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TECHNICAL PAPER

Some investigations on surface roughness of aluminium metal composite primed by fused deposition modeling-assisted investment casting using reinforced filament

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Abstract Fused deposition modeling-assisted investment casting (FDMAIC) has shown its capability to substantially shorten the product development time and cost. However, this additive technology suffers badly from poor surface finish of the patterns which affects the surface quality of cast specimens. The resulting casting often requires post-surface finishing operation before their service assignments, and is the major factor for increased production cost. In the present research work, surface roughness of aluminium matrix composites developed has been improved by introducing a pre-finishing stage, to fused deposition modeled pattern made of reinforced filament, as barrel finishing (BF) process. Six controllable process parameters of FDMAIC and BF, namely filament proportion, volume of cubical pattern, density of pattern, burnishing time, burnishing media weight and number of slurry layers were studied at 1^2 and 5^3 parametric levels using Taguchi L18 orthogonal array to find out their effect on surface roughness of casted aluminium matrix composites. It has been found that surface roughness of final castings was significantly improved by the introduction of BF in FDMAIC.

Keywords Surface roughness · Aluminium metal composite · Fused deposition modeling · Reinforced filament · Investment casting

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Abbreviations

AMC	Aluminium metal composite
BF	Barrel finishing
DOE	Design of experimentation
FDM	Fused deposition modeling
FDMAIC	Fused deposition modeling-assisted investment casting
IC	Investment casting
R_a	Surface roughness

1 Introduction

Aluminium matrix composites (AMCs) have proved their importance to conventional alloys with regard to high strength and stiffness in various industrial applications like space shuttles, launching vehicles, auto-mobile and mineral processing [1, 2]. A wide variety of AMC development techniques have been explored for including vapor state methods, liquid phase methods and solid state methods [3, 4]. In order to develop low cost and net-shape AMC, existing casting processes can be used due to their adaptability to flexibility [5, 6]. Among various casting techniques investment casting (IC) method, often known as precision casting process, is a valuable option as it has the capability of producing good surface finish, accurate and intricately detailed castings, poor machinability and workability of components [7]. In the past decade, researches have taken place to modify conventional IC process by hybridizing with rapid prototyping (RP) technique which effectively reduced the pattern development time and production cost. Fused deposition modeling (FDM) is one of the available RP techniques that works on layer manufacturing and builds three-dimensional parts by extruding plastic-based material (acrylonitrile–butadiene–styrene) on a platform

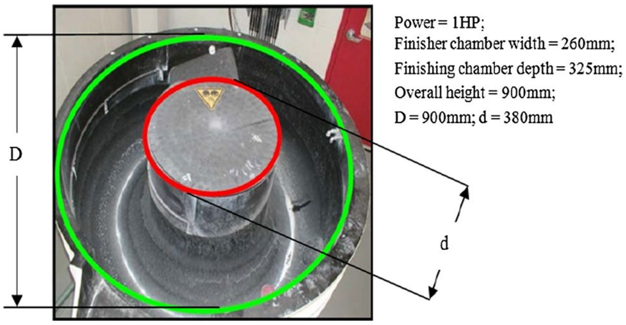


Fig. 1 Barrel finisher (TVBF-120 model) [17]

through computer aided design (CAD) [8, 9]. FDM can benefit IC process due to its advantages that include low maintenance costs, quick production of thin parts, clean burnout, robustness and part dimensional stability [10, 11].

Besides the various advantages of FDMAIC route hurdles like poor surface finish of FDM patterns may outweigh the advantages [12]. Generally, it is observed that the lesser the layer thickness of the part to be made the better the surface finish FDM machines produce, but surface finish is also affected by staircase effect, road width, air gap between roads and model temperature [13].

In literature, several researchers have proposed different methods to reduce the surface roughness (R_a) of the FDM parts of ABS. Most of the researches are based on optimization of FDM process parameters while other proposed a chemical treatment method [14, 15]. Nowadays, a barrel finishing (BF) is a new mass finishing operation used in additive manufacturing industries nowadays [16]. BF in typical setup (Fig. 1) consists of a container fluidizes a bed of granular media (pyramid, conical, cylindrical and spherical shapes) creating a circulating bulk flow to machine variety of sizes, shapes and materials batch to batch. The charge is composed of the components to be finished, media compound within a rotating barrel and process ranges from heavy de-burring to very fine finishing [17, 18].

