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Multifactor optimization for development of hybrid aluminium matrix composites

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The present study aims to multi factor optimization for preparation of aluminum matrix composites (AMC) by reinforcement of SiC/ Al_2O_3/ Al_2O_3+ SiC particles having dual particle size (DPS) and triplicate particle size (TPS) based upon signal to noise (S/N) ratio analysis. In this work the amalgamation of fused deposition modelling (FDM) and vacuum moulding (V-process) assisted stir casting (SC) has been employed for the development of AMC. The process parameters under investigation are: particle size (DPS/ TPS); reinforcement type (Al_2O_3/ SiC/ Al_2O_3+ SiC); vacuum pressure (VP) (300-400 mm of Hg); moulding sand grit size (American foundry society (AFS) No. 50-70); vibration time (VT) (4-6 sec) and reinforcement proportion/composition (5/7.5/10 by wt.%). The S/N ratio based upon the wear performance (pin-on disc tester), micro hardness (HV) and dimensional accuracy/deviation (Δt) has been evaluated by using Minitab-17 software which further acts as input for multifactor optimization. The best parametric setting proposed for multi objective/factor optimization is: DPS of Al_2O_3+ SiC reinforcement at 350 mm of Hg VP with 50 AFS No. sand grain size, 4sec VT and 10% composition/proportion. The results of analysis of variance (ANOVA) highlight that particle size (with 18.49% contribution) and reinforcement type (with 42.13% contribution) have significant influence on multi factor optimization for the development of AMC. Confirmatory experiments have been performed which shows that the proposed amalgamation of FDM and V-process assisted SC can be successfully applied for enhancing the performance of AMC. Finally the X-chart and R-chart have been plotted at the proposed settings, which highlights that amalgamation process is controlled and useful for mass/ batch production.

Keywords: Multi factor optimization, Hybrid AMC, DPS, TPS, V-process assisted stir casting

1 Introduction

In past one decade the applications of AMC with customized properties has increased in daily life[1]. The AMC is made from Al metal and reinforcements in scattered stages are fixed in the matrix[2,3]. There are some advantages of reinforced AMC materials such as: better tensile strength (with less weight), wear resistance capability, thermal extension coefficient, stiffness, hardness, thermal conductivity and damping capabilities[4]. The AMC based components are used in tribological system requiring better wear properties. The reported literature reveals that the ceramics (such as: Al_2O_3, B_4C, SiC etc.) can be successfully used as reinforcements in AMC to impart customized mechanical, morphological and tribological properties[5-8].

In the modern era, AMC are prepared with the incorporation of different types of ceramic particulates into a Al matrix gaining more importance. Hybrid AMC has the potential to fulfill industry requirement due to their tailor made properties as compared to single particle size (SPS) reinforced composites[9,10]. It is considered difficult to consolidate wide range of properties within the composite materials with SPS reinforcement.

Rajmohan *et al.* observed that tensile strength/ hardness and resistance to wear capability of hybrid AMC reinforced with mica and SiC have been superior than the SPS reinforced Al/SiC composites[11]. In an another study Devaraju *et al.* has confirmed that the hybrid composite shows better hardness and wear resistance capabilities as compared to the parent material[12]. Suresha *et al.* outlined the tribological and mechanical properties of hybrid composite (Al/SiC)[13]. Prasada *et al.* observed that the hybrid reinforcement of SiC and Al_2O_3 in the Al matrix is able to deliver adequate wear resistance and strength[14]. Similar trends were found in another study, that the hybrid reinforcement of SiC and Al_2O_3 successfully enhanced the mechanical and tribological properties of another Al matrix material (LM25)[15].

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Improvement in tribological performance was also observed in the hybrid AMC's obtained with reinforcement of different particle size[16]. In an attempt, Parbhakar *et al.* examined the effect of reinforcement particle size on the wear performance of Al-356/SiC and found that DPS reinforced composite shows better wear resistance as compared to the SPS reinforced composites[17]. Whereas in another study, the wear performance of TPS based Al/20%SiC was found better as compared to DPS reinforcement[18]. Abdulmumin *et al.* have also investigated the effect of multiple particle size (80μm, 40μm and 15μm) of SiC reinforced AMC on the wear properties and found that coarse particles significantly influenced the wear resistance capabilities in comparison to fine particle sizes[19]. From these investigations it was found that the hybrid AMC are being developed to achieve high strength, low density, high hardness and superior tribological properties[7, 10-19].

It is quite evident from the literature that properties of the AMC are governed by type, size and quantity of reinforcement[4,10]. However, the processing route of AMC may have profound influence on the properties. The processing route should be able to deliver requisite wetting, bonding and homogeneous distribution of the reinforcement[20]. As per reported literature different processing route has been adopted in past to prepare AMC (such as: SC[20], compocasting[21], squeeze casting[22], powder metallurgical[23] and friction stir process[24]) but SC is one of the most preferred economical route due to ease, flexibility and large quantity of production[22, 22-26]. In SC, the reinforcement particles are uniformly mixed in molten matrix with mechanical stirrer[27]. The cast component requires additional machining to attain the exact dimensions.

