A GENETIC ALGORITHM WITH DESIGN OF EXPERIMENTS APPROACH TO PREDICT THE OPTIMAL PROCESS PARAMETERS FOR FDM

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Abstract

This paper describes a Genetic Algorithm (GA) with Design of Experiments (DoE) approach to predict the optimized surface roughness and porosity characteristics of the parts produced using ABS material on stratasys FDM 2000 machine. The Mathematical Model (MM) was developed by using Response Surface Methodology (RSM). It is to predict and investigate the influence of selected process parameters namely slice thickness, road width, liquefier temperature and air gap and their interactions on the surface roughness and porosity. The developed MM is the fitness function in GA in order to find out the optimal sets of process parameters and to predict the corresponding surface quality characteristics. These results have been validated and the experimental results after GA are found to be in conformance with the predicted process parameters.

Introduction

Rapid prototyping refers to a group of commercially available processes, which are used to create solid 3D parts from CAD, also known as Layered Manufacturing Techniques (LMT). Rapid Manufacturing uses LMTs for the direct manufacture of solid 3D products to be used by the end user either as parts of assemblies or as stand – alone products. They also discussed the advantages of applying rapid prototyping for direct manufacture in terms of various costs, lead times, freedom in product design and production design. Rapid manufacturing uses layer manufacturing techniques for the direct manufacture of solid 3D products to be used by the end user either as parts of assemblies or as stand alone products. Small parts with high geometric complexity to be made in relatively small volume are the most suitable candidates for rapid manufacturing (Neil Hopkinson and Phil Dickens 2001).

Rapid prototyping trends and developments

Rapid Prototyping and Manufacturing (RPM) is still in its infancy. The physical models made by most of these systems cannot be used as working parts, mostly due mostly to material and economic constraints. The major problems in the current RPM systems include: part accuracy, limited material variety and economical performance. In Stratasys Inc. conducted experimental research using various control parameters and materials on FDM systems. Data is presented to help the user to choose the appropriate material for specific applications. The in-depth research on FDM processes results in system refinements in accuracy, speed and surface finish (Xue Yan and Gu 1996).Anitha et al (2001) analyzed the effect of process variables such as layer thickness, road width and speed of deposition on the surface roughness of the components produced by the FDM process using Taguchi technique. They found that layer thickness is the most significant factor and other factors road width and speed of deposition also contribute to surface roughness.

Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problem in which a response of interest is influenced by several variables and the objective is to optimize this response. RSM allows for better understanding of relations between the inputs and the response. In the case of FDM process the inputs refer to slice thickness, road width, liquefier temperature and air gap and the responses are porosity and surface roughness. The relationship can be written in the form of a polynomial function describing a surface such as in equation (1). This equation has been used in this work to develop a second order response surface mathematical model.

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i + \sum_{i=1}^{k} \sum_{\substack{j=1 \\ i \neq j}}^{k} b_{ij} X_i X_j \qquad (1)$$

As RP is moving towards rapid manufacturing, there is an increasing demand on obtaining good surface quality parts (Pulak M. Pandey et al 2003). Richard H. Crawford (1993) discussed processing of geometric data, computer based analysis and design for SFF manufacturing. The discussion of geometric processing issues focuses on accuracy and completeness of the input models and the algorithms required to process such models.

Fused deposition modeling

The FDM method forms three-dimensional objects from computer generated solid or surface models like in a typical RP process. As the first step towards understanding the behavior of process parameters in RP-FDM 2000, to develop a mathematical model to determine the most influential parameters affecting porosity and surface roughness during fabrication of ABS polymer. Since the RP parts will be employed as functional products, modeling of their performance under various processing conditions becomes necessary. Experiments were conducted on Stratasys FDM2000 machine using specific combination of levels of significant process parameters. Required numbers of experiments have been conducted with desired process parameter settings. For the study of the surface roughness, the roughness average (Ra) was taken as a parameter and measured with Taylor Hobson surtronic 3+ surface roughness tester. The weight of the components was measured by electronic weighing machine and the porosity of the components fabricated is calculated.

