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Development of Hybrid Al-MMC by an Innovative V-Process Assisted Stir Casting and Process Capability Evaluation

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Abstract: Aluminum based metal matrix composite (Al- MMC) are widely used due to their high strength to weight ratio, low cost and high wear resistance properties (especially in structural applications, aerospace and automobile industry). In this research work an attempt has been made to prepare Al-MMC with hybrid reinforcement (5%, 7.5% and 10% by weight) of double particle size (DPS) and triple particle size (TPS) Al_2O_3 and SiC, by using vacuum moulding (V-process) assisted stir casting process. Further process capability of the hybrid process has been evaluated in term of dimensional accuracy. The study highlights the percentage contribution of significant process parameters (particle size 9.19%, type of reinforcement 12.99%, vacuum pressure 35.18% and moulding sand grit size 28.10%) on the dimensional accuracy of hybrid Al-MMC. Finally the calculated value of process capability indices (Cpk) more than 1.3 highlighted that the developed hybrid process is statistically controlled for batch and mass production.

Keywords: Al-MMC; DPS; TPS; V-process; Process capability

I. INTRODUCTION

Aluminium metal matrix composites (Al-MMC) has become an attractive material for engineering application due to significantly improved properties like high specific strength, specific modulus, damping capacity and good wear resistance as compared to unreinforced alloys. Al-MMC's are widely used for the automobiles and aerospace industry and a variety of other applications [1] [2]. The new generation hybrid metal matrix composites (HMMC's) developed by the interaction of more than one type, shape and sizes of reinforcements have recently evoked the keen interest of the researchers due to their better tribological properties as compared to single reinforced composites [3] [4]. Hybridization gives more freedom to design a material for any specific application with less cost. In recent years, hybridization of reinforcements has gained significant importance in enhancing the properties of Metal Matrix Composites (MMCs) [5]. Gurcan & Baker [6], Wang et al. [7] and Park [8] developed hybrid Al-MMC / Al_2O_3 / SiC and observed the superior wear properties of hybrid composites. Suresha et al. [9] has also reported better wear resistance of Al-SiC-Gr hybrid composite. Therefore, hybrid MMC's are being developed to achieve high strength and superior tribological properties in comparison to the super-alloys and become the most preferred choice in the aerospace industry for structural application. The fabrication process and the type, shape, size & quantity of reinforcement governed the properties of the composites [10] [11]. However, the required properties can be attained successfully if the fabrication process is able to deliver requisite wetting, bonding, stability and homogeneous distribution of the reinforcement in the matrix [11]. Researchers have used the various techniques such as Stir Casting [11[, Compocasting [12], Squeeze Casting[13], Powder Metallurgy[14] and Friction Stir Process[15] to fabricate hybrid composites. Among all these processing route, the stir casting is one of the most promising liquid metallurgy route used to fabricate Al-MMC due to its simplicity, flexibility and applicability for large scale production at comparatively low cost [16] [17].The stir casting is a liquid state method has been wieldy used for the fabrication of composites, in which the reinforcement particles are uniformly mixed with a molten matrix metal by means of mechanical stirring [18]. The liquid composite material is then cast by die casting methods which need additional machining process to get exact size. The machining to get exact shape after casting of MMC component become difficult due to the abrasive nature of the reinforcement. As the complexity of part increases, exceptionally high cost and time is involved in the development, modification and repair of the dies.

The v- process/vacuum moulding (VM) was developed by Japanese in 1971 has emerged as a green technique for developing the mould of unbounded sand rigidized with vacuum (250 - 450 mm of Hg) [19]. The casting obtain from VM is free from draft allowance which further eradicate machining cost and time [20]. Apart from smooth casting with high degree of dimensional

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accuracy, VM has many other advantages such as no sand moisture related defects, excellent sand permeability, no pollution due to burning of the binders to make it environment friendly, no defects like gas holes and reuse of moulding sand [19]-[23] .VM can be able to develop the mould with complex geometry in a short time which will help to eliminate the lead times for die generation. The lower solidification rate of metal in a vacumm mould also promotes the development of fine grain microstructure which further improves the mechanical properties [24][25]. Singh[26] and Boparai and Singh [27] has been suggested that vacuum moulding (VM) is a highly capable process for the development of Al- MMC and can be employed for batch/mass production activities.