Recently, an invention was made in a patent which suggested a hybrid route for developing metal matrix composite (MMC) by combining FDM (using reinforced filament) and IC [19]. According to this invention, when a reinforce (consisting of abrasive fillers) FDM pattern is used as master pattern in IC process, it will deposit its abrasive particles in the mould cavity when autoclaved and these particles will actively participate in the development of metal matrix composite with aluminium metal. The outer surface of AMC developed via this route will be harder with soft core inside and can be subsequently used for engineering services where a wear-resistive surface is required like in automotive and textile industries, etc.

The present research work is aimed at optimization of surface roughness of the AMC developed parts using

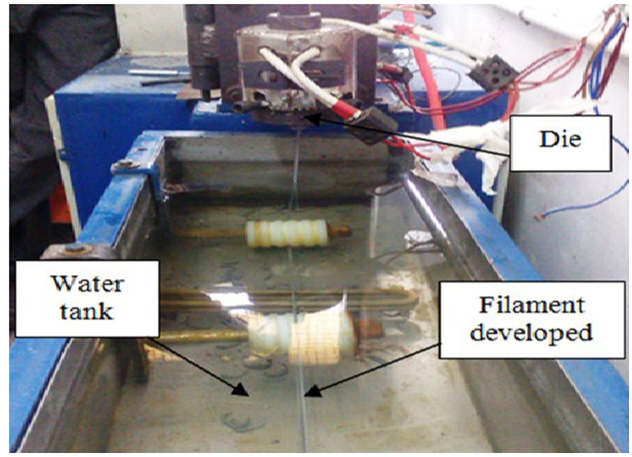


Fig. 2 Extrusion of wire from single screw extruder

above-defined route. BF, as an intermediate process to FDMAIC, has been used for surface roughness improvement and experimentation is designed using Taguchi L18 orthogonal array DOE is made on process parameters, namely filament proportion (A), volume of cubical pattern (B), density of pattern (C), burnishing time (D), burnishing media weight (E) and number of slurry layers (F). Pyramid-shaped burnishing media were used in BF process. Reinforced FDM filament of 60 % nylon6, 30 % Al, 10 % Al_2O_3 (C1) and 60 % nylon6, 28 % Al, 12 % Al_2O_3 (C2) proportions has been fabricated on single screw extruder whose melt flow index was tested as per ASTM-D-1238-95 standard and matched with manufacturer's patented material (acrylonitrile–butadiene–styrene). Cubical pattern with three different volumes and three densities were fabricated on FDM system using reinforced filaments (C1 and C2) and subjected to BF process prior to IC. The density of FDM-based pattern is an available option and can be effectively for different applications. Although change in FDM pattern density is insignificant for IC process (as it has to sacrifice for mould cavity at end) but in the present research work patterns were made under low density, high density and solid conditions as the weight of pattern changed with density. This means that patterns made under different conditions of density not only have different weights but proportions of Al_2O_3 too. Usually, it has been observed that weight of the cube with 0.7-in. side made at low density, high density and solid condition is 2.925, 4.377 and 5.257 gm, respectively.

2 Experimentation

At first stage of pilot experimentation, alternative reinforced FDM filaments were developed using single screw extruder (shown in Fig. 2). Melt flow index (MFI) of the