Mathematical model for porosity

Mathematical model developed to predict the percentage of porosity had an adjusted R-squared value of 0.9694 and it is shown in equation (2)

$$\text{Porosity (\%)} = -5.85298 + 353.71408 \times A - 35.23580 \times B - 0.051890 \times C + 306.30239 \times D - 580.30875 \times A^2 + 31.66310 \times B^2 - 77.24794 \times A \times B - 304.96094 \times B \times D \qquad (2)$$

Where, A-Slice Thickness B- Road Width C-Liquefier Temperature D- Air Gap

From the analysis of variance the sum of squares and F-statistic suggest that road width is the most significant of the process parameters and also it is involved in interactions with slice thickness and air gap.

Response surface graphs for porosity

Effect of slice thickness and road width on porosity

Figure 1 shows the effect of slice thickness and road width on porosity at constant liquefier temperature and air gap. As seen from the surface plot, with increase in road width and decrease in slice thickness, porosity decreases. The porosity is found to be less for minimum slice thickness of 0.178 mm and higher road width of 0.8 mm.

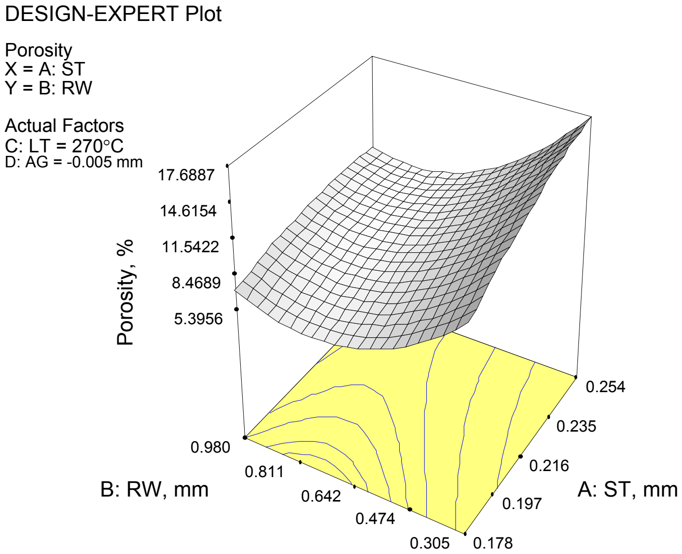

Figure 1 Effect of slice thickness and road width on porosity

Voids formed between two layers at the junction of the crosshatched areas will cause air entrapment, thereby increasing porosity. A lower value of slice thickness is chosen because it reduces these voids between two layers, thereby decreasing the porosity (Arumaikkannnu et al, 2004).

Effect of road width and air gap on porosity

Figure 2 shows response surface graph for effect of Road Width and Air Gap on Porosity at constant slice thickness and air gap. The minimum porosity occurs for this interaction at 0.8 mm road width and air gap of -0.01 mm. A larger road width decreases the air gap, covers up the sub perimeter voids, hence porosity decreases.

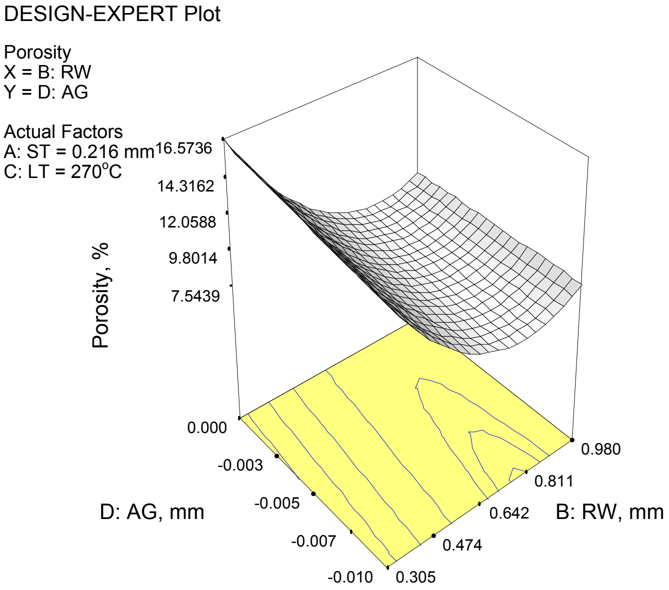

Figure 2 Effect of road width and air gap on porosity

Effect of liquefier temperature on porosity

The Porosity decreases linearly with increase in Liquefier Temperature. The porosity is larger when the model temperature is minimum. Liquefier temperature is the temperature at which the model material is melted. As the liquefier temperature increases, the fluidity increases, resulting in bulging and latter flattening of the road as it is being laid down (Bharath et al 2000). These make the material flow easy to occupy the unfilled spaces and hence decreasing the porosity. The minimum porosity occurs at a temperature of 290°C. Slower cooling of molten material and higher liquefier temperature promotes topside flattening because of the lower viscosity which enhances the flow process.The defect between adjacent roads occurs as a void or simply as a weak interface depends on the degree of bonding between adjacent roads. The bonding between adjacent roads depends on the temperature during the formation of the roads and on the lateral flow of material.