Therefore, to develop near-net-shape geometries i.e. dimensional accuracy and to eliminate the shortcomings of die casting the vacuum moulding shows potential to be used for the fabrication of hybrid Al-MMC. The moulding sand size, vacuum pressure, duration of vibration and constitution and composition of composite are the crucial factors affects obviously the dimensional accuracy.

It is evident from literature that lot of research work has been reported for the fabrication of hybrid Al-MMC with stir casting [10] [11] and optimization of vacuum moulding [21] [25]-[32]. But hitherto very less work has been reported on combining vacuum moulding and stir casting (together) for the fabrication of the hybrid Al-MMC. Considering all these aspect the aim of the present study is to develop hybrid Al-MMC by innovative v-process assisted stir casting and its process capability evaluation in term of dimensional accuracy.

II. EXPERIMENTATION

A. Charged Material

Industrial pure (≥99.6 wt% Al) Al-6063 is used as a matrix material and detailed chemical composition is given in Table 1. Al_2O_3 and SiC of grit size 100(122µm), 120(102µm) and 150(89µm) are used as reinforcement and their properties are shown in Table 2. The double particle size (DPS) & triple particle size (TPS) reinforcement is obtained by mixing of 100 and 120 grit size and 100, 120 and 150 grit size in equal proportion, respectively.

TABLE 1 CHEMICAL COMPOSITION OF Al-6063

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt %	0.2-0.6	0.35	0.10	0.10	0.45-0.9	0.10	0.10	0.10	Balance

B. Fabrication Process

A disc of 50 mm diameter and 10 mm thickness was selected for this study (Fig.1) and the perforated pattern of the selected component was generated on FDM machine. The perforated pattern in placed at the center of the base plate and a preheated thin plastic sheet is drawn onto the pattern contour by imposing vacuum (300-400 mm of Hg). Then a mould box (drag) is placed on the base plate and the formed plastic sheet is fixed with the mould box. The dry un-bonded silica sand (AFS No. 50-70) fills in the mold box and get compacted with vibration (3-5 Sec.), the other open side of the mould box is sealed with second plastic sheet sealed and then vacuum is further applied to compact the sand. The vacuum of the base plate is released and the mold box is flipped off. The pattern is easily slipped out and second mould box (cope) is placed on the first mould box. The mold box is filled with dry unbounded sand and sealed with plastic sheet. The sand gets compactness with the application of vibration and vacuum. The proper gating arrangement is given in the cop. The two halves are properly sealed and the mold cavity under vacuum is ready for metal pouring. The schematic view of vacuum moulding setup is shown in Fig.2.

For the fabrication of Al-MMC, the required quantity of Al-6063 alloy was melted in a graphite crucible at 800˚C and the reinforcement particles were preheated at 450˚C to drive off the moisture before charging. A mild steel stirrer is immersed upto two thirds depth of the molten metal and stirred at the speed of 450 RPM. Magnesium (1wt. %) was further added during stirring to improve wetting and to reduce the agglomeration of reinforcing particles [11]. Finally, the molten metal was poured into the mould under negative pressure and get solidify. After cooling the vacuum is released and free-flowing sand drop away, leaving a clean required casting without sand lumps.

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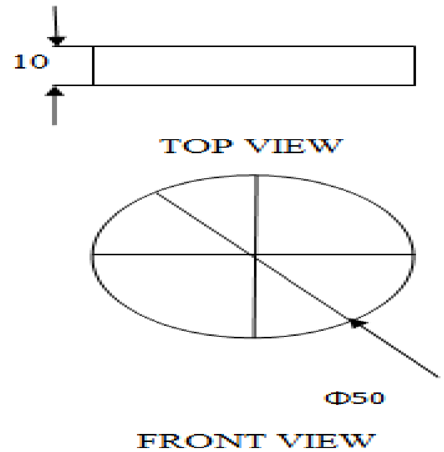

Fig. 1 Dimensions and 2D view of FDM based patterns.

