composite material. Minitab Software Version 18 is used to create the ANOVA and analyse the results.

The MPI and S/N ratio values are calculated and tabulated in Table 7 for stir casting process and Table 8 for powder metallurgy route.General linear model ANOVA identifies the optimum process parameters for the given experimental responses. The results obtained using Minitab 18 software is shown in Table 9 and 10.

From the Response Table 11 and Fig 1, it is observed that the process temperature is the most significant factor in stir casting process, which affects the properties of the composite. It is found that the optimal process parameters for the stir casting process in the preparation of ADC-12 alloy with 10% SiC composite are stirring speed 600 rpm, stirring time 10minutes and processing temperature 800 ºC.

From the Response Table 12 and Fig 2, sintering time plays an important role in powder metallurgy technique in deciding the properties of the composite. The optimal process parameters for the powder metallurgy process in the preparation of pure aluminium metal with 10% SiC composite are Compaction pressure of 120MPa, Sintering temperature of 600℃, sintering time of 180 minutes.

After applying the optimal setting of process parameters, confirmation test for stir casting and powder metallurgy process was carried out to validate the analysis. The improvement of the compression strength from the initial condition to the multi optimal condition is about 9% and reduced sliding wear, micro abrasive wear approximately 10 % and coefficient of thermal expansion approximately 6% from individual optimal-condition.

4. CONCLUSION

Aluminium metal matrix composite is prepared with 10% SiC by weight by stir casting with process parameters stirring temperature, stirring time, stirring speed and powder metallurgy process considering compaction pressure, sintering temperature and sintering time as process parameters under various experimental conditions designed by Taguchi's orthogonal array.

Processing temperature is more influencing to increase the mechanical properties [12]. From the experimental results on the process parameters of stir casting and powder metallurgy process, it is inferred that in stir casting process, at significant level of 5 %, process temperature is the significant parameter and the optimal process parameters are stirring speed 600 rpm, stirring time 10minutes and processing temperature 800 ºC.

Sintering temperature is the most influencing factor to improve mechanical properties of composite [10].In powder metallurgy process, it is inferred that Sintering temperature is significant parameter and the optimal process parameters are compaction pressure of 120MPa, sintering temperature of 600℃, sintering time of 180 minutes.

In this research, three parameters are taken into account and four properties are analyzed. Same procedure can be carried out for any number of properties as required for the application which is the advantage of this analysis over other methods.

Table 5 Designed operating conditions, measured properties for the specimens of stir casting process

Specimen No.	Designed Operating conditions			Sliding wear resistance (mm³/m)	Compression strength (MPa)	Micro abrasive Wear volume (mm³)	Coefficient of thermal expansion (1/K)
	Stirring speed (rpm)	Stirring time (min)	Process temperature (℃)				
S1	400	5	700	0.000113	292	0.024129	2.30E-05
S2	400	10	750	0.000299	312	0.011440	2.04E-05
S3	400	15	800	0.000382	294	0.003262	2.37E-05
S4	500	5	750	0.000376	292	0.022382	2.19E-05
S5	500	10	800	0.000226	277	0.006904	2.08E-05
S6	500	15	700	0.000238	206	0.009521	2.26E-05
S7	600	5	800	0.000151	297	0.001476	2.30E-05
S8	600	10	700	0.000459	250	0.009268	2.15E-05
S9	600	15	750	0.000254	224	0.020731	1.94E-05

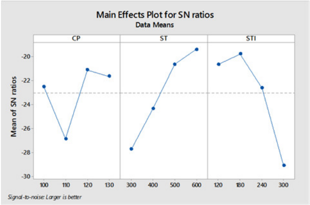

Fig 1 Stirring speed, stirring time, stirring temperature plot for S/N ratio – Stir Casting Process

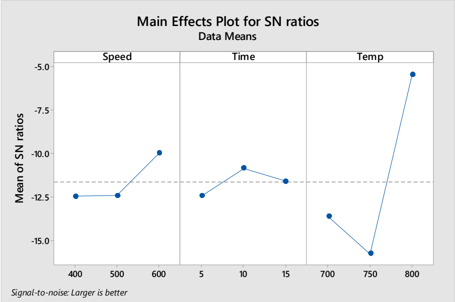

Fig 2 Compaction pressure, sintering temperature and sintering time plot for S/N ratio – Powder Metallurgy Process

Table 6 Designed Operating Conditions, Measured properties for the specimens of Powder Metallurgy Process