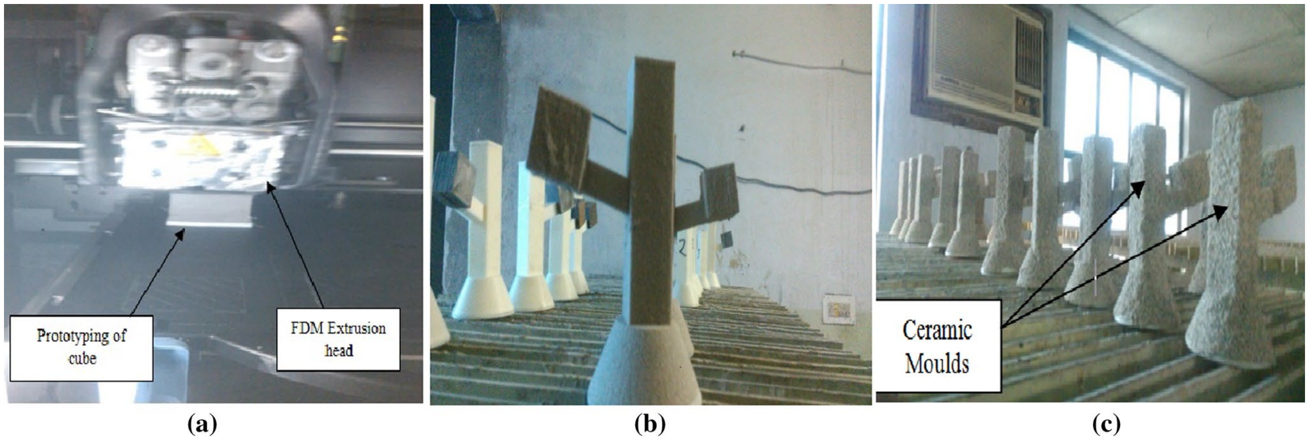


Fig. 3 Prototyping of cubical pattern (**a**); assembled casting tree (**b**) and ceramic moulds (**c**)

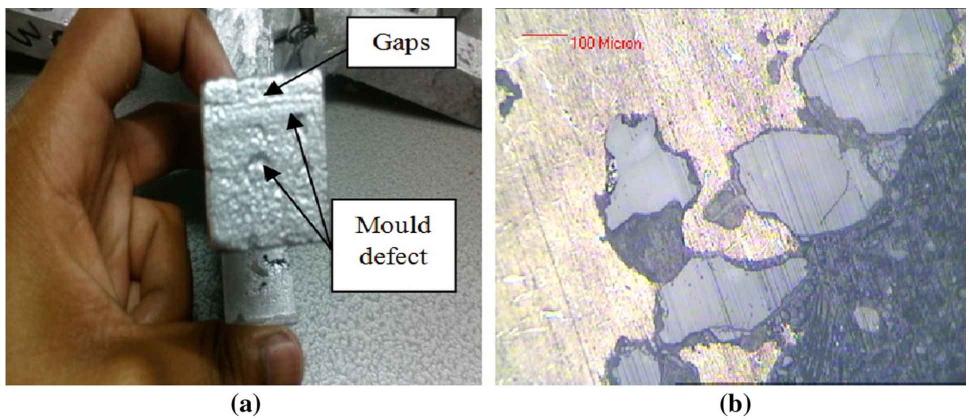


Fig. 4 Surface gaps in casting (**a**); micrograph of casted specimen at 100× (**b**)

proportions of filaments were matched with the manufacturer's acrylonitrile–butadiene–styrene (ABS). Two proportions (C1 and C2) were developed by varying proportions of Al (325 mesh) and Al_2O_3 (100–120 mesh) to 2 % as significant alteration causes an unmatched MFI of selected proportions and ABS. Each developed filament was then fired on existing FDM system (uPrintSE make: Stratasys Inc.) and cubical patterns were prototyped with 0.254-mm layer thickness (as shown in Fig. 3a). While gating, pouring cups and riser were fabricated using the manufacturer's ABS material and the complete assembly of all is shown in Fig. 3b. IC moulds were prepared once casting trees were ceramic coated (shown in Fig. 3c) and baking was performed at 1150 °C keeping the pouring cup up-straight in order to lock the abrasive Al_2O_3 particles in the mould cavity. Molten Al-6063 alloy is then poured into the resulting cavity and the finally casted AMC cube is shown Fig. 4a. Microstructural analysis made on casted specimen (refer Fig. 4b) indicated the non-uniform distribution of Al_2O_3 particles (geometrical shapes).

In the present research work, AMCs were developed through FDMAIC route without the introduction of BF and it has been found that R_a of AMC developed was significantly high indicating poor finish (refer Table 1). The main reason encountered was the use of alternative filament packed with abrasive Al_2O_3 particle that reduced the sticking ability of nylon6 during its layering while prototyping and resulted in micro-gaps between two adjacent layers. These pattern micro-gaps were filled by clay during IC ceramic coating and the negative shape was attainted by molten aluminium metal as shown in Fig. 4a. In the second stage of pilot experimentation BF process was introduced as an intermediate step in FDMAIC using wooden pyramid (rhomboid)-shaped burnishing media as shown in Fig. 5. It has been observed that besides the reduction of casting R_a layer gaps were also overcome. Figure 6 shows digital photograph (taken with 3264 × 2448 pixels, auto-focused camera) and roughness profiles for comparison of surface texture before and after BF of FDM patterns. As observed from Fig. 6, after BF operation the surface becomes more uniform in texture (having less waviness). Table 2 shows the BF process parameters studied in second stage of the pilot experimentation. It has been seen from Table 2 that introduction of BF in FDMAIC reduced the R_a of FDM