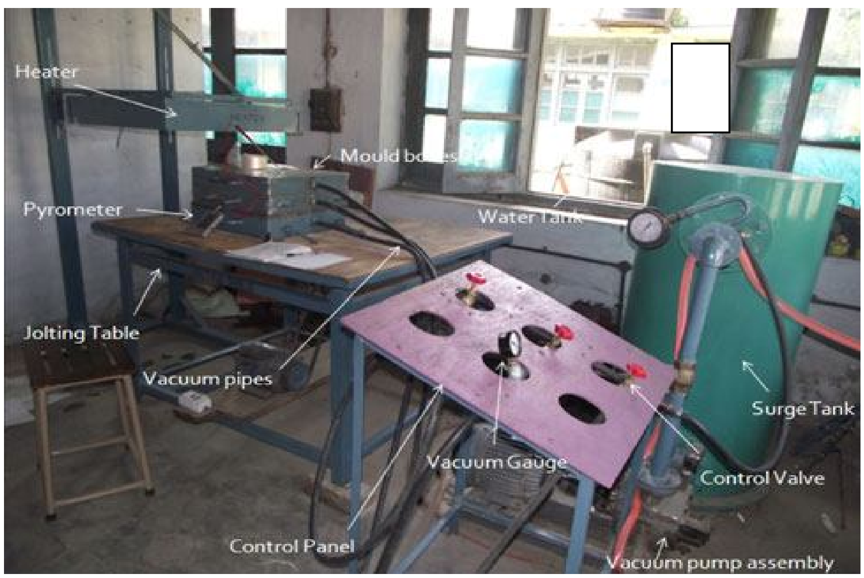

Fig. 2 The schematic view of vacuum moulding.

In order to reduce the number of experiments Taguchi L_{18} (2^1 X 3^7) OA frame work has been employed for the fabrication of Al-MMC with hybrid reinforcement. It has one factor of two levels and five of three levels as given in Table 2. The other parameters like molten metal temperature; vibration frequency and plastic film thickness were kept constant. Three repetitions of experimentation at same setting have been performed in order to minimise the experimental error.

Table 2 Control Factors and Their Levels

S.No.	Input factor	Designation	Levels			D.O.F.
			1	2	3	
1	Particle Size	A	DPS	TPS	-	1
2	Type of Reinforcement	B	Al_2O_3	SiC	Al_2O_3+ SiC	2
3	Vacuum Pressure (mm of Hg)	C	300	350	400	2
4	Moulding Sand Grit Size (AFS No.)	D	50	60	70	2
5	Vibration Time (sec.)	E	4	5	6	2
6	Composition (%)	F	5	7.5	10	2

III. RESULTS AND DISCUSSION

After casting, the effect of selected input parameters has been studied on the process capability of this novel process in term of dimensional accuracy. The dimension, thickness of the disc (t=10) was selected and dimensional deviation (Δt) of each cast component from standard dimension as per drawing (Fig. 2) was calculated by using a digital vernier caliper. As the dimension deviation represents the dimensional accuracy, therefore less (Δt) means more dimensional accuracy.

A. Analysis of S/N Ratio

The influence and variation caused by each input factor on Δt is determined with signal to noise ratio(S/N). The major benefit of using S/N ratio is that it uses a single measure, mean square deviation (MSD), which incorporates the effect of changes in mean as well as the standard deviation with equal priority [33]. The main aim of this study is to minimize 'Δt'. Therefore, S/N ratios were calculated using Eq. (1) on the basis of 'lower is better' approach for the responses.

$$S/N = -10 \log \left[1/r \sum Y_i^2 \right] \quad (1)$$

Y_i = Observed value of the response characteristic; r= number of repetitions

MINITAB-17 statistical software has analyzed the experimental results [34]. The L_{18} OA frameworks with input factor and their selected levels used for the experiment; the average dimensional deviation of three repetitions and calculated S/N ratio is shown in Table 3. The higher value of S/N ratio shows the lower dimension deviation or high dimensional accuracy.

Table 3 Taguchi L_{18} Oa Provides Details Of Experiment Plan And Results

Exp. No.	A	B	C	D	E	F	Δt (mm)	S/N Ratio
1	DPS	Al_2O_3	300	50	4	5	0.92	0.724243
2	DPS	Al_2O_3	350	60	5	7.5	0.84	1.480015
3	DPS	Al_2O_3	400	70	6	10	0.71	2.974833
4	DPS	SiC	300	50	5	7.5	0.86	1.27643
5	DPS	SiC	350	60	6	10	0.72	2.85335
6	DPS	SiC	400	70	4	5	0.68	3.349822
7	DPS	Al_2O_3+SiC	300	60	4	10	0.96	0.354575
8	DPS	Al_2O_3+SiC	350	70	5	5	0.72	2.85335
9	DPS	Al_2O_3+SiC	400	50	6	7.5	0.74	2.615366
10	TPS	Al_2O_3	300	70	6	7.5	0.70	3.098039
11	TPS	Al_2O_3	350	50	4	10	0.82	1.723723
12	TPS	Al_2O_3	400	60	5	5	0.71	2.974833
13	TPS	SiC	300	60	6	5	0.76	2.383728
14	TPS	SiC	350	70	4	7.5	0.65	3.741733
15	TPS	SiC	400	50	5	10	0.69	3.223018
16	TPS	Al_2O_3+SiC	300	70	5	10	0.79	2.047458
17	TPS	Al_2O_3+SiC	350	50	6	5	0.84	1.514414
18	TPS	Al_2O_3+SiC	400	60	4	7.5	0.72	2.85335
Average								2.3356