Mathematical model for surface roughness

$$\text{Surface Roughness (Ra), } \mu\text{m} = 1167.276 + 1347.281 \times A + 141.465 \times B - 9.933 \times C - 4649.567 \times D + 0.021 \times C^2 - 4.770 \times A \times C + 23512.090 \times A \times D - 0.493 \times B \times C - 989.508 \times B \times D \quad (3)$$

Where A – Slice Thickness B – Road Width C– Liquefier Temperature D – Air Gap

The simplified model representing the surface roughness Ra in µm, as seen in equation 3, had an adjusted R-squared value of 0.9425. The mathematical equation developed has shown that the surface finish is a parabolic function of the road width, slice thickness, air gap and liquefier temperature. From the analysis of variance the road width, liquefier temperature and slice thickness were found to be the most significant process parameters. The interactions between slice thickness and liquefier temperature and slice thickness and air gap influence more on the surface finish. In addition the interactions between road width with liquefier temperature and road width with air gap are also found to be significant for the same. Hence all the four process parameters have the influence on the surface quality of RP products.

Response surface graphs

Effect of slice thickness and liquefier temperature on surface roughness

Figure 3 shows response surface graph for the effect of slice thickness and liquefier temperature on surface roughness at constant road width and air gap. The temperature settings are set manually, and therefore, all build layer thickness must be fabricated at the same temperature configuration. Minimum surface roughness occurs at a liquefier temperature of 275°C and a slice thickness of 0.254 mm. The liquefier temperature which is the temperature at which the model material melts should be high enough so that the fluidity is more and therefore the melt can flow easily and fill up the voids. Also at higher temperature the road bulges leading to flattening of the top surface of the road. This leads to better surface finish. But a very high liquefier temperature (290°C) is not recommended because at higher temperatures the fluidity is excess which deteriorates the build especially on the top surface due and resulting in poor surface finish.

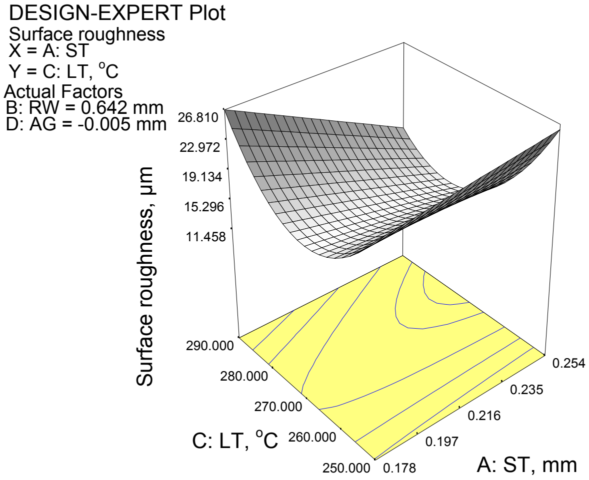

Figure 3 Effect of slice thickness and liquefier temperature on surface roughness

Effect of slice thickness and air gap on surface roughness

Figure 4 shows the response surface for effect of slice thickness and air gap on surface roughness. Here, the surface finish is found to improve at a higher slice thickness of 0.254 mm and minimum air gap of -0.01 mm. Even at zero air gap there will be physically some gap between adjacent roads which leads to poor surface finish due to unfilled space formed. More negative air gap ensures that there is no gap between adjacent roads which covers up the unfilled space and leads to better surface finish. Much better inter road bonding is obtained using a negative air gap setting which minimizes surface roughness and improves surface finish.