Table 1 R_a obtained at first stage of pilot experimentation

Exp. no.	A	B (mm^3)	C	R_a of FDM pattern (µm)	R_a of casted AMC (µm)
1	C1	26 × 26 × 26	Low density	6.44	5.65
2	C1	26 × 26 × 26	High density	8.38	7.09
3	C1	26 × 26 × 26	Solid	8.14	7.47
4	C1	30 × 30 × 30	Low density	7.62	5.97
5	C2	30 × 30 × 30	High density	8.21	6.03
6	C2	30 × 30 × 30	Solid	8.96	7.08
7	C2	34 × 34 × 34	Low density	7.47	5.14
8	C2	34 × 34 × 34	High density	7.12	6.31
9	C2	34 × 34 × 34	Solid	8.42	7.58

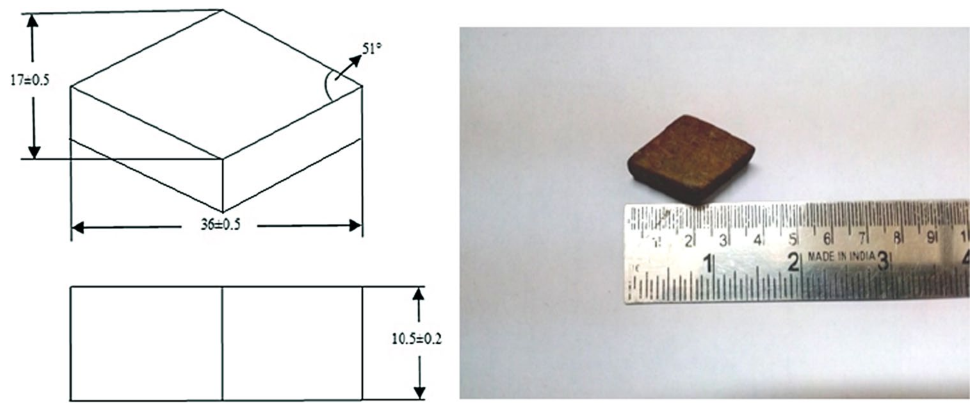


Fig. 5 Isometric view of pyramid-shaped burnishing media

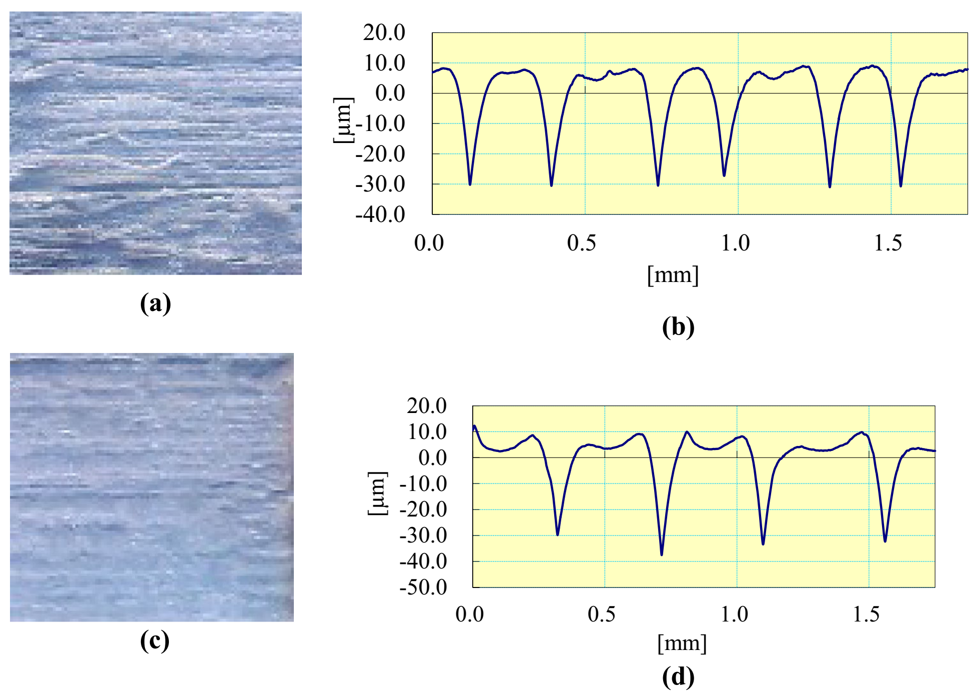


Fig. 6 Digital photograph of FDM pattern before BF (**a**); roughness profile FDM pattern before BF (**b**); digital photograph of FDM pattern after BF (**c**) and roughness profile of FDM pattern after BF (**d**)