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B. Analysis of Variance (ANOVA)

Based on the observation in Table 3 analysis of variance (ANOVA) was executed on the S/N ratio of the responses to find the significance of each input factor and its percentage contribution to the desired output response, as shown in Table 4. The input factor having higher percentage contribution affects more the output response so by governing these factors the whole variation can be controlled or minimized which lead to improved process.

Table 4 Anova Results For Δt

Source	D O F	SS	Adj.SS	Adj.MS	F-value	P-value	% Contribution
Particle Size (A)	1	1.4327	1.4327	1.4327	6.39	0.045	9.194
Type of Reinforcement (B)	2	2.0249	2.0249	1.0125	4.52	0.064	12.994
Vacuum Pressure (C)	2	5.4824	5.4824	2.7412	12.23	0.008	35.181
Moulding Sand Grit Size (D)	2	4.3798	4.3798	2.1899	9.77	0.013	28.106
Vibration Time (E)	2	0.6104	0.6104	0.3052	1.36	0.325	3.917
Composition (F)	2	0.3085	0.3085	0.1542	0.69	0.538	1.980
Residual Error	6	1.3446	1.3446	0.2241			8.628
Total	17	15.5833					

Table 5 Ranking Of Input Parameters Based Upon Sn Ratio Of Δt For Smaller Is Better.

Level	A	B	C	D	E	F
1	2.054	2.163	1.647	1.846	2.125	2.300
2	2.618*	2.805*	2.361	2.150	2.309	2.511*
3		2.040	2.999*	3.011*	2.573*	2.196
Delta	0.564	0.765	1.351	1.165	0.449	0.315
Rank	4	3	1	2	5	6

*Represents higher S/N

Based upon Table 4, the input factor particle size, type of reinforcement, vacuum pressure and moulding sand grit size with P-value less than 0.05 (95% confidence) are the significant model terms. The percentage contribution of all the input factors is shown in Fig.3.