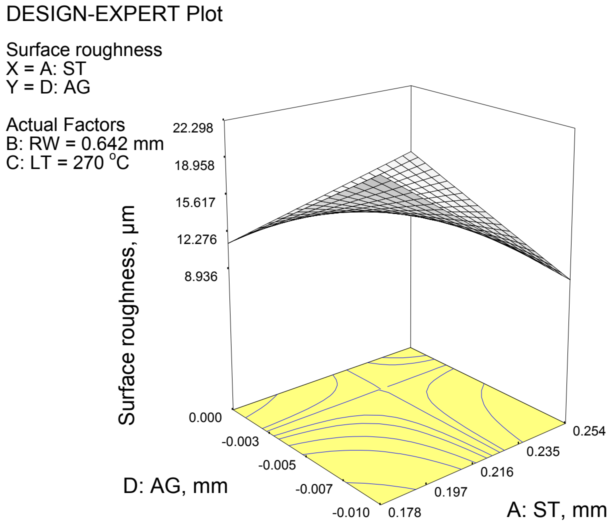

Figure 4 Effect of slice thickness and air gap on surface roughness

Effect of road width and model temperature on surface roughness

Figure 5 shows the response surface graph for effect of road width and liquefier temperature on surface roughness. Better surface finish is observed when a high liquefier temperature of 275°C and a minimum road width of 0.305 mm were set. At minimum road width, the adjacent road laid down will be very near to the previous one which leads to more uniform and more number of profiles resulting in minimum surface roughness. Also the higher melting temperatures make the road bulge because of decrease in viscosity and hence flow and flatten thereby resulting in better surface finish of the part produced (Berins, 1991).

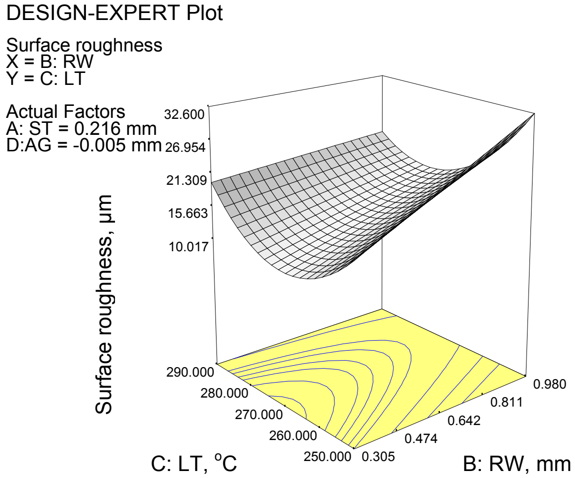

Figure 5 Effect of road width and liquefier temperature on surface roughness

Effect of road width and air gap on surface roughness

Figure 6 shows the influence of road width and air gap on surface finish. Better surface finish could be achieved at a more negative air gap of -0.01 mm and minimum road width of 0.305 mm. A negative air gap makes two roads overlap which fills inter road gap and also the peaks formed by the road widths will be nearer to each other which results in uniform surface finish. This conclusion is in agreement with that shown in Figure 5. Better surface finish could be obtained with higher slice thickness, minimum road width and air gap, and at temperature of 275°C.

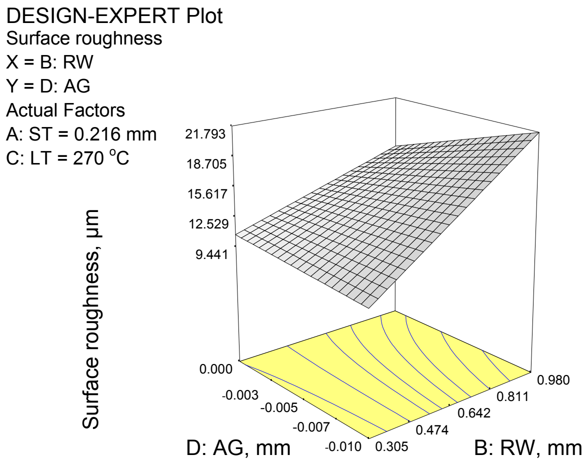

Figure 6 Effect of road width and air gap on surface roughness

Genetic algorithm

Many practical problems can be modeled as optimization problems. In order to solve these optimization problems, many methods have been developed. Inspired by the principles of biological evolution, many simulated evolutionary algorithms have been developed. Hence optimization of FDM process parameters has been taken into considerations in this research work and an efficient genetic algorithm has been used for optimization. The input process parameters are optimized using Real Coded Genetic Algorithm (GA) to obtain the required characteristics. For this problem a real-parameter GA with an efficient crossover operator known as the Simulated Binary Crossover (SBX) is employed. The real-parameter GA with SBX has self-adaptive properties, which have been shown to exist in evolution strategies and evolutionary programming. The population is a collection of chromosomes during any generation and the number of chromosomes in a population remains a constant. In this research work a chromosome represents the input process parameters namely slice thickness, road width, air gap and liquefier temperature. Each chromosome in the population consists of input process parameters with different combinations of respective values within their limits.