The Japanese had developed V-process in 1971 in which mould was developed with unbounded sand got rigid under negative pressure (vacuum)[28]. The casting produced by V-process is free from draft allowance and has good dimensional accuracy which further helps to reduce the machining cost[29]. Due to the use of unbounded sand the castings are free from the defects of moisture and gas holes. The reduction in pollution caused due to the burning of the binder and reuse of moulding sand has made it an environment friendly process[28-32]. The lower solidification rate of metal in a vacuum mould also helps to attain fine grain microstructure which further improves the mechanical properties[33,34]. Singh *et al.* has proposed macro model for the hardness and dimensional accuracy for AMC with V-process. This study highlighted the effect of molding sand, VP and component volume on the properties of AMC[35]. Singh and Singh had investigated the effect of process parameter of vacuum moulding and reinforcement (size and proportion by wt. %) on the wear performance of Al/SiC. The study highlighted the contribution of sand grain size, VP, particle size (SiC) and composition 5%, 10.14%, 10.71% and 73.2%, respectively to attain the optimum wear performance[36]. It has been established that the V-process is capable for development of AMC and a lot of studies have been reported on parametric optimization of V-process[35-38]. The literature review reveals that there are some challenging technical issues for the development of hybrid AMC[2,3,37-41], which needs to be overcome (like affordable and fast processing technique capable to deliver adequate mixing of reinforcement in the matrix and characterization and control of properties). The present work is an extension of previous reported studies on surface hardness improvement of AMC with reinforcement[3]. In the present study, combination of FDM with V-process has been employed for the development of AMC to contribute incredibly towards high wear resistance, micro hardness and dimensional accuracy from multi factor optimization view point. The validation of this novel process has been done with multifactor optimization (supported with rendered 3D image of photomicrographs) which has not been previously reported.

2 Experimentation

2.1 Fabrication process of hybrid AMC

The perforated master pattern disc of Φ50 mm (10mm thick) of selected component was printed with FDM, which was further used in V-process. Fig.1 shows: (a) schematic of FDM setup (b) actual 3D printing of master pattern. The fixed input parameters were 0.3 mm nozzle diameter, 1.75±0.05mm filament diameter, 55±2°C bed temperature, 80% infill density, 60° infill angle and 60 mm/sec infill speed.

For development of AMC, the desired quantity of Al-6063 alloy (≥99.6 weight% Al) was melted at 800˚C and the reinforcements (SiC/ Al_2O_3) were preheated to 450˚C to remove the moisture before charging. The DPS/ TPS reinforcement were prepared by mixing different particle sizes in equal proportion by weight (Table 1). The development of hybrid AMC was planned as per Taguchi L_{18}, Table 2 and 3 shows the input parameter and their levels and L_{18} control log, respectively. The detailed stepwise

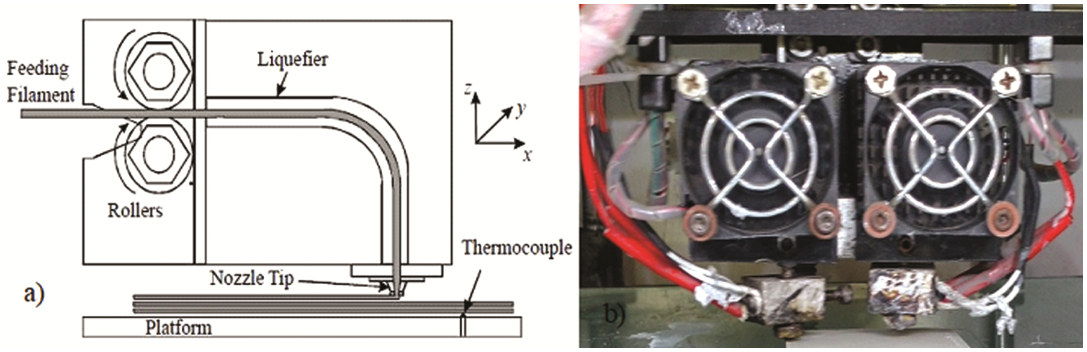

Fig.1 — (a) Schematic of FDM set-up and (b) 3D printing of master pattern (Make: Divide by Zero, India).

Table 1 — Particle size combination (in equal proportion wt.%) of reinforcement[3].

Particle size (SiC and Al_2O_3)	I	II	III
DPS (µm)	122	102	-
TPS (µm)	122	102	89

Note: The particle sizes were taken as per supplier data (Shiva chemicals, Ludhiana, India).

Table 2 — Input parameter and their levels[3].