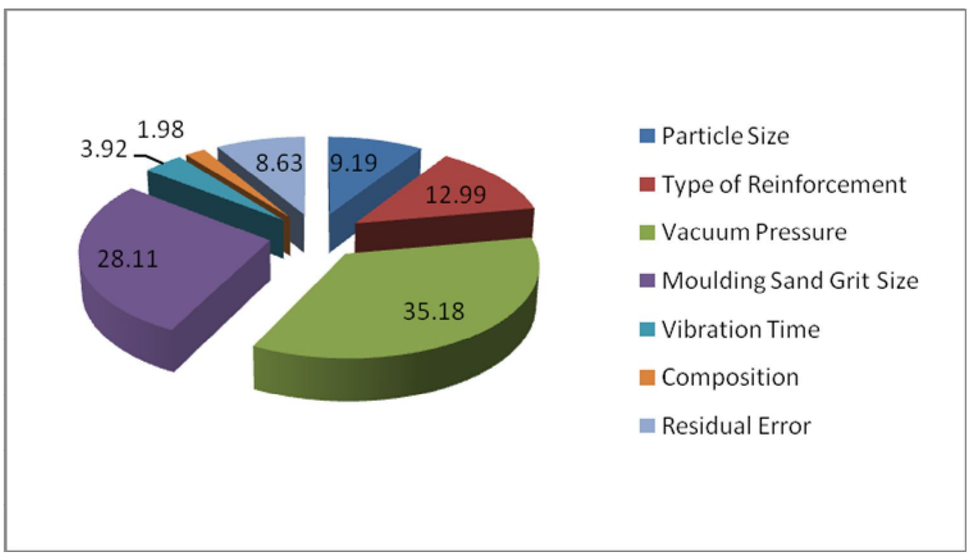

Fig. 3 Percentage Contribution Chart

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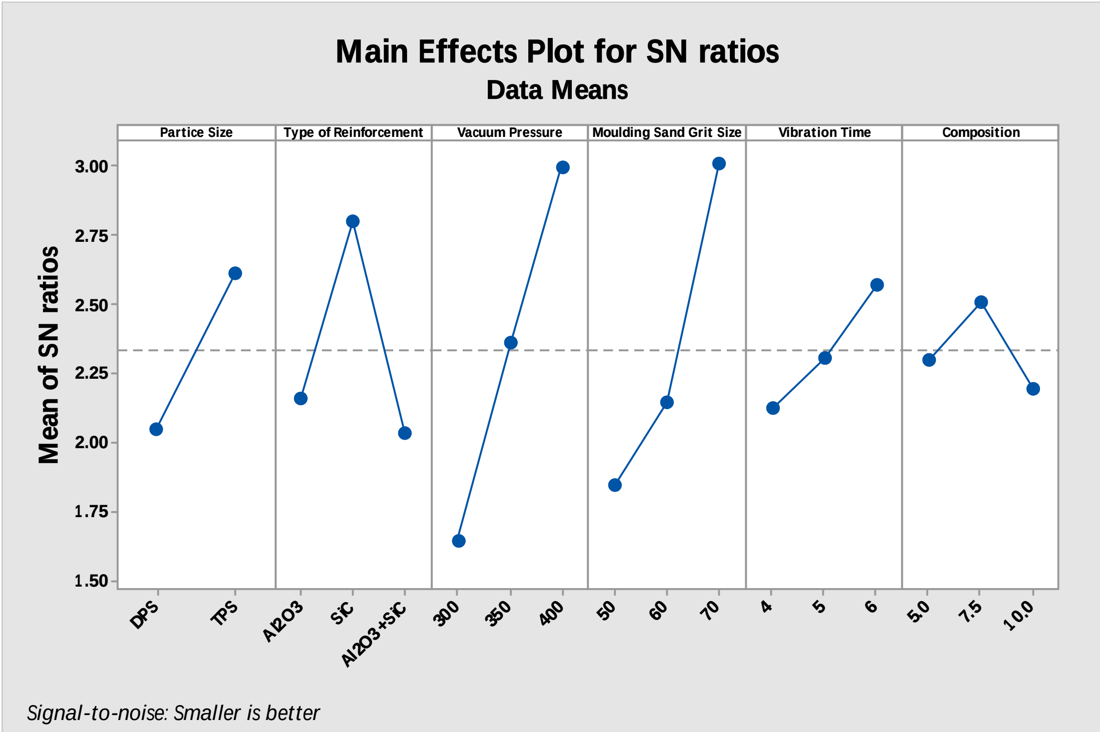

Fig. 4 Main effects plot for SN ratios

The main effect plot of various factors on Δt is shown in Fig.4, it has been found out that the reinforcement of SiC with TPS exhibit better dimensional accuracy due to excellent bonding of three different particle sizes then DPS. The TPS particles were closely packed with aluminum in the MMC results in better dimensional accuracy.

For good dimensional accuracy, vacuum pressure was best found out at 400 mm of Hg, because with increase in pressure the mould tightness increases. This tight mould, results in good dimensional accuracy in casting due to less deviation than loose mould. So, as observed in sand grain size 70 (A.F.S. No.) the dimensional accuracy was the best because of closely packed fine particles of the sand settle better under vacuum pressure and vibration. It has been also observed that the composition has no significant effect on the dimensional accuracy.

C. Optimization and Confirmation Experiments

From Table 5 the optimum levels (factor levels with highest S/N ratio) have been identified for the significant factors in order to achieve maximum dimensional accuracy as shown in Table 6.

TABLE 6 OPTIMUM LEVELS AND THEIR CORRESPONDING VALUES.

