CHAPTER - 9
CONCLUSIONS AND SCOPE FOR FUTURE WORK

9.1 Conclusions

Based on the results of experimentations performed in the present research work, following conclusions may be drawn:

9.1.1 Feasibility Analysis of Developing Composites Using Reinforced FDM Pattern in IC Process

The significance of the present research work was to explore the feasibilities of the development of AMCs by using alternatively prepared reinforced filaments for the fabrication of sacrificial patterns of IC process on existing FDM system. The results of the study demonstrate the capabilities of the new route for AMCs development. Although the results of the present work are inferior comparative to the results reported by other researchers but the present methodology could be used for the development of functionally graded material (FGM) for better surface properties in-terms of hardness and wear. Followings are the major outcomes of the present research work:

1. Alternative FDM feedstock filaments of two different proportions of nylon-6, Al and Al₂O₃ have been successfully prepared by using single screw extruder.

2. The commercial FDM filament material has been replaced with the alternative in-house based reinforced filament without making any change in the software and the hardware of the FDM setup. It has been observed that melt flow index (MFI) played a very significant role for the proper selection of the filament ingredient proportions. Presently, the MFI of alternative filament proportions has been matched with the commercial material. It has been found that with an increase in the Al₂O₃ content (by %wt.) in nylon-6 the MFI of the mixture was reduced.

3. Extrusion of the selected proportions in FDM filaments form was carried out on single screw extruder operated at constant process parameters (such as: barrel temperature, screw speed and die temperature). However, the take up unit speed was selected judiciously during the extrusion for maintaining the diameter of the alternative FDM
filaments in range of 1.170-1.180mm (as per the requirements of the uPrint-FDM-SE system).

4. Further, the in-house based filaments were satisfactorily used in existing FDM system without making any change in the hardware and software of the system. Reinforced IC sacrificial patterns were fabricated with three different volumes (17576 mm$^3$, 27000 mm$^3$ and 39304 mm$^3$) at three available densities of FDM system (such as: low density, high density and solid density).

5. Presently, patterns fabricated on FDM system were used as the sacrificial pattern of IC and changing the density of these patterns doesn’t seem to be a good choice as input parameter. It has been found during experimentation that by changing the density of the FDM patterns from low to high and from high to solid have significantly affected the %wt. of Al$_2$O$_3$ particles in the patterns.

6. A little amount of residual ash has been found to be present inside the ceramic moulds after burnout of the plastic patterns and the amount of ash content increased as the density of the FDM patterns increased.

7. Microscopic analysis of the castings highlighted the presence of Al$_2$O$_3$ particles near the sample-Bakelite boundary. Most of the Al$_2$O$_3$ particles were presented on the outer surface of the castings hence the composites developed in the present research work offered better surface properties in-terms of hardness and wear. It has also found that maximum content of Al$_2$O$_3$ particles was gathered at the bottom most surface of the casting as during burnout of the ceramic mould most of the particles were fell down due to gravitational effect.

8. The results of the hardness and wear properties of the composites developed through the present methodology are inferior comparative to the other commercial route but the present methodology can be used for the development of components with tailor made properties i.e. harder outer surface and softer core. The present methodology can be adopted for the development of composites that can be used for numerous applications in the field of grinder wheel, brakes, textile industry, etc.
9.1.2. Analysis of Quality Characteristics of AMCs Developed Using Taguchi DOE Method

9.1.2.1 Surface Roughness

The surface roughness of the composite castings developed through present methodology has been successfully optimized through Taguchi L18 orthogonal array. Following are the conclusions for surface roughness:

1. The proportion of Al₂O₃ particles in alternative FDM filament has been found to possess a linear relation with the surface roughness of composite castings. By increasing the %wt. of Al₂O₃ particle in alternative FDM filament the resulting finish of the castings was poor. This was mainly due to the fact that the proportion of Al₂O₃ based abrasive particles in ‘C2’ type filament proportion was higher as compared to C1 type filament proportion by 2% which resulted into rough internal surface of mould cavity respectively.

2. In case of parameter ‘B’, it has been found that the surface roughness of the composite castings was increased by increasing the volume of FDM pattern. The main reason behind this trend was due to the existence of stair-case effect of AM. The slicing step in FDM prototyping is an approximation of the original model depending upon geometry and produces a physical object. Larger the volume of the cubical pattern more will be the impact of stair-case effect on the resulted part.