patterns as well as casted AMCs. The BF process parameters (D and E) were selected judicially as because the FDM patterns are packed with brittle alumina particles, so increase in media weight (parameter E) and time for BF (Parameter D) may cause unnecessary erosion of the surface. This may lead to fracture of pattern surface too.

Table 2 R_a obtained at second stage of pilot experimentation

Exp. no.	A	B (mm^3)	C	D (min)	E (kg)	R_a of FDM pattern (μm)	R_a of BF pattern (μm)	R_a of casted AMC (μm)
1	C1	26 × 26 × 26	Low density	20	10	6.95	5.50	4.88
2	C1	26 × 26 × 26	High density	20	10	8.77	7.54	5.40
3	C1	26 × 26 × 26	Solid	20	10	8.13	7.53	5.63
4	C1	30 × 30 × 30	Low density	20	10	7.45	6.81	4.24
5	C2	30 × 30 × 30	High density	20	10	8.73	7.80	5.80
6	C2	30 × 30 × 30	Solid	20	10	8.94	7.54	6.01
7	C2	34 × 34 × 34	Low density	20	10	7.31	6.90	5.01
8	C2	34 × 34 × 34	High density	20	10	7.02	6.49	5.57
9	C2	34 × 34 × 34	Solid	20	10	8.63	7.27	6.29

Table 3 Input parameters, levels and control log of experimentation

Exp. no.	Parameter 1 A	Parameter 2 B (mm^3)	Parameter 3 C	Parameter 4 D (min)	Parameter 5 E (kg)	Parameter 6 F
1	C1	26 × 26 × 26	Low density	20	10	7
2	C1	26 × 26 × 26	High density	40	15	8
3	C1	26 × 26 × 26	Solid	60	20	9
4	C1	30 × 30 × 30	Low density	20	15	8
5	C1	30 × 30 × 30	High density	40	20	9
6	C1	30 × 30 × 30	Solid	60	10	7
7	C1	34 × 34 × 34	Low density	40	10	9
8	C1	34 × 34 × 34	High density	60	15	7
9	C1	34 × 34 × 34	Solid	20	20	8
10	C2	26 × 26 × 26	Low density	60	20	8
11	C2	26 × 26 × 26	High density	20	10	9
12	C2	26 × 26 × 26	Solid	40	15	7
13	C2	30 × 30 × 30	Low density	40	20	7
14	C2	30 × 30 × 30	High density	60	10	8
15	C2	30 × 30 × 30	Solid	20	15	9
16	C2	34 × 34 × 34	Low density	60	15	9
17	C2	34 × 34 × 34	High density	20	20	7
18	C2	34 × 34 × 34	Solid	40	10	8

2.1 Experimental procedure

To obtain maximum realistic information with the minimum number of well designed experiments and factors those affecting R_a of casted AMCs must be optimized using design of experiments (DoE). Taguchi L18 orthogonal array has been introduced to design the final control log of experimentation as shown in Table 3.

A total of 54 (18 × 3) experiments were conducted by repeating each experimental condition thrice to reduce the affect of errors indulged due to environmental, equipment and human variations.

3 Results and discussions

The surface roughness of casted AMC cubes has been measured using Mitutoyo-SJ-210 (ISO 1997) roughness tester at 0.5 mm/s stylus speed, cut-off length at 0.25 mm and X at 5. The results obtained by final experimentation have been optimized by using Taguchi L18 orthogonal array and signal-to-noise (S/N) ratio analysis has been conducted for best setup of process. Table 4 shows the comparison between the two-stage surface roughness, i.e., FDM prototyping stage, and BF stage. It has been seen that R_a of the FDM prototypes are significantly improved