Specimen No.	Designed Operating conditions			Sliding wear resistance (× 10^{-3} mm³/m)	Compression strength (MPa)	Micro abrasive Wear volume (mm³)	Coefficient of thermal expansion (1/K)
	Compaction Pressure (MPa)	Sintering Temperature (℃)	Sintering Time (min)				
S1	100	300	120	121.21	128.97	0.044839	2.30E-05
S2	100	400	180	15.33	173.47	0.074253	2.36E-05
S3	100	500	240	37.54	234.76	0.099645	2.19E-05
S4	100	600	300	38.54	279.36	0.030598	2.17E-05
S5	110	300	180	22.05	138.4	0.091017	2.42E-05
S6	110	400	120	74.57	170.7	0.053585	2.47E-05
S7	110	500	300	5.72	209.9	0.074253	2.20E-05
S8	110	600	240	47.09	240.09	0.038651	2.18E-05
S9	120	300	240	2	177.44	0.042437	2.46E-05
S10	120	400	300	59.7	183.31	0.060941	2.21E-05
S11	120	500	120	0.59	173.44	0.050838	2.22E-05
S12	120	600	180	71.07	290.57	0.092414	2.16E-05
S13	130	300	300	24.37	139.96	0.022871	2.43E-05
S14	130	400	240	34.29	200.06	0.037209	2.27E-05
S15	130	500	180	49.43	170.35	0.073658	2.20E-05
S16	130	600	120	91.46	247.53	0.074253	2.25E-05

Table 7 Calculation of normalized data, principal components, MPI and S/N ratio for analysis of sliding wear, compression strength, micro abrasive wear volume and coefficient of thermal expansion for stir casting process

Specimen No.	Normalized data				Principal component				MPI	S/N ratio
	Sliding wear resistance (mm³/m)	Compression strength (MPa)	Wear volume (mm³)	Coefficient of thermal expansion (1/K)	PC 1	PC 2	PC 3	PC 4		
S1	1	0.935897	0.061171	0.843478	0.214	0.039	−0.527	−0.733	−0.25175	−12.479
S2	0.377926	1	0.129021	0.95098	0.379	0.009	0.083	−0.156	0.07875	−12.428
S3	0.295812	0.942308	0.452483	0.818565	0.318	−0.551	0.401	−0.195	−0.00675	−9.996
S4	0.300532	0.935897	0.065946	0.885845	0.378	0.562	0.094	−0.152	0.2205	−12.456
S5	0.5	0.887821	0.213789	0.932692	0.383	−0.435	−0.012	−0.023	−0.02175	−10.848

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S6	0.47479	0.660256	0.155026	0.858407	0.371	−0.061	−0.127	0.316	0.12475	−11.599
S7	0.748344	0.951923	1	0.843478	0.079	0.159	0.704	−0.334	0.1125	−5.489
S8	0.246187	0.801282	0.159258	0.902326	0.372	0.401	0.161	0.168	0.2755	−13.638
S9	0.444882	0.717949	0.071198	1	0.371	0.009	−0.091	0.371	0.165	−15.775

Table 8 Calculation of normalized data, principal components, MPI and S/N ratio for analysis of sliding wear resistance, compression strength, micro abrasive wear volume and coefficient of thermal expansion for powder metallurgy route

Specimen No.	Normalized data				Principal component				MPI	S/N ratio
	Sliding wear resistance (mm^3/m)	Compression strength (MPa)	Wear volume (mm^3)	Coefficient of thermal expansion (1/K)	PC 1	PC 2	PC 3	PC 4		
S1	0.004868	0.443852	0.510069	0.93913	0.256	-0.204	0.077	-0.377	-0.062	-22.49
S2	0.038487	0.596999	0.308014	0.915254	0.268	0.111	-0.116	-0.019	0.061	-26.85
S3	0.015717	0.807929	0.229525	0.986301	0.259	-0.054	-0.165	0.241	0.07025	-21.07
S4	0.015309	0.961421	0.747467	0.995392	0.253	-0.214	0.242	0.198	0.11975	-21.60
S5	0.026757	0.476305	0.251283	0.892562	0.262	-0.171	-0.161	-0.157	-0.05675	-27.71
S6	0.007912	0.587466	0.426817	0.874494	0.27	-0.041	0.033	-0.063	0.04975	-24.32
S7	0.103147	0.722373	0.308014	0.981818	0.263	-0.256	-0.167	0.103	-0.01425	-20.61
S8	0.012529	0.826272	0.591731	0.990826	0.266	-0.074	0.126	0.106	0.106	-19.36
S9	0.295	0.610662	0.53894	0.878049	0.266	0.11	-0.028	-0.212	0.034	-20.61
S10	0.009883	0.630863	0.375297	0.977376	0.27	-0.015	-0.058	-0.047	0.0375	-19.74
S11	1	0.596896	0.44988	0.972973	-0.022	-0.176	-0.725	-0.411	-0.3335	-22.59
S12	0.008302	1	0.247484	1	0.25	0.036	-0.132	0.421	0.14375	-29.07
S13	0.02421	0.481674	1	0.888889	0.186	-0.093	0.475	-0.472	0.024	-23.49
S14	0.017206	0.688509	0.614663	0.951542	0.264	0.119	0.167	-0.07	0.12	-24.85
S15	0.011936	0.586261	0.310503	0.981818	0.267	0.838	-0.118	-0.081	0.2265	-26.07
S16	0.006451	0.851877	0.308014	0.96	0.261	-0.163	-0.091	0.287	0.0735	-25.60

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