3. With regards to parameter ‘C’, it has been found from Fig. 5.2 that the percentage contribution of this parameter in surface roughness of castings was only 3.03%. The S/N response of this parameter highlighted that when the density of FDM pattern was increased from low to high the resulting surface roughness value decreased. However further increase in the density to solid resulted into an increase in the surface roughness value. Generally at low density option, FDM fabricates pattern with sparse packing which formed gaps between the layers on outer surface. Hence the surface roughness value of the castings was reduced at high density condition as the FDM based pattern were fabricated with dense packing respective to the low density condition. While the increase in the density to solid condition resulted into increase in the surface roughness of castings that may be due to the increase in the %wt. of Al₂O₃ particles.
4. In case of parameter ‘D’, when the BF time increased from 20 to 40min the material removal rate was increased due to longer machining exposure time. However, with the further increase in BF time to 60min resulted into the over processing of FDM reinforced pattern. The over processing of FDM reinforced pattern caused unnecessary erosion of material from the surface and formation of new peaks has taken place.

5. As parameter ‘E’ is concerned, the S/N ratio curve shows a decline in surface roughness of composite castings when the media weight increased from 10kg to 15kg. It has been observed that with 10kg media loading reinforced pattern was rolled six times per lap around the bowl channel while with 15kg loading the rolls/lap reduced to five. Due to the reduction in rolls/lap the reinforced pattern contacted less number of pyramid media machining edges. When media weight was further increased to 20kg reinforced pattern rolling further decreased by one roll/lap but material removal rate may became higher.

6. Parameter ‘F’ has negligible contribution (about 2.94%) in surface roughness of the composite castings. The S/N plot shows that with an increase in number of layers there was an increase in surface roughness the castings. Microstructure analysis of castings with 7, 8 and 9 number of layers resulted into 3, 5 and 6.5 grain size respectively. This means that in case of 9 number of slurry layers maximum numbers of grains were formed per inch\(^2\). So, during surface roughness measurement the stylus has moved over the more number of peaks and valleys in case 9 number of layers as compared to 7 number of slurry layers.

7. As per ANOVA, no input process parameter was found to be significant for surface roughness of the casted AMC. The optimized setting suggested by Taguchi L18 OA is: filament proportion - ‘C1’, volume of FDM pattern - 26×26×26 mm\(^3\), FDM part density - high, BF cycle time - 40min. BF media weight - 20kg and number of slurry layers - 7. Confirmatory experiment at recommended parametric setting has been conducted and highlighted 5.9% improvement in surface roughness at proposed parametric setting produced was 4.113\(\mu\)m.
9.1.2.2 Dimensional Accuracy

Dimensional accuracy of composite castings developed by using reinforced FDM based sacrificial pattern for IC process has been successfully optimized using Taguchi L18 OA. Following are the conclusions for dimensional accuracy:

1. It has been found in the pilot experimentation that in case of FDM patterns based on C2 proportion more amount of Al₂O₃ particles were presented in the resulting casting as compared to FDM patterns based on C1 proportion. Although in the present study, this parameter was found as in-significant in-terms of dimensional accuracy of the castings but it has affected the %wt. of Al₂O₃ particles in castings.

2. In case of parameter ‘B’, it has been found that by increasing the volume of the pattern from 26×26×26mm³ to 30×30×30mm³, deviation was increased. This may be due to the fact that by increasing the surface area of the cavity the casting will solidify rapidly due to which shrinkage might have occurred. Further, it was observed that in case of 30×30×30mm³ volume of the casting the riser solidified earlier than casting due to which liquid to semi-liquid stage and semi-liquid to semi-solid stage were not back supported. However with further increase in volume to 34×34×34mm³ the deviation of the castings was decreased due to solidification of the casting prior to the riser.

3. With regards to the parameter ‘C’, it has been found that the percentage contribution of this parameter in deviation was 19.61%. The S/N response highlighted that when the density of the cube was changed from low to high density, deviation was increased. However, further increase in the density to solid condition resulted into decrease in the deviation. The main reason behind the deviation can be due to the presence of residual ash particle which were formed a thin layer on the mould cavity and resulted into the castings with sown size. It has been found that in case of low density comparatively lesser amount of residual ash was formed as compared to high and solid density conditions. Further in case of solid density, it has been seen that the ash contents were spilled out of the cavity (as shown in Fig. 5.6) might be due to respectively higher evaporating pressure of nylon6.

4. As parameter ‘D’ is concerned, Fig. 5.4 highlighted that with an increase in the BF time, deviation of the composite castings was decreased. In case of parameter ‘E’, it was initially assumed that up to certain extent media load is directly proportional to material
removal rate. The same trend was indicated by S/N ratio (refer Fig. 5.4) as a decline in deviation when the media weight was increased from 10kg to 15kg. It has been observed that with 10kg, 15kg and 20kg media weight the FDM reinforced pattern rolled six, five and four rolls/lap respectively.

5. In case of parameter ‘F’, it has been found that the deviation in the composite castings was maximum with 7 number of IC layers. This may be due to the fact that lesser the mould wall thickness more will be the heat transfer from the cavity hence the casting will shrink. When the number of layers was increased from 7 to 8, deviation of the castings was reduced as obvious. However with further increasing the number of layers to 9, deviation was increased which might be due to the fact that the extremely slow cooling of metal in resulted into cut-off the feeding channels.