Input parameter	Designation	Level 1	Level 2	Level 3
Particle Size	A	DPS	TPS	-
Type of reinforcement	B	Al_2O_3	SiC	Al_2O_3+ SiC
VP (mm of Hg)	C	300	350	400
Moulding sand grit size (AFS No.)	D	50	60	70
VT (sec.)	E	4	5	6
Composition/proportion (%)	F	5	7.5	10

Table 3 — Control log of experimentation.

Exp. No.	A	B	C	D	E	F
1	DPS	Al_2O_3	300	50	4	5
2	DPS	Al_2O_3	350	60	5	7.5
3	DPS	Al_2O_3	400	70	6	10
4	DPS	SiC	300	50	5	7.5
5	DPS	SiC	350	60	6	10
6	DPS	SiC	400	70	4	5
7	DPS	Al_2O_3+SiC	300	60	4	10
8	DPS	Al_2O_3+SiC	350	70	5	5
9	DPS	Al_2O_3+SiC	400	50	6	7.5
10	TPS	Al_2O_3	300	70	6	7.5
11	TPS	Al_2O_3	350	50	4	10
12	TPS	Al_2O_3	400	60	5	5
13	TPS	SiC	300	60	6	5
14	TPS	SiC	350	70	4	7.5
15	TPS	SiC	400	50	5	10
16	TPS	Al_2O_3+SiC	300	70	5	10
17	TPS	Al_2O_3+SiC	350	50	6	5
18	TPS	Al_2O_3+SiC	400	60	4	7.5

V-process, SC process used for the preparation of AMC is shown in Fig. 2 (a-l).

2.2 Wear

The application of AMC in tribological system is mostly evaluated in term of wear performance[42,43]. For this study, wear tests were performed on “pin-on-disc" tester with test specimen pin (Ø8 mm×25 mm) prepared from AMC as per ASTM G99 at ambient conditions (Table 4).

2.3 Micro-hardness

In this work as per ASTM E384, micro hardness of the AMC was examined with computerized Vickers hardness tester HVS-1000BVM (Make: Laizhou Huayin Testing Instrument Co. Ltd. China).

2.4 Dimensional accuracy

Thickness of the disc was selected for this study and Δt of each cast component of standard dimension (t=10mm) was calculated.

2.5 Taguchi method

Taguchi’s parametric design approach is a simple and systematic technique to optimize design for performance, quality and cost[44]. In this technique optimal parametric conditions are evaluated in term of S/N ratio. There are three types of S/N ratios (namely: smaller is better, larger is better and nominal the better). In the present study smaller is better (for wear and Δt) and larger is better (for micro hardness) criterion is used in the optimization process as given below:

For smaller is better

$$S/N = -10 \log [1/r \sum Yi2] \quad \ldots (1)$$

For larger is better

$$S/N = -10 \log [1/r \sum 1/ Yi2] \quad \ldots (2)$$

Where Y_i = Observed values of the responses (i =1, 2, 3…n); r= number of repetitions