Chromosome representation

	ST	RW	AG	LT
Chromosome	.221 mm	.523 mm	-.05 mm	262° C

Table 1.0 Chromosome representation

The chromosome is a collection of four variables each representing the four input parameters. The variable takes up a random value between the ranges specified for each input parameter. Table 1.0 shows the representation of chromosome with values.

Evolution process

The selection mechanism works like the “guidance system” of the “evolution process” in GA as shown in Figure 7.0.

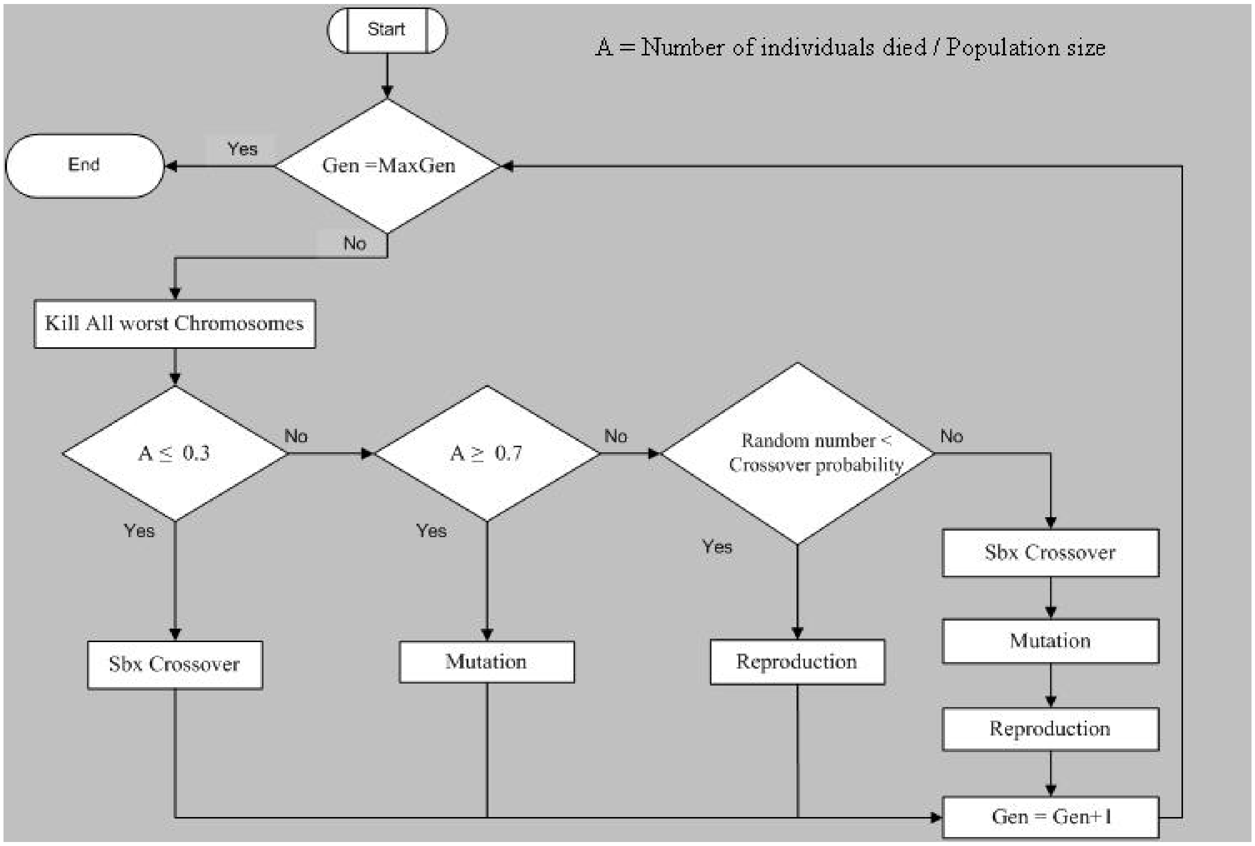

Figure 7 Evolution process

Due to the stochastic nature of responses, this operator may result in moving the search in a wrong direction if fitness values are obtained from one or few simulation replications. The genetic operators such as reproduction, crossover and mutation make the genetic search to search a wide state space. Before the selection of operator takes place the worst chromosomes in the population are removed and the dead chromosomes are replaced with the chromosomes produced by the selected genetic operator so that the size of the population is constant throughout the cycle. By maintaining the population size constant throughout the search space extends to a wide area. For example:

Population size = 200, Number of generation = 250,
The total no of chromosomes generated = 200 × 250 = 50000.

Genetic operators

The number of individuals dying during a generation is dependent on the closeness of individuals to the solution. The genetic operators used in this optimization are discussed below.

SBX (Simulated Binary Crossover) Crossover

The crossover operator is the main genetic operator. The crossover operator is used where there is a need for hybrid chromosome in the population. The hybrid chromosomes are needed at instances when most of the chromosomes in the population are closer to the solution. When the ratio of the number of died to the population size is lesser than 0.3 then SBX Crossover operator is chosen. The chromosomes needed for the crossover are chosen from the remaining 70 % of the population. The SBX crossover operator is μ, which is a random value selected between 0 and 1 during each cycle.

$$\begin{aligned} \text{Child1} &= \text{Parent1} \times \mu + \text{Parent2} \times (1-\mu) \\ \text{Child2} &= \text{Parent2} \times \mu + \text{Parent1} \times (1-\mu) \end{aligned}$$

The order allocation for Child1 and Child2 for a particular run is shown in Table 2.0.

ST	RW	AG	LT	Parent 1
.205 mm	.516 mm	-.01 mm	252 ° C	