S.No.	Input factor	Highest mean S/N ratio	Optimum level	Optimum Value
1	Particle Size	2.618	A_2	TPS
2	Type of Reinforcement	2.805	B_2	SiC
3	Vacuum Pressure (mm of Hg)	2.999	C_3	400
4	Moulding Sand Grit Size(AFS No.)	3.011	D_3	70
5	Vibration Time (sec.)	2.573	E_3	6
6	Composition (%)	2.511	F_2	7.5

For optimization following formula based upon Taguchi design has been used to predict optimum response in term of S/N ratio (ηopt) by using the mean S/N ratio of significant factors [35] [36].

$$\eta opt = m+(m_{A2}-m) + (m_{B2}-m)+(m_{C3}-m)+ (m_{D3}-m) \quad (2)$$

$$\eta opt = 2.618 + 2.805+2.999+3.011 - 3(2.3356)$$

$\eta opt = 4.4262$ dB

Where 'm' is the overall mean of S/N data, m_{A2} is the mean of S/N data for A at level 1 and similarly m_{B2}, m_{C3} and m_{D3}.
By using Eq.1 predicted dimensional deviation is 0.64mm. The confirmatory experiments were performed by using the obtained set of optimum factor values. The confirmation test values of the dimensional deviation lie between 0.62 and 0.65mm, close to the predicted value.

D. Process capability

The capability of a process represents a measure for standardization of a process. The process capability is analyzed and assessed through the usage of capability indicators such as: potential index or preciseness of a process Cp (measure for process dissipation) and capability preciseness index Cpk (measure for process adjustment) [37]. Cp and Cpk is evaluated by QI Macros-2015 software on the samples cast at optimum parameter settings as shown in Fig. 5. In this work, corresponding to a Cpk value of 1.38 for the selected dimension, area under the normal curve is 0.999936360 and non-confirming parts per million is 63.6403. As, the Cpk value greater than 1.3 indicated that the proposed process is statistically controlled and can be employed for batch/mass production.

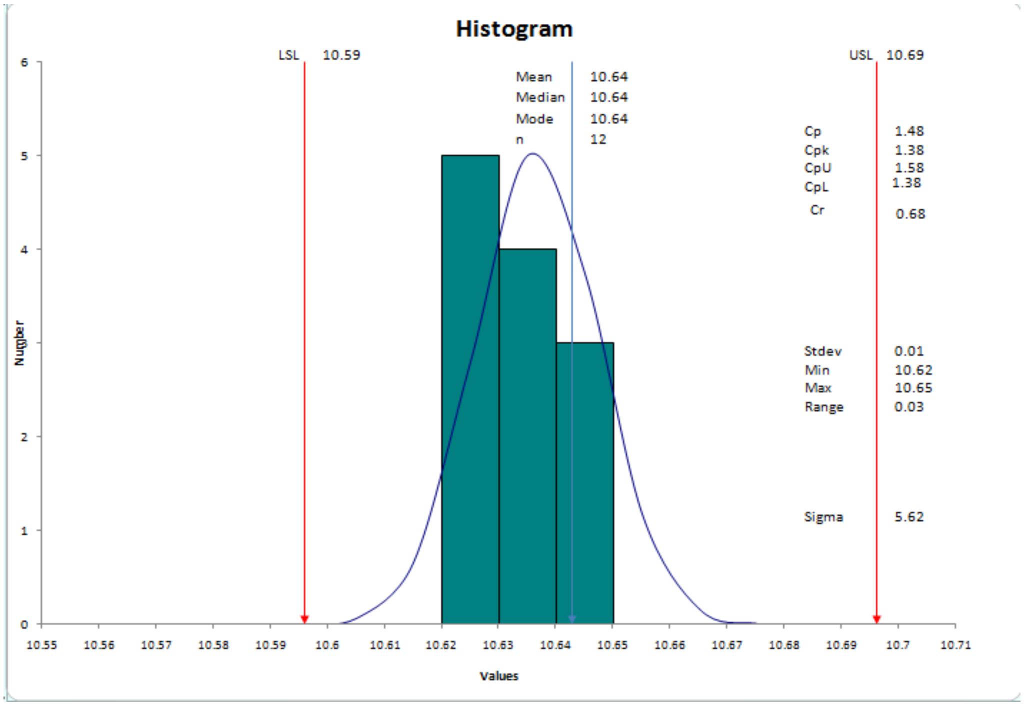

Fig. 5 Process Capability

IV. CONCLUSION

From this research work, the following conclusions have been made:

A. Al-MMC with hybrid reinforcement (5%, 7.5% and 10%) of DPS and TPS Al_2O_3 and SiC has been developed successfully by using vacuum moulding (V-process) assisted stir casting technique.
B. ANOVA revealed that the percentage contribution of significant process parameters particle size 9.19%, type of reinforcement 12.99%, vacuum pressure 35.18% and moulding sand grit size 28.10% on the dimensional accuracy of hybrid Al-MMC.
C. The optimal dimensional accuracy is found with triple particle size (A_2), SiC (B_2), vacuum pressure 400 mm of Hg (C_3), 70 A.F.S. No. (D_3), vibration time of 6 seconds (E_6) and composition of 7.5 % by weight (F_2).
D. Process capability indices (Cpk) more than 1.3 highlighted that the developed hybrid process is highly capable and statistically controlled for batch and mass production.