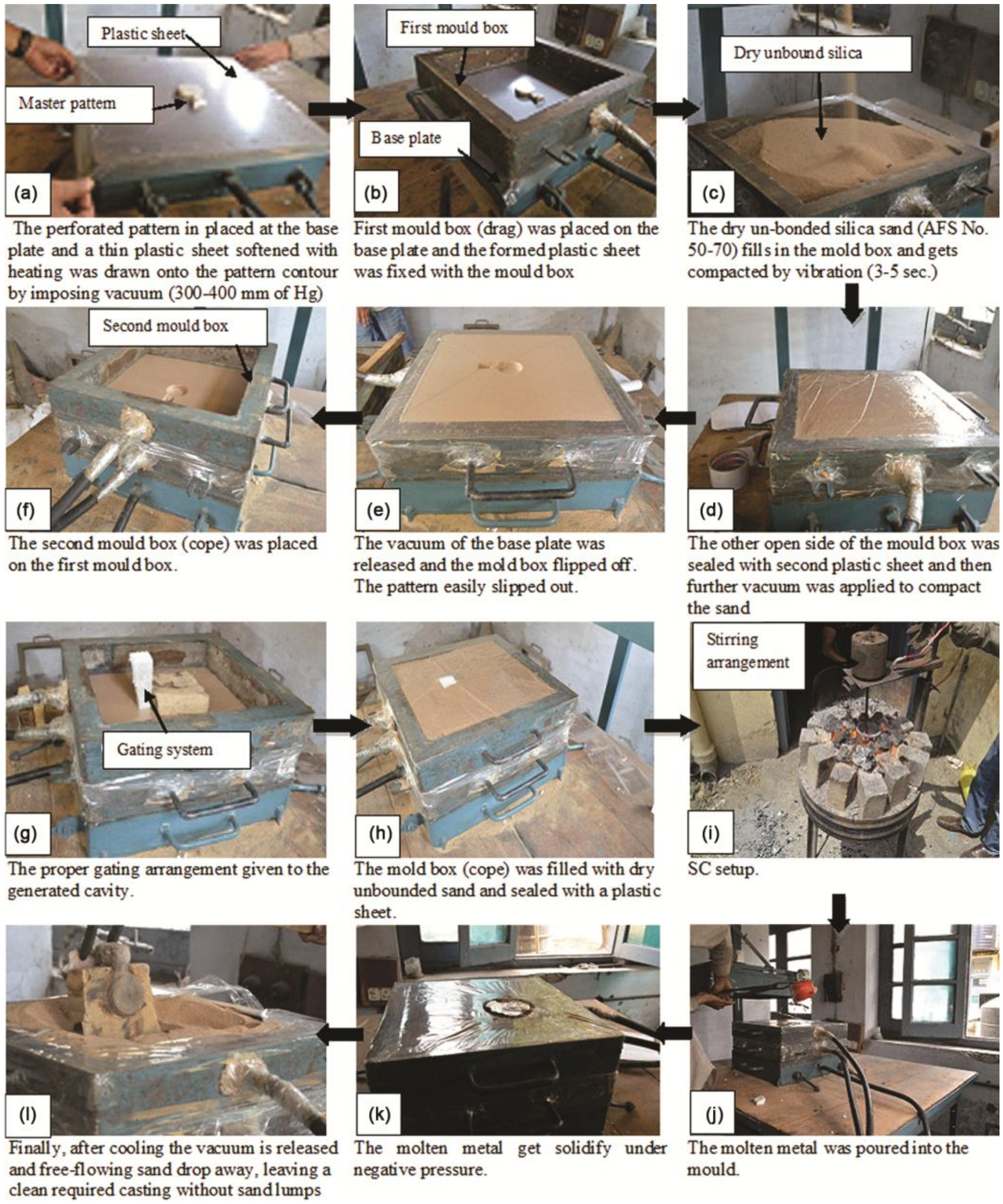

Fig. 2 — Steps for the fabrication Al-AMC using V-process and SC.

3 Results and Discussion

The average results of wear test, micro hardness and Δt are shown in Table 5. The S/N ratio based on these results of wear and Δt at "smaller is better" condition and micro hardness at "lager is better" condition has been evaluated by using Minitab-17 software, as given in Table 5.

Table 5-Average test results and S/N ratio results (raw and normalized)- wear (µm), micro hardness (HV) and Δt

3.1 Wear

The main effects of parameters for wear (µm) of AMC are shown in Fig. 3. It has been observed that wear decreases with the increase in the particle size of reinforcement and minimum wear was observed with reinforcement of Al_2O_3+SiC. The rise in VP and a reduction in the size of moulding sand reduce the permeability of the mold which further increases the solidification time and promote fine grain structure. The fine grain structure results improvement in the wear resistance of AMC. It is also observed that the increase in reinforcement helps to improve the wear resistance capabilities. The best wear result was obtained with DPS based Al_2O_3+SiC of 10% composition by weight at the VP of 350 mm of Hg with moulding sand grit size of 70 AFS and vibration for 4 sec.

3.2 Micro-hardness

The influence of type and size of reinforcement, VP, molding sand grit size and VT on the micro hardness of the AMC is shown in Fig. 4. As highlighted in Fig.4, TPS based AMC exhibit better micro hardness may be due to the presence of more No. of fine particle size reinforcement as compared to DPS. It has been found that the micro hardness of SiC reinforced AMC are better as compared to AMC reinforced with either Al_2O_3 or Al_2O_3+SiC. The micro hardness also improved with the rise of VP and reduction in the grit size of moulding sand due to same reason as discussed in case of wear. The quantity of reinforcement (wt. %) has a great effect on the performance of AMC and found that the micro hardness increases with the increase in %composition of the hard reinforcement particles in the soft matrix (Al). The optimum result for micro hardness was obtained with TPS, 10% of SiC and 350 mm of Hg VP with 70 AFS No. sand grit size and vibration for 4 sec.

Table 4 — Wear test conditions.

Size of Pin	Ø8mm X 25mm polished on 800 grit emery paper
Disc	En-31 steel disc hardened to 60 HRC and ground to 1.6 Ra surface roughness.
Normal Load	30 N
Sliding Speed	1 m/sec
Time	10 min.