Table 4 Comparison between R_a of FDM prototypes and BF patterns

Exp. no.	R_a of FDM pattern (μm)	R_a of BF pattern (μm)
1	7.52	7.50
2	7.98	7.54
3	7.76	7.53
4	7.37	6.81
5	7.33	6.80
6	7.40	6.94
7	7.52	7.50
8	7.78	7.19
9	7.77	7.17
10	7.69	6.99
11	7.02	6.91
12	7.68	6.62
13	7.70	7.01
14	7.82	7.12
15	7.52	7.26
16	8.91	8.70
17	7.09	6.43
18	6.92	6.62

Table 5 R_a of finally casted AMCs

Exp. no.	R_a (μm)			S/N value (db)
	R1	R2	R3	
1	4.78	4.78	4.71	−13.55
2	4.89	5.81	4.75	−14.2744
3	4.73	4.72	4.87	−13.5870
4	4.55	4.54	4.00	−12.8267
5	5.57	5.69	5.48	−14.9378
6	6.09	6.01	6.17	−15.6995
7	5.37	5.36	5.36	−14.5968
8	5.64	5.68	5.65	−15.0543
9	6.36	6.25	6.58	−16.1310
10	4.71	4.76	4.64	−13.4591
11	4.69	4.50	4.51	−13.2057
12	4.66	4.74	4.55	−13.3652
13	5.27	5.22	5.39	−14.4854
14	5.97	5.89	5.79	−15.4025
15	6.82	6.79	6.91	−16.7077
16	8.48	8.67	8.53	−18.6543
17	5.89	5.67	5.59	−15.1516
18	5.94	5.82	5.90	−15.4090

after BF which impacted the final stage casting roughness also. Finally, R_a of casted AMCs was optimized using MINITAB-16, S/N response has been analyzed to investigate the effect of selected FDMAIC and BF process parameters on R_a. The R_a values for finally casted AMCs (total 54 samples) and their S/N values are shown in Table 5.

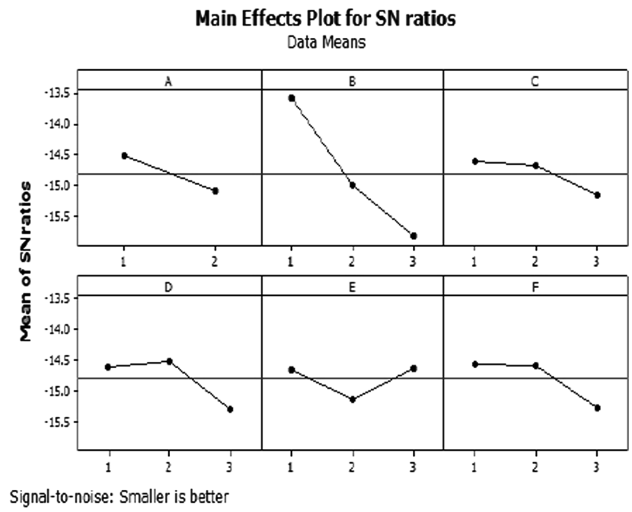


Fig. 7 S/N response to R_a data

The values of Table 5 and Fig. 7 show the S/N ratio plots obtained at smaller the better condition. Also, analysis of variance (refer Table 6) of S/N ratio for R_a has been performed at 95 % confidence level. As per Table 6, no input process parameter is significant for the obtained R_a value. In Table 7, two least contributing parameters (C and E as per Table 6) were pooled and it has been found that parameter B contributes significantly (Fisher value > 4.1028) for R_a value.

From Fig. 7, it has been seen that with parameter 'A' C1 R_a of AMC produced better surface finish as compared to 'C2'. This is due to the fact that abrasive contents (Al_2O_3) in 'C2' proportion are higher than C1 by 2 % resulting in rough internal surface of the mould cavity. In case of parameter 'B', it has been found that with an increase in the volume of the cube R_a of AMC was also increased. This is may be due to the staircase effect of FDM manufacturing in which prototyping is an approximation of the original model depending upon geometry and physical object [20]. Larger the volume of cube the more will be the impact of staircase effect and hence the higher roughness of the FDM parts.

