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Technical Paper

Development of functionally graded material by fused deposition modelling assisted investment casting

S. Singh [a], R. Singh [b,*]

[a] Punjab Technical University, Kapurthala 144601, India
[b] Production Engineering, GNDEC, Ludhiana 141006, India

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ABSTRACT

In order to attain sound geometrical details, excellent surface finish and required dimensional accuracy, investment casting (IC) process is one of the best options available commercially in the manufacturing sector. The IC process has got all the attentions for the development of metal matrix composites, as one is getting finished product for tailor made applications. In the present research work an attempt has been made for development of Al/Al_2O_3 composite as a functionally graded material (FGM) by using an alternative reinforced fused deposition modelling (FDM) pattern in IC process. The study is made with six controllable parameters (1^2 and 5^3 levels) to highlight their affect on wear resistance and micro-hardness of composite prepared. The X-ray diffraction analysis was performed to understand wear, micro-hardness of FGM and for establishing the novelty of proposed route.

1. Introduction

Casting industry being as a vital segment of manufacturing sector benefitted textile, paper, automobile, aerospace and sports industries by producing extremely intricate parts (having internal features and varying thickness), excellent surface finish and negligible metallurgical defects [1]. In early days, IC process was limited to a small and specialized sector of casting activity but soon it had attained a key position at the time of 2nd world war [2,3]. About 200 alloys are available with IC which are ranging from ferrous (stainless steel, tool steel, carbon steel and ductile iron) materials to non-ferrous (aluminium, copper and brass) materials.

Further, in the fabrication of metal matrix composites (MMCs) this process is particularly attractive when compared to other casting techniques [4,5]. Conventional IC process starts with a wax pattern coated with refractory material (silica) to make a mould and afterwards the wax is removed and molten metal is poured into the mould cavity [6]. Patterns made from expandable wax have limit properties and their applications suffered in precision casting when thin geometries of pattern break or deform during handled or stucco coating [7–10]. It has been reported that a cost for manufacturing wax injection machine and die machining is in thousands of dollars ($3000–$30,000) [11]. According to a report by Winker of Stratasys Inc., with the replacement of wax patterns by ABS patterns made using FDM system the tooling cost could be eliminated as well as the lead time for a cast part is slashed to 10 days on average which yields to save $30,000 and 2–4 weeks for a typical project [12].

The FDM technology established in the late 1980s dispenses two materials: one material to build the part/model and the other material for a disposable support structure [13]. To produce a part the filament is fed into a temperature-controlled extrusion head and heated to a semi-liquid state. The head extrudes and directs the material with precision in ultra thin layers onto a fixtureless base [14]. The result of the solidified material laminating to the preceding layer is a plastic 3D model built up one strand at a time.

The system operates in *X*, *Y* and *Z* axes, drawing the model one layer at a time [15]. The FDM process starts with importing a .STL file of a model into pre-processing software [16]. After reviewing the path data and generating the tool paths, the data is downloaded to the FDM machine. It has been found that the 'root mean square' value measured for the surface of prototyped part was greater than the expected average surface roughness [17]. So under normal manufacturing of prototypes on FDM system leads to poor surface texture being one of the serious problems as macro-texture of these patterns are easily transferred to the casted metallic parts. This will tend to increase the post machining expenses. However, various researchers have reported that building process parameters of FDM system has a major effect on the surface finish of the

* Corresponding author.
E-mail addresses: snprt.singh@gmail.com (S. Singh), rupindersingh78@yahoo.com (R. Singh).

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prototypes which could be optimized [18–20]. But these iterations are not available with all FDM model (such as uPrint-SE). For those machines which do not allows parametric optimizations, treatment of the FDM prototyped surfaces, either mechanically or chemically, are good options [21,22].

2. Literature review

Various researchers have carried out the researches on characterization of the mechanical, tribological as well as microstructural characterization of Al composites prepared using different commercial techniques [23,24]. It has been established in earlier researches that Al_2O_3 addition affected the hardness of composites and also resulted into increased level of the tensile strength, compression strength and flexural strength [25].

Resistance to wear of the composite samples prepared using stir casting increased with addition of the Al_2O_3 particle content. It has been found that the wear rate at 6 wt.% Al_2O_3 is only 1/10th of the wear rate for the pure matrix material [26]. Recently, researchers have developed Al micro and nano composites using stir and compo casting processes. It has been reported that method used for fabrication of composites had a significant effect on mechanical properties. Further it has been concluded in their research that the percentage of porosity and grain size in compo casting was lower than stir casting process [27].