3.3 Dimensional variation

Figure 5 shows, the main effect plot of various factors on Δt and found that the reinforcement of SiC with TPS exhibit better dimensional accuracy as compared to DPS. Because the presence of smaller particle size reinforcement in TPS causes closely packed structure with matrix (Al) and results in better dimensional accuracy. It is observed that the dimensional accuracy improves with the rise of VP. Because the rise in VP increases the tightness of the mold which further reduces the Δt. It is also observed that the finer grit size of moulding sand (70 AFS) with longer duration of vibration (6sec) improves the dimensional accuracy. Because finer grit size moulding sand settle better under VP and vibration to

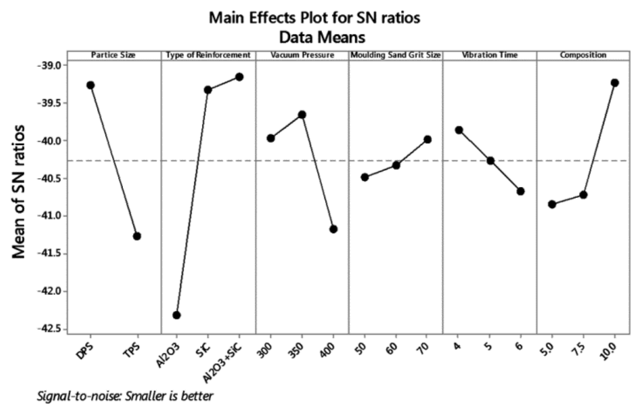

Fig. 3 — Main effect plot for S/N ratios-wear.

Table 5 — Average test results and S/N ratio results (raw and normalized)- wear (µm), micro hardness (HV) and Δt.

Exp. No.	Average value			S/N Ratio			S/N Ratio (Normalized)			Combined S/N ratio
	Wear (µm)	Micro hardness (HV)	Δt	µm	HV	Δt	µm	HV	Δt	
1	124	30.17	0.92	-40.51	29.54	0.72	9.49	79.54	50.72	24.11
2	106	33.00	0.84	-40.29	30.32	1.48	9.71	80.32	51.48	24.31
3	103	34.00	0.71	-41.85	30.6	2.97	8.15	80.60	52.97	22.85
4	81	35.00	0.86	-38.14	30.83	1.28	11.86	80.83	51.28	25.94
5	80	39.00	0.72	-38.03	31.78	2.85	11.97	81.78	52.85	26.03
6	88	41.00	0.68	-38.89	32.22	3.35	11.11	82.22	53.35	25.43
7	65	36.00	0.96	-36.31	31.1	0.35	13.69	81.10	50.35	27.08
8	78	39.67	0.72	-37.85	31.95	2.85	12.15	81.95	52.85	26.15
9	118	34.33	0.74	-41.46	30.7	2.62	8.54	80.70	52.62	23.24
10	153	35.27	0.70	-43.69	30.93	3.10	6.31	80.93	53.10	20.68
11	120	38.47	0.82	-41.61	31.68	1.72	8.39	81.68	51.72	23.09
12	198	33.50	0.71	-45.92	30.5	2.97	4.08	80.50	52.97	16.95
13	109	40.83	0.76	-40.75	32.19	2.38	9.25	82.19	52.38	23.91
14	101	43.67	0.65	-40.12	32.79	3.74	9.88	82.79	53.74	24.46
15	100	45.00	0.69	-40.03	33.05	3.22	9.97	83.05	53.22	24.54
16	90	41.03	0.79	-39.09	32.23	2.05	10.91	82.23	52.05	25.27
17	98	39.47	0.84	-39.82	31.89	1.51	10.18	81.89	51.51	24.69
18	105	43.00	0.72	-40.40	32.64	2.85	9.60	82.64	52.85	24.22
				Average						24.05

reduce the Δt, whereas the composition has no significant effect on the dimensional accuracy of AMC casting.

3.4 Multi-objective/factor optimization

It has been found that in case of individual optimization the parametric setting for the best result of each response is not similar with other. It is a challenging task in selecting the optimal combination for all response i.e. wear, micro hardness and dimensional accuracy. Therefore, in present study S/N ratio based multi objective/factor optimization method is employed to propose best parametric setting which should be able to deliver optimum wear resistance, micro hardness and dimensional accuracy. The Minitab-17 software was used at "larger is better" condition to analyze S/N ratios of individual response. S/N ratios of individual response based on results are shown in Table 5. It has been found that the S/N ratios in case wear are of a negative nature and other two are of positive nature due to which it is not possible to process data. To normalize the data "100" is added in the S/N ratios of all the response. Finally, Minitab-17 deduced combined S/N ratio by using normalized S/N ratios of individual response (Table 5). Based on the combined S/N ratios analysis of variance (ANOVA) was executed to evaluate the contribution of each input parameter. The percentage contribution of each input parameter is shown in Table 6 and Fig. 6. & Fig. 7 shows, main effects plot for S/N ratios for multi objective/factor optimization. It has been observed that the particle size (with

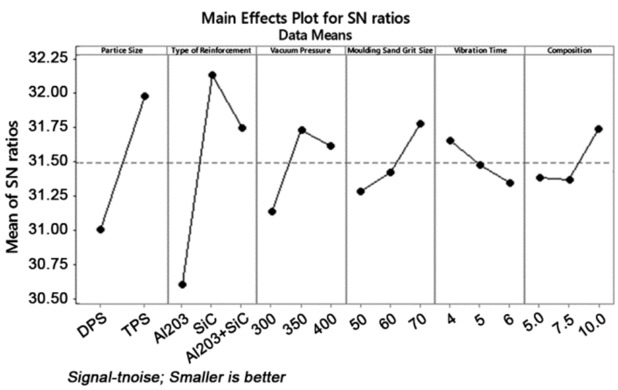

Fig. 4 — Main effect plot for S/N ratios-micro hardness.

