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# Effect of process parameters on micro hardness of Al–$Al_2O_3$ composite prepared using an alternative reinforced pattern in fused deposition modelling assisted investment casting

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ABSTRACT

Aluminium matrix composites (AMCs) have numerous applications in manufacturing sector. In the present research work, fused deposition modelling (FDM) assisted investment casting (IC) route has been explored for the development of Al–$Al_2O_3$ based functionally graded material. Initially, two alternative FDM filaments consisting of nylon-6, Al and $Al_2O_3$ (in different proportions) were fabricated on single screw extruder. These filaments were further used to prepare reinforced FDM patterns (which were barrel finished) for IC process. Taguchi L18 orthogonal array has been used to study the effect of processing parameters (like: filament proportion, volume of reinforced FDM pattern, density of FDM pattern, barrel finishing time, barrel finishing media weight and numbers of IC slurry layer) on micro hardness ($M_H$) of Al–$Al_2O_3$ composites. Analysis of variance has been used to study the percentage contribution of input parameters and their significance effect on $M_H$. The results of the study highlighted that density of FDM pattern and numbers of IC slurry layer have contributed around 80% for $M_H$. Micro-structural analysis carried out on castings has justified the $M_H$ data.



## 1. Introduction

During the past two decades, there was a critical need of advanced engineering materials having reasonable mechanical and physical properties for the areas of aerospace, automobile, land vehicles etc. This was one of the major driving forces for the rapid development of composite materials [1,2]. Metal matrix composites, a category of composite material, is widely known for their superior mechanical, functional properties and their many applications in sporting goods, robot parts, electrical parts, aircraft, aerospace and brake discs/drums in railway vehicles [3–6]. Further, aluminium matrix composites (AMCs) have been proven useful for a variety of applications due to their superior strength-to-weight ratio. Aluminium oxide ($Al_2O_3$) is most commonly used reinforcement of AMC as it results into strongly bonded compounds [7,8]. There are excellent reviews of mechanical/metallurgical/tribological properties of Al/$Al_2O_3$ composites [9–11].

For the development of AMCs, various techniques are commercially available. These techniques can be classified as per the state of processing namely; liquid phase processes or castings, liquid–solid processes or semi-solid forming and solid-state processes or powder metallurgy [12–15]. Casting route is particularly attractive and the distribution of particulate over the liquid metal is quite uniform [16–18]. Among casting routes, fabrication of AMCs with investment casting (IC) process is beneficial due to its various benefits [19,20]. Further modification in conventional IC process can be made through the assistance of additive manufacturing (AM) techniques which will help to shorten the long lead time and high tooling cost associated with the fabrication of metal moulds for producing IC wax patterns [21–25].

Fused deposition modelling (FDM) is one of the most widely used AM technique which works on the principle of layer manufacturing (LM) [26]. The material after its extrusion from the head of the system is layered down on a fixtureless platform [27]. Acrylonitrile–Butadiene–Styrene (ABS), OEM material, is commonly used material. This material in the form of filament cartridge is unwounded and supplied to the extrusion head which extrude 0.254 mm thick layers [28]. In OEM's FDM system, various options (such as density of part, part orientation, road width etc.) are available [29]. Practically, it has been observed that the weight of 17.78 mm cubical pattern made of ABS at low density, high density and solid condition is 2.925, 4.377 and 5.257 g respectively. This means that altering the density of the parts can affect their

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**Nomenclature**

| | |
|---|---|
| IC | investment casting |
| AMC | aluminium matrix composite |
| FDM | fused deposition modelling |
| FDMAIC | fused deposition modelling assisted investment casting |
| $M_H$ | micro-hardness |
| $V_P$ | volume of reinforced FDM pattern |
| $F_P$ | filament proportion |
| $BF$ | barrel finishing |
| ABS | Acrylonitrile–Butadiene–Styrene |
| MFI | melt flow rate |
| OEM | original equipment manufacturer |
| $D_P$ | density of FDM pattern |
| $N_{SL}$ | numbers of IC slurry layer |
| $BF_T$ | barrel finishing time |
| $BF_W$ | barrel finishing media weight |
| Al | aluminium |
| $Al_2O_3$ | aluminium oxide |
| S/N ratio | signal/noise ratio |
| $F$-value | Fisher's value |