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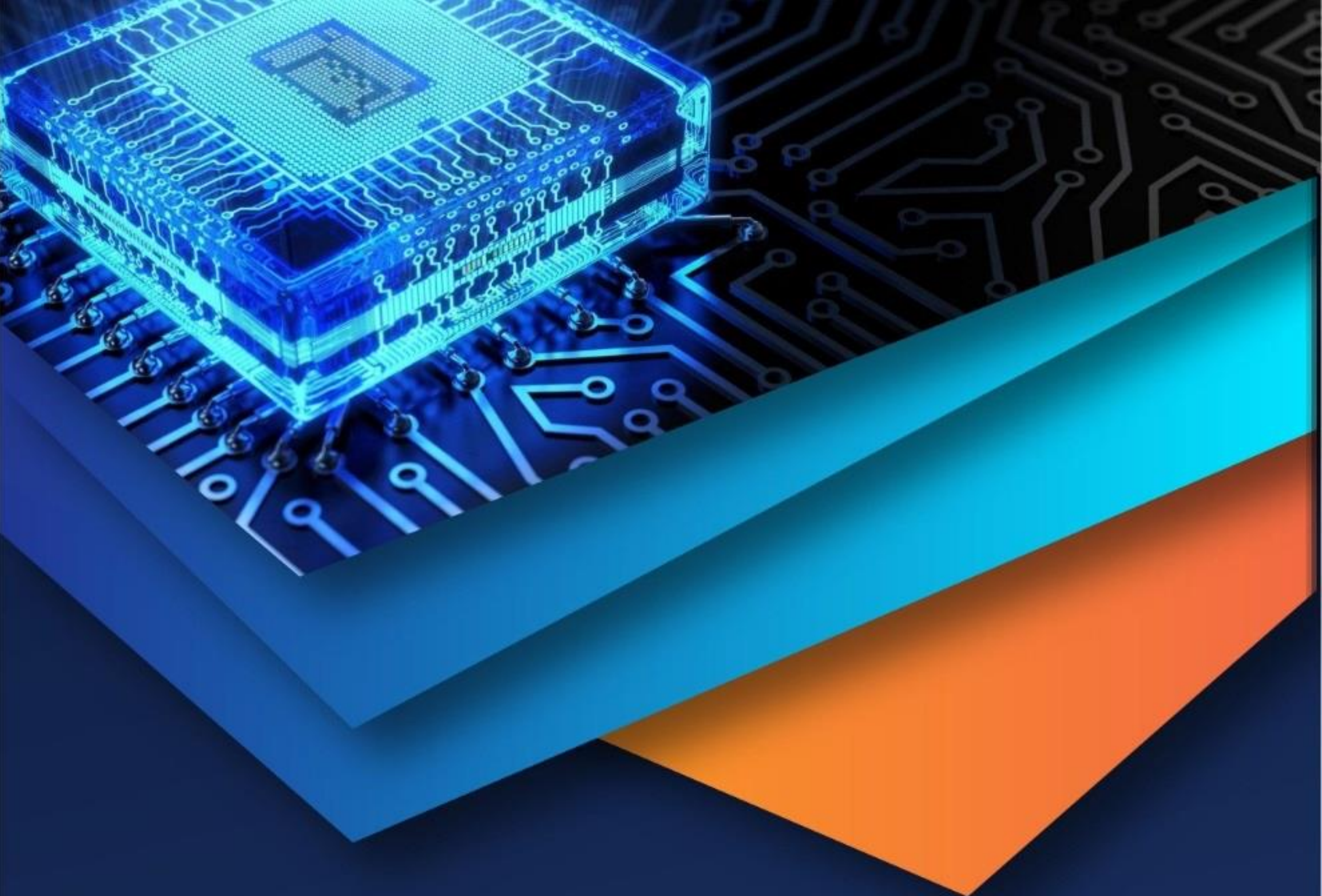

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