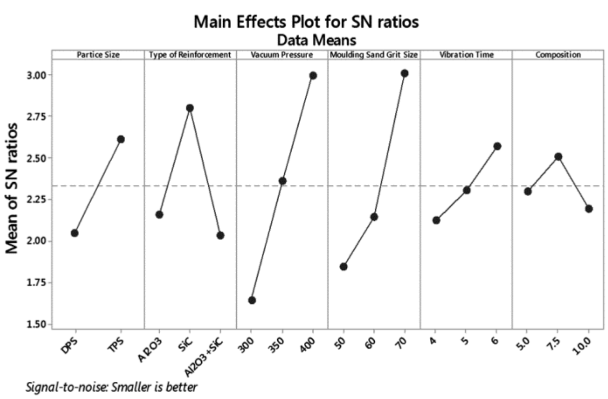

Fig. 5 — Main effects plot for SN ratios- Δt.

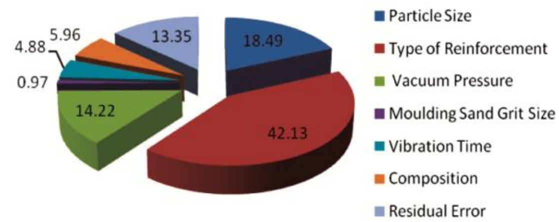

Fig. 6 — Percentage contribution of input parameter on multi objective/factor optimization.

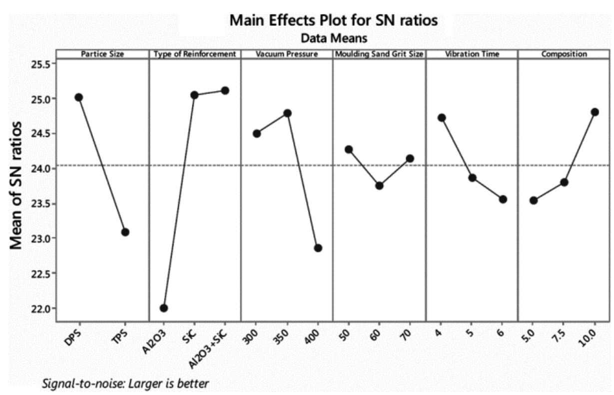

Fig. 7 — Main effects plot for S/N ratios-multi objective/factor optimization.

Table 6 — ANOVA results for multi objective/factor optimization.

Source	D O F	SS	Adj.SS	Adj.MS	F-value	P-value	% Contribution
Particle Size	1	16.6817	16.6817	16.6817	8.31	0.028	18.49
Type of Reinforcement	2	38.0046	38.0046	19.0023	9.47	0.014	42.13
VP	2	12.8266	12.8266	6.4133	3.2	0.114	14.22
Moulding Sand Grit Size	2	0.8762	0.8762	0.4381	0.22	0.81	0.97
VT	2	4.4041	4.4041	2.2021	1.1	0.393	4.88
Composition	2	5.3724	5.3724	2.6862	1.34	0.331	5.96
Residual Error	6	12.0401	12.0401	2.0067			13.35
Total	17	90.2056					100.00

18.49% contribution) and type of reinforcement (with 42.13% contribution) are significant factor from multi objective/factor optimization view point.

The best parametric setting proposed for multi objective/factor optimization is: DPS, Al_2O_3+ SiC reinforcement, 350 mm of Hg VP, 50 AFS No. sand grain size, 4sec VT and 10% composition.

3.5 Confirmatory test

Finally confirmatory experiments were conducted on the proposed parametric setting as given in Table 7. It should be noted that best settings suggested after applying multi-factor optimization (Table 7, Fig. 7) are different from settings suggested for best setting of individual output parameters (Fig. 3-5). This may be because of the fact that multi factor optimization was performed for larger the better type case, where already optimized S/N ratios were further maximized in second stage, where as wear and Δt was optimized for smaller the better type case and hardness was optimized for larger the better type case. The results of the confirmatory experiments at proposed settings for wear, micro hardness and Δt are presented in Table 8. The plot for wear and frictional force of confirmatory test are shown in Fig. 8. Fig. 9 shows the photomicrograph of AMC prepared at proposed settings (with confirmed presence of Al_2O_3 and SiC contributing towards the improved wear resistance and micro hardness). The observations are in line with the findings of other researchers[36-39].

Table 7 — The best parametric setting proposed for multi objective/factor optimization.