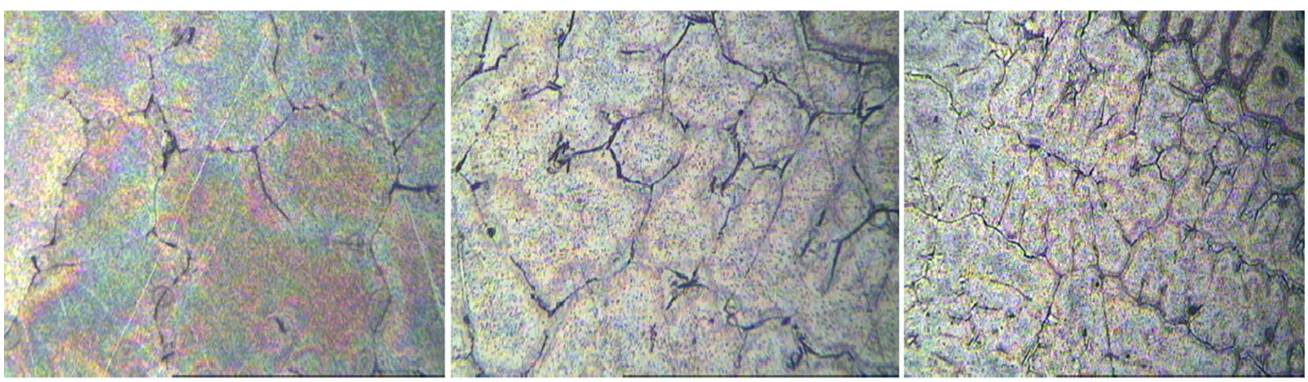
With regard to parameter 'C', it has been found from Table 6 that the percentage contribution of this parameter in R_a of AMC is only 3.03 % (refer Table 6). S/N response of density of cube to R_a of AMC (shown in Fig. 7) highlighting that when the density of the cube is changed from low to high, casting surface roughness decreased which is further increased when density changed from high to solid. It is very clear that under low-density condition FDM usually fabricates pattern with sparse packing which formed gaps between the layers on outer surface. R_a value of the casting decreased significantly at high-density condition as pattern packed denser than low-density condition.

Table 6 Analysis of variance for S/N ratio

Factor	DoF	Sum of square	Variance	Fisher's value	Contribution (%)	Significance at 95 % (Y/N)
A	1	0.6079	0.6079	0.56	2.99	N
B	2	8.1769	4.0885	3.73	40.28	N
C	2	0.2746	0.1373	0.13	1.352	N
D	2	3.1404	1.5702	1.43	15.47	N
E	2	0.5623	0.2812	0.26	2.769	N
F	2	0.9687	0.4843	0.44	4.7719	N
Error	6	6.5690	1.0948	–	–	–
Total	17	20.2999	–	–	–	–

Table 7 Analysis of variance for S/N ratio (after pooling)

Factor	DOF	Sum of square	Variance	Fisher's value	Significance at 95 % (Y/N)
A	1	0.6079	0.6079	0.82	N
B	2	8.1769	4.0885	5.52	Y
C					
D	2	3.1404	1.5702	2.12	N
E					
F	2	0.9687	0.4843	0.65	N
Error	10	7.4059	0.7406	–	–
Total	17	20.2999	–	–	–



(a) (b) (c)

Fig. 8 Microstructure of experiment with 7 (**a**), 8 (**b**) and 9 slurry layers (**c**) (at 100×)

When the density is further increased to solid condition R_a of casting increased as a fact of higher Al_2O_3 contents. As parameter 'D' is concerned, it has been found that an increase in time from 20 to 40 min increased the material removal rate as larger peak area is machined at the top of the profile without affecting the valleys. While further increase in BF time to 60 min is of no use as most of the peaks were smoothened in 40 min only. Over processing of FDM-reinforced pattern caused unnecessary erosion of material from the surface and formation of new peaks has taken place.

As regards parameter 'E', S/N ratio curve shows a decline in casting R_a when media weight was increased from 10 to 15 kg. It has been analyzed that at 10 kg media loading reinforced pattern is rolled six times per lap around the bowl channel while at 15 kg loading it is rolled five times per lap. Due to the reduction in roll time per lap reinforced pattern contacted less number of pyramid media machining edges. When media weight is further increased to 20 kg reinforced pattern rolling further decreased by one roll per lap, material removal rate may became higher due to media weight in terms of gravitational force participating actively in the machining action. Finally, parameter 'F' is found to contribute negligibly (2.94 %) in R_a of the casted AMC (see Table 6). S/N trends (Fig. 7) shows that with an increase in number of layers there is an increase in