6. As per ANOVA, no input process parameter was found to be significant for dimensional accuracy of the composite castings. The optimized setting suggested by Taguchi L18 OA was: filament proportion - ‘C1’, volume of FDM pattern - 26x26x26 mm³, FDM part density - high, BF cycle time - 60min. BF media weight - 20kg and number of slurry layers - 8. Confirmatory experiment at recommended parametric setting has been conducted and highlighted 1.07% improvement in deviation at proposed parametric setting as the final deviation was 0.01583mm.

7. Composite castings developed in the present research work were found to be acceptable as per International tolerance grades as per UNI-EN- 20286-i (1995). The present study highlighted that the values of deviation are statistically approved as the $C_p$ and $C_{PK}$ values are more than 1. Hence the process can be used for commercial batch production activities.

9.1.2.3 Hardness

Hardness of composite castings developed by using reinforced FDM based sacrificial pattern for IC process has been successfully optimized using Taguchi L18 OA. Following are the conclusions for hardness:

1. In case of parameter ‘A’, it has been found that by increasing the %wt. of Al₂O₃ particles in filament proportion the comparative hardness of the resulting casting was more. This
was due to the fact that higher %wt. of Al₂O₃ in C₂ filament which offered better hardness value as compared to C₁ filament.

2. With regard to parameter ‘B’, it has been observed from S/N plot that by increasing the volume of the FDM pattern the resulting hardness of composite castings was reduced. This may be due to an increased volume of Al-matrix metal in the cavity resulting into lowering the hardness value at this level.

3. Further, in case of parameter ‘C’, maximum hardness of the composite castings was obtained at the 3rd level (i.e. as solid density) which decreased linearly the level decreased to 2nd and 1st respectively. One of the most obvious reasons behind this trend was the weight of Al₂O₃ particle that increased with the density of FDM pattern. So, in case of solid pattern maximum Al₂O₃ particle were presented in FDM patterns hence in the casted specimens.

4. From Table 5.10, it can be seen that the percentage contribution of parameter ‘D and ‘E’ was negligible i.e. 1.03% and 0.8% respectively. Finally, in case of parameter ‘F’, it has been found that maximum hardness was obtained at 1st level which decreased as the number to IC slurry layers increased. This may be due to fact that rate of heat transfer in IC process depends upon the mould wall thickness.

5. As per ANOVA, parameter ‘A’, ‘B’, ‘C’ and ‘F’ are found to be significant for hardness of the composite castings. The optimized setting suggested by Taguchi L18 OA was: filament proportion - ‘C₂’, volume of FDM pattern - 26×26×26 mm³, FDM part density - solid, BF cycle time - 60min. BF media weight - 20kg and number of slurry layers - 7.

6. A confirmation experiment was performed using the optimum setting of the control factors. It has been observed that the predicted and the experimental hardness results are very close to each other (with a marginal gap) confirming towards the obtained experimental results with optimum process parametric levels. Further the predicted hardness of the composite castings at optimal level was lying in between the extreme ranges at 95% confidence interval.

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9.1.2.4 Wear

Wear of composite castings developed by using reinforced FDM based sacrificial pattern for IC process has been successfully optimized using Taguchi L18 OA. Following are the conclusions for wear:

1. In case of parameter ‘A’, it has been found that by increasing the Al\(_2\)O\(_3\) weight content in the FDM filament proportion results into more wear resistance of composite castings. This was due to the fact that higher %wt. of the Al\(_2\)O\(_3\) in C2 filament offered better hardness value as compared to C1 filament.

2. For parameter ‘B’, it has been found that with an increase in the volume of the pattern to 34×34×34 mm\(^3\), the wear of the composite castings was higher. This may be due to the fact that as the volume of the pattern increased the respective cavity volume also increased. With this the volume of Al-matrix inside the cavity to be filled was also higher resulting into reduction of the respective content of Al\(_2\)O\(_3\) particles.

3. With regards to parameter ‘C’, it has been observed that the wear resistance of the composite castings was higher when solid pattern is used for the casting. One of the most obvious reasons behind this trend was due to the higher %wt. of Al\(_2\)O\(_3\) particles in the FDM pattern made at solid density.

4. In case of parameter ‘D’, ‘E’ and ‘F’, the S/N trends (Fig. 5.9) are almost linear for three individual levels and their respective contribution in wear was 0.40%, 0.080%, 0.11%.

5. As per ANOVA, parameter ‘B’ and ‘C’ are found to be significant for dimensional accuracy of the casted AMC. The optimized setting suggested by Taguchi L18 OA was: filament proportion - ‘C2’, volume of FDM pattern - 26×26×26 mm\(^3\), FDM part density - solid, BF cycle time - 60min. BF media weight - 15kg and number of slurry layers - 8.