S. No.	Input factor	Optimum level	Optimum Value
1	Particle Size	A_1	DPS
2	Type of Reinforcement	B_3	SiC+Al_2O_3
3	VP (mm of Hg)	C_2	350
4	Moulding Sand Grit Size (AFS No.)	D_1	50
5	VT (sec.)	E_1	4
6	Composition (%)	F_3	10

Table 8 — Results of the confirmatory experiments.

S. No.	Response	Optimum condition	Value
1	Wear (μm)	A_1, B_3, C_2,	70
2	Micro Hardness (HV)	$D_{1,}$	41
3	Δt (mm)	E_1 and F_3	0.71

Further image processing software has been used to see the 3D rendered image of photomicrograph (Fig. 9) and corresponding surface roughness (Ra) value has been calculated (at cut-off length of 0.04mm). Fig. 10 clearly depicts the cavity size/shape confirming reinforcement types (a) and average Ra of 382.5nm (b) which is acceptable in conventional manufacturing.

3.6 X-chart and R-chart

After the satisfactory results of confirmation experiment at the proposed parametric setting, the development process of AMC, 06 trails (repetitions) were performed at proposed input parametric settings (Table 9). Based on these results of micro hardness, wear and dimensional data (Table 9) X-chart and R-chart for each performance characteristics were drawn by using Q1-Micros software. Finally, Fig. 11 (a-f) confirmed that the process is under statistically control.

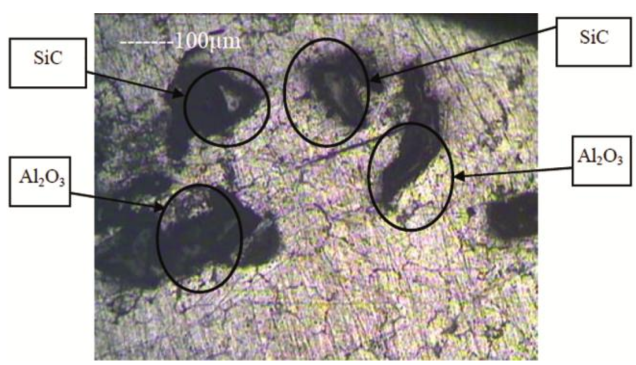

Fig. 9 — Photomicrograph of confirmatory test sample (at 100x).

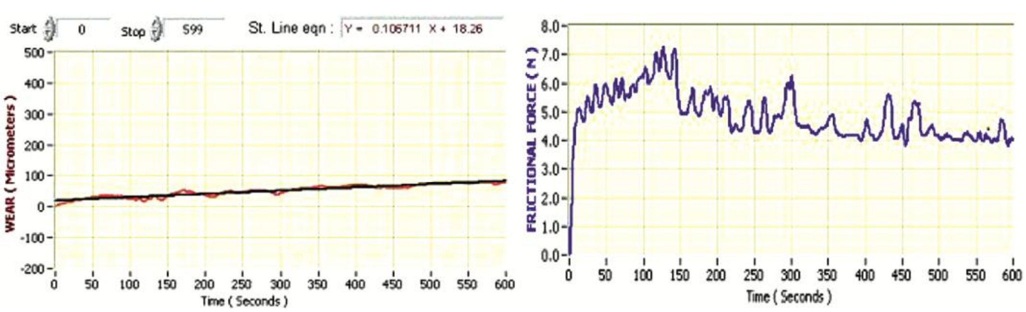

Fig. 8 — Results of confirmatory test (a) Wear and (b) Frictional force.