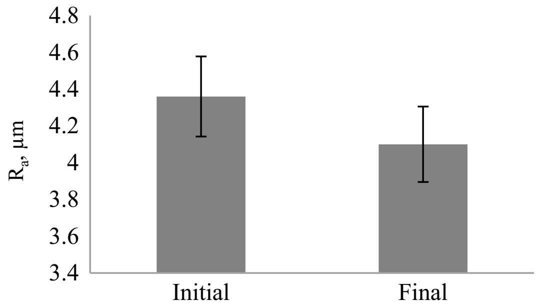


Fig. 9 Comparison of initial and final R_a

R_a of casting. This may be due to the fact that the more the heat transfer rate the smaller the grain size number. Small grain size number here means lesser number of grains per inch^2 as per ASTM-E112-10 standard [21]. The grain size per inch^2 has been calculated as per Eq. 1.

$$N_{\mathrm{AE}} = 2^{G-1}, \tag{1}$$

where 'N_{AE}' is the number of grains per inch^2 at 100× magnification and 'G' is the grain size number.

Microstructures of casted AMC with seven, eight and nine slurry layers has been analyzed at 100× (refer Fig. 8) and it was found that with seven slurry layer grains formed of ASTM grain size number is '3', with eight slurry layer ASTM grain size number is '5' and with nine slurry layer ASTM grain size number is '6.5'. It means that in case of nine slurry layers maximum number of grains were formed per inch^2 and as the stylus of surface roughness tester moved on surface more number of peaks and valleys were encountered due to closely packed grain boundaries, whereas it happened lesser in case of seven slurry layers.

Experiment has been performed at optimized setting and the result of final experiment indicated initial (least value from Table 5) and optimized values of R_a (see Fig. 9).

4 Conclusions

The R_a of casted AMC developed via FDMAIC route using reinforced filament has been successfully optimized by introducing an intermediate BF process through Taguchi L18 orthogonal array. Following are the conclusions of present study:

- It has been found that Al_2O_3 proportion in developed FDM filament has a linear relation with R_a of AMC. Filament 'C1' has proportions of 60 % nylon6, 30 % Al and 10 % Al_2O_3, whereas filament 'C2' has 60 % nylon6, 28 % Al and 12 % Al_2O_3. There is a marginal difference of 2 % of Al_2O_3 proportion between these two filaments that resulted in variation in the ceramic mould cavity surface roughness.
- With an increase in the volume of the cube there is an increase in the R_a value of AMC due to FDM staircase manufacturing. This is due to the fact that volume of geometry is in direct relation to FDM staircase effect, as shown in Fig. 7.
- When density of the cube is changed from low to high, casting roughness decreased and increased further when density changed from high to solid. At low-density condition FDM usually fabricates pattern with sparse packing which retained minor gaps between the layers on outer surface. R_a value of the casting decreased significantly at high-density condition due to denser packing. At solid condition R_a of casting increased as a fact of higher Al_2O_3 contents.
- With BF time increasing from 20 to 40 min, material removal rate is also increased due to longer machining exposure. While further increase in BF time to 60 min led to over processing of FDM-reinforced pattern which caused unnecessary erosion of material.
- There is a decline in casting R_a when media weight increased from 10 to 15 kg. It is found that at 10-kg media loading reinforced pattern rolled six times per lap around the bowl channel, while at 15-kg loading they rolled five times per lap. Due to reduction in roll per lap reinforced pattern contacted less number of pyramid media machining edges. But when media weight is further increased to 20 kg also roll per lap is further decreased by one; however, material removal rate became higher due to media weight in terms of gravitational force participated in machining action.
- From microstructure analysis of casted AMC it has been found that with seven slurry layer grains formed of ASTM grain size number is '3', with eight number of slurry layer ASTM grain size number is '4' and with nine number of slurry layer ASTM grain size number is '5.5'. Small grain size number means lesser number of grains per inch^2 and as the stylus of surface roughness tester moved on surface less number of peaks and valleys were encountered due to less number of grain boundaries in measurement area.
- As per the results of Taguchi DOE analysis, it has been found that R_a of casted AMC will be minimum when filament proportion 'C1' used to prototype $26 \times 26 \times 26$ mm^3 at high density is BF for 40 min at 20 kg load and IC mould is prepared using seven slurry layers. Confirmatory experiment at recommended parametric setting has been conducted and highlighted 5.9 % improvement in R_a at the proposed parametric settings.

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