In an another research, wear resistance of the composites was significantly larger than pure (unfilled/un-reinforced) aluminium alloy which increased by increasing Al_2O_3 particles content and size whereas decreased by increasing the sliding distance, wear load and abrasive grit size [28]. Zakaria has studied various Al/SiC composites with different volume fractions (up to 15 vol.%) and different SiC particulates (average sizes i.e. 11, 6 and 3 μm) were fabricated using conventional powder metallurgy route. Static immersion corrosion tests were performed in 3.5 wt.% NaCl aqueous solution at various temperatures. It has been found that the reduction in SiC particles size and/or increasing the vol.% fraction of the SiC particles reduced the corrosion rate of the Al/SiC composites [29]. Microstructural analysis has been carried out on Al/Al_2O_3 composite prepared by mechanical alloying. The results show that increase in the milling time caused to make fine alumina powders as well as uniform distribution within aluminium [30].

Goo et al. developed A356/SiC and A390/SiC composite with 30 μm and 60 μm SiC particles size of 20% volume fraction. It has been reported in their research that a temperature higher than Al melting point led to floating of SiC particles on its surface. SEM analysis has been carried out for the identification of the worn phases [31].

The literature review highlighted that lot of researches have been done in the field of characterization of various aspects of aluminium composites however a very little work has reposted the feasibility of alternative reinforced FDM pattern in IC process for the development of Al/Al_2O_3 composite as a FGM. Recently, an invention was made in patent form which highlighted a hybrid route for developing MMC through FDM-IC route using reinforced filament [32]. Accordingly, when FDM pattern (containing abrasive particles) will be used in IC process as master pattern in IC process it will deposit abrasive particles on the surface of mould as autoclaved. These particles will actively participate as reinforcement in matrix metal which will improve the mechanical properties of the finally prepared casting and could be categorized as functionally graded Al-casting (with enhanced mechanical properties). MMC developed through this route will have harder surface with soft core inside as reinforcements will be limited to the surface only. Taguchi L18 orthogonal array has been used as DOE to study the effect of processing parameters like; filament proportion (FP), volume of pattern (VP), density of pattern (DP), burnishing time (BFT), burnishing media weight (BFW) and number of slurry layers (NSL). Wear, micro-hardness and X-ray diffraction analysis was done to characterize the surface of Al/Al_2O_3 prepared. Schematic of work route of present research is shown in Fig. 1.

3. Experimentation

Experimentation in present research work has been divided into three main categories namely: preliminary, pilot and final as discussed below:

3.1. Preliminary experimentation

The very first step in preliminary experimentation phase was the selection of ingredient materials for filament proportion. Development of new FDM materials based on metals and other filler materials like: aluminium oxide, aluminium, iron, copper, silicon carbide, fibres and ceramics offers a challenging task because of the specific requirement of feed stock filament and the FDM system without making any hardware changes [33]. It has been investigated the thermal and mechanical properties of metal-particle filled ABS composites for FDM application [34]. A similar work was carried to develop metal/polymer composite material for FDM using iron particle in nylon matrix for rapid tooling application [35]. In present research work, nylon-6 (extrusion grade) in granular form whereas Al and Al_2O_3 in powder form was selected. Al (size ranging 120–150 μm) and Al_2O_3 (size ranging and 200–220 μm) were selected as lubricant and reinforcement respectively. As original equipment manufacturer (OEM) FDM machine was used without making any change in the hardware/software of the machine so it became necessary that the proportions of the filament selected must have flow behaviour similar to OEM material. Couple of test was conducted on filament proportion on melt flow tester as per ASTM recommended standard D-1238 (at 230 °C barrel temperature and 3.8 kg plunger force). It has been found that with 60% of nylon-6, 30% of Al and 10% of Al_2O_3 flow rate was 2.411 g/10 min (similar to OEM material). Then a little variation was made in the defined proportion keeping percentage of nylon-6 constant and decreasing Al proportion to 2% and increasing Al_2O_3 by 2%. Melt flow rate of the second proportion was found to lie within the acceptable range i.e. 2.335 g/10 min. The two defined proportions; 60%-nylon-6:30%-Al:10%Al_2O_3 (C1) and 60%-nylon-6:28%-Al:12%-Al_2O_3 (C2) were then fabricated on single screw extruder of L/D ratio 20. Diameter of the filament is one of the most critical parameter of OEM-FDM so efforts were made to maintain its diameter within 1.170–1.178 mm. Fig. 2 shows finally developed FDM reinforced filament.

3.2. Pilot experimentation

Filament C1 and C2 were then loaded on OEM-FDM machine and run for initial testing for material purge problem. Cubical geometrical shape of 27,000 mm^3 volume designed on CAD software package was converted into .STL file format and fired on the machine at low density condition as shown in Fig. 3. Basically, there are three options available on OEM-FDM machine for prototype density such as low density, high density and solid. It has been practically observed with OEM material that weight of cubical patterns of 0.343 in^3 prepared at low density, high density and solid condition were 2.925, 4.377 and 5.257 g respectively. So, in present work OEM-FDM density option found to have an effect on the Al_2O_3 contents in the prototyped pattern.

Reinforced pattern was attached with pouring cup; gate and runner fabricated using OEM material. Fig. 4 shows schematic of IC tree (a), assembled IC tree (b) and finally prepared IC ceramic mould