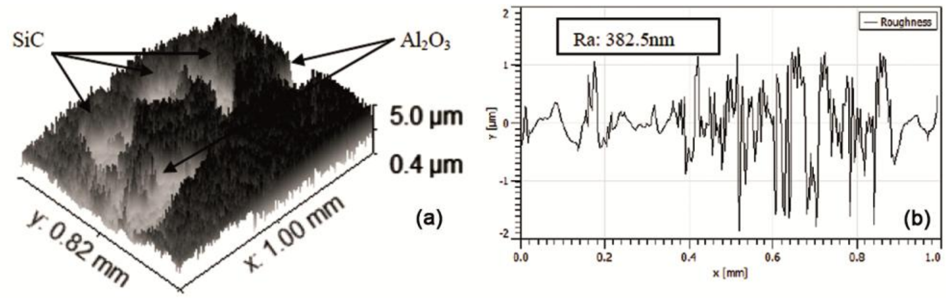

Fig. 10 — (a) Rendered 3D image of confirmatory test sample and (b) Ra profile

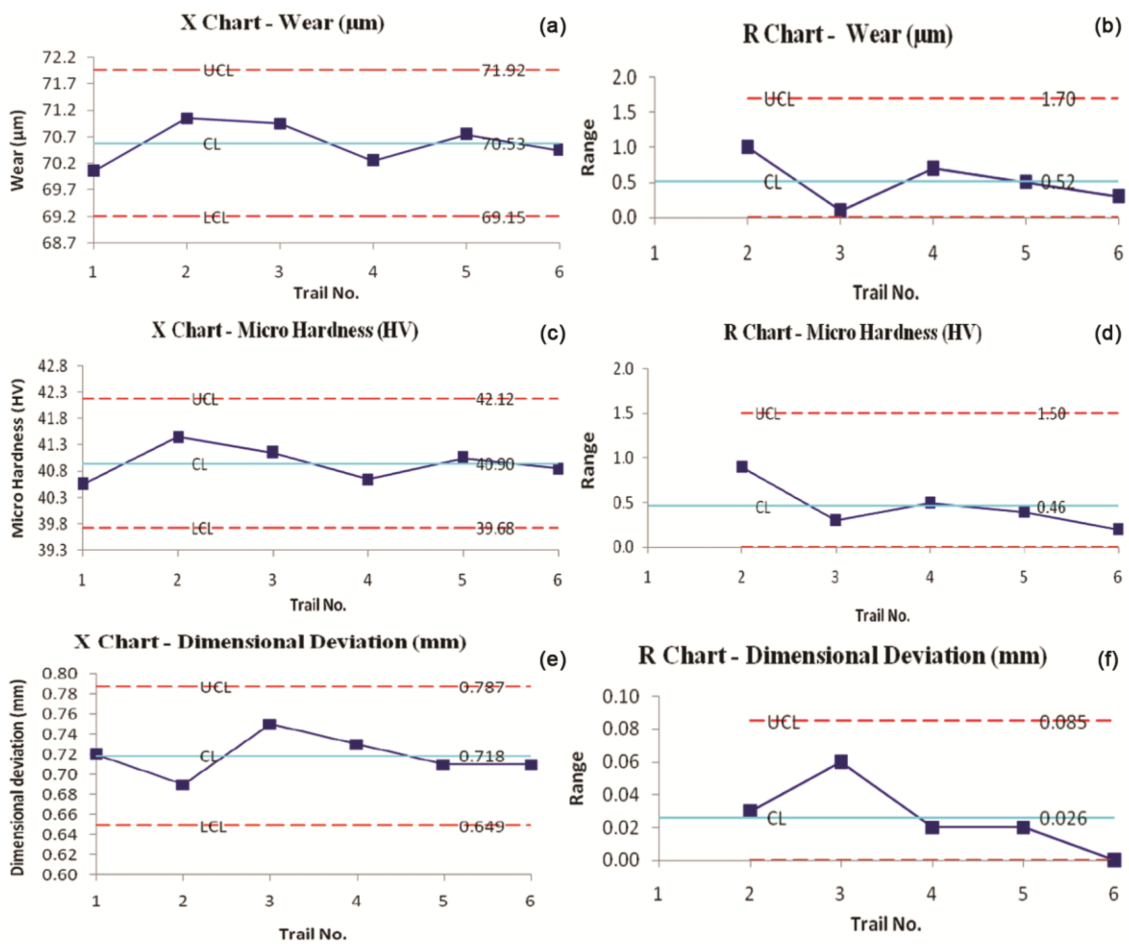

Fig. 11 — X Chart and R Chart ((a-b) for wear, (c-d) for micro hardness, (e-f) for Δt).

Table 9 — Results of the experiments conducted at optimum conditions.

Trail No.	Wear (µm)	Micro Hardness (HV)	Δt (mm)
1	70.0	40.5	0.72
2	71.0	41.4	0.69
3	70.9	41.1	0.75
4	70.2	40.6	0.73
5	70.7	41	0.71
6	70.4	40.8	0.71

4 Conclusions

As per S/N ratios of experimental observations of dry wear test, micro hardness and dimensional accuracy to achieve multi objective optimization for the development of hybrid AMC following conclusion may be drawn:

(i) The particle size (with 18.49% contribution) and type of reinforcement (with 42.13% contribution) have strong influence on multi objective/factor optimization for the development of hybrid AMC. The best parametric setting proposed for multi objective/factor optimization is: DPS, Al_2O_3+ SiC reinforcement, 350 mm of Hg VP, AFS No. 50 sand grain size, 4sec VT and 10% composition/proportion respectively.

(ii) The result of confirmatory experiments confirmed that the AMC developed at the optimal settings have an adequate micro hardness (41HV) with reasonable wear (70µm) and controlled Δt (0.71mm). Further based upon photomicrograph of confirmatory experiment 3D rendered image and Ra profile was captured, which clearly depicts the shape/size of cavity formed (as reinforcement) in Al matrix. Also it has been ascertained that AMC prepared have acceptable Ra for conventional manufacturing applications.

(iii) X-chart and R-chart for micro hardness, wear and Δt based upon the repeated runs at optimum parametric conditions confirmed that the process is controlled and can be employed in mass/ batch production.

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