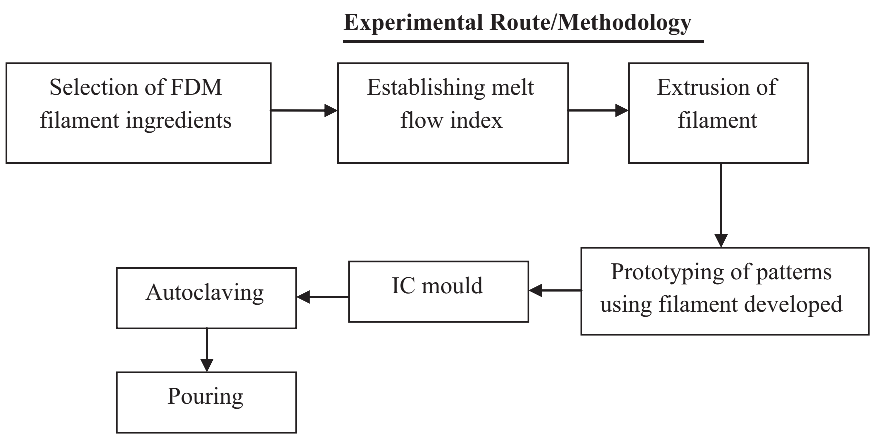


**Fig. 1.** Experimental route.

physical and mechanical properties. Various researchers, academicians, scientists have developed different types of alternative FDM filament materials from abrasives, ceramics, fibres, polymers etc. [30–36].

Recently, an invention was made in patent form which suggested a hybrid route (combination of existing methods) for developing AMC by using an alternative reinforced (consisting of abrasives) pattern in fused deposition modelling assisted investment casting (FDMAIC) process [37]. Accordingly, when a reinforced FDM pattern will be used as sacrificial pattern in IC, the abrasive particles (presented on outer surface of pattern) will stick to the walls of the mould cavity while the rest of particles will settle down in the cavity by gravity (during burn out of sacrificial pattern). The composite prepared with this methodology (refer Fig. 1) will offer better surface properties due to the presence of reinforcements at surface of the castings. A typical application of such composites may be as pick-holder (component of textile industry) which the researchers have developed through the combination of stir casting and IC [18]. Since, light weight and wear resistance of pick-holder are the two major requirements which can be achieved through this methodology. In present research work Barrel Finishing (BF) as an intermediate process to FDMAIC has been used for the improvement of surface finishing [38]. Various proportions of nylon-6, $Al_2O_3$ and Al were tested on melt flow indexer (MFIer) for obtaining the required melt flow rate (MFR) of alternative filaments which can be used in OEM's FDM system without making any change in the hardware/software of the system. Filament proportions 60%nylon-6+30%Al+10%$Al_2O_3$ ($C^1$) and 60%nylon-6+28%Al+12%$Al_2O_3$ ($C^2$) were finally selected and developed in the form of FDM filament on screw extruder. Levels of input process parameters; proportion in FDM filament ($F_P$), volume of reinforced FDM pattern ($V_P$), density of FDM pattern ($D_P$), barrel finishing ($BF_T$), barrel finishing media weight ($BF_W$) and numbers of IC slurry layers ($N_{SL}$) were fixed on the basis of pilot study. Taguchi L18 orthogonal array was used for the optimization of $M_H$ of Al/$Al_2O_3$ composites developed.

## 2. Experimentation

Alternative reinforced FDM filaments were fabricated on single screw extruder (shown in Fig. 2a). Commercial available $Al_2O_3$ powder of 100–170 μm size (supplied by Thomas Baker, Mumbai) as abrasive, Al of 44 μm size (supplied by Thomas Baker, Mumbai) and nylon-6 granules (Gujarat Fertilizers, India) as binder were used as filament ingredients. MFI of the proportion of filaments were matched with the OEM's ABS as per ASTM-D-1238 standard at 230 °C and 3.8 kg weight. It has been found that proportions $C^1$ and $C^2$ were having MFR of 2.410 and 2.408 g/600 s respectively which was within the acceptable range of OEM's ABS (2.411 g/600 s). The diameter of the alternative filaments is maintained within the range of 1.170–1.178 mm as per the OEM's FDM system requirements. Cubical patterns (shown in Fig. 2b and c) of volume 17,576 $mm^3$, 27,000$mm^3$ and 39,304 $mm^3$ were prepared with alternative reinforced filament at low density, high density and solid density. BF process was used for the improvement of surface finish of reinforced FDM pattern. The finishing operation was carried out at three loadings of pyramid shaped wooden media. The BF was used as an indirect approach for improving the finish of castings as machining of casting faces here may erode $Al_2O_3$ particles from the surface. IC moulds were prepared once casting trees were stucco (ceramic) coated (refer Fig. 2d). Burn out of the reinforced patterns was performed at 1150 °C keeping the pouring cup up-straight in-order to lock the $Al_2O_3$ particles inside the mould cavity. Molten Al-6063 matrix was then poured into the resulting cavity and the finally casted cube is shown in Fig. 2e.

Taguchi method, as being one of the optimization techniques, has been used to optimize input parameters without increasing