6. A confirmation experiment was performed using the optimum setting of the control factors. It has been observed that the predicted and the experimental wear results are very close to each other (with a marginal gap) confirming towards the obtained experimental results with optimum process parametric levels. Further the predicted wear of the composite castings at optimal level was lying in between the extreme ranges at 95% confidence interval.
9.1.3 Characterization of castings

Characterization of casted AMC developed has been carried out using Optical Microscope, Scanning Electron Microscopy, Energy Dispersive Spectrometry and X-ray Diffraction Analysis. Following are the conclusions for characterization of AMCs:

1. Micro-structural results highlighted the presence of non-uniform distribution of Al$_2$O$_3$ particles in case of castings prepared with low and high density patterns while in case of solid density patterns the distribution of Al$_2$O$_3$ particles was quite uniform. This may be due to increase in the %wt. of Al$_2$O$_3$ particles in sacrificial IC patterns when fabricated at solid density.

2. It has been further observed that parameter: densities of FDM pattern have maximum affect on the %wt. distribution of Al$_2$O$_3$ particles in Al matrix while the other two parameters: filament proportion and volume of FDM pattern have also affected the same up-to some extent. However, rest of parameters namely: BF media weight, BF cycle time and number of IC slurry layers have not participated in the Al$_2$O$_3$ particle distribution trends.

3. SEM-EDS results justified the presence of geometrical shapes in the composite castings prepared. Further, EDS plots ensured the geometries, identified with SEM, as Al$_2$O$_3$ from the peaks of ‘Al’ and ‘O’ element. However, peak of ‘C’ was also highlighted by EDS in some castings may be due to the residuals ash of nylon-6 pattern material.

4. It has been observed from XRD plots that the intensity of peaks of Al$_2$O$_3$ phase depends upon FDM filament proportion and density of FDM patterns. Further in case of volume of FDM pattern established an inversely proportion relationship with the intensity of peaks of Al$_2$O$_3$ phase as observed in optical microscopic and SEM analysis.

9.1.4 Mathematical Modelling

Mathematical modelling for the prediction of the quality characteristics (such as: surface roughness, dimensional accuracy, surface hardness and wear) of the composite castings obtained through FDMAIC process has been carried out.
1. Mathematical modelling on the basis of Buckingham’ π based approach is very efficient technique for data interpretation obtained after conducting experiments as per Taguchi L18 OA. In present research work, Buckingham’s π-theorem was employed for the development of mathematical models of surface roughness, dimensional accuracy, surface hardness and castings obtained using FDMAIC process using reinforced pattern. Using obtained modelling equations, surface roughness, dimensional accuracy, surface hardness and wear the castings may be predicted without performing the expensive experimentations.

2. The obtained results of main experimentation and Taguchi DOE show that the selected control factors have unnoticeable effect on surface roughness and dimensional accuracy of the obtained castings. However modelling predicting surface roughness and dimensional accuracy are also developed in present work.

9.1.5 Concluding Remarks

Following are the concluding remarks of the present research work:

1. The investigated approach based on the use of reinforced FDM based pattern in IC process has justified the novelty for the development of AMCs. The feasibility of the process to produce composites having different process parameters has been demonstrated based on the quality characteristics such as: dimensional accuracy, surface roughness, hardness and wear.

2. Further, characterization of composite castings developed carried out using optical microscope, scanning electron microscope, EDS and XRD verified the presence of Al₂O₃ particles in Al matrix. This gives a valid proof for the improvement of casting properties such as hardness and wear.

9.2 SCOPE OF FUTURE WORK

1. Further studies may be focused on more types of filler, multiple filler filling and their level. Extrusion temperature affect may be explored in future works because of its importance in injection moulding applications.
2. The effect of pouring temperature and pouring speed on castings produced using investigated approach for different ferrous and non-ferrous materials may also be analysed in order to strengthen this approach.

3. The similar study may be performed by focusing on different end user applications in order to compare their functional ability and to gather more data base for development of FGM by this approach.

4. Investment casting process parameters such as: clay viscosity, costing drying temperature, coating drying time, autoclaving temperature and autoclaving time are important as regards to quality characteristics of casting and may be studied in future research work. Apart from this, work may be carried out to more appropriate casting tree design and autoclaving method in order to arrest abrasive particles inside the mould cavity.

5. The feasibility of present research route may also be investigated using newly developed FDM printers series of Fortus, Object and Dimension having large build area as compared to FDM uPrint-SE in order to produce large sized castings.

6. Waste thermoplastic materials may be used in future research work with an aim to development alternative FDM filament and to recycle hazardous waste significantly.