ST	RW	AG	LT	Parent 2
.183 mm	.495 mm	-.05 mm	265 ° C	

Random value $\mu = 0.36$

ST	RW	AG	LT	Child 1
.191	.503 mm	-.036 mm	260 ° C	

ST	RW	AG	LT	Child 2
.197 mm	.508 mm	-.024 mm	256 ° C	

Table 2.0 SBX Crossover

The slice thickness for child 1 calculated as

$$\begin{aligned} ST_{\text{child 1}} &= ST_{\text{parent1}} \times \mu + ST_{\text{parent2}} \times (1-\mu) \\ \therefore ST_{\text{child 1}} &= .205 \times 0.36 + .183 \times (1-0.36) \\ ST_{\text{child 1}} &= .191 \text{ mm} \end{aligned}$$

Mutation operator

Mutation operator helps the genetic search to move in a random direction thereby eliminating the problem of being stuck in local minima. A simple way to achieve mutation would be to alter one or more genes. In genetic algorithms, mutation serves the crucial role of either (a) replacing the genes lost from the population during the selection process so that they can be tried in a new context or (b) providing the genes that were not present in the initial population. The optimal mutation rate used for this problem is 0.05. Table 3.0 shows the mutation operation on a chromosome, wherein the slice thickness value of the chromosome is randomly assigned a value within the limits.

ST	RW	AG	LT
.183 mm	.485 mm	-.006 mm	285 ° C

ST	RW	AG	LT
.196 mm	.485 mm	-.006 mm	285 ° C

Table 3.0 Mutation operation

A random chromosome is chosen and the input process parameter is also randomly chosen and its value is randomly assigned within its limits. Mutation operator is chosen when the number of died chromosomes to population size ratio exceeds 0.70. This occurs only when the population's average fitness drops to 60 %. To improve the average fitness of the population new domains in the state space must be analyzed. Hence the mutation operator is selected for inserting random chromosomes in the population.

Reproduction operator

The reproduction operator is applied to emphasize good solutions and eliminate bad solutions in a population, while keeping the population size constant. This is achieved by identifying good (usually above-average- 95 %) solutions in a population, making multiple copies of good solutions, and eliminating bad solutions from the population so that multiple copies of good solutions can be placed in the population. The commonly used reproduction operator is the proportionate reproduction operator where a chromosome is selected for the mating pool with a probability that is proportional to its fitness.

Fitness function

The MM developed using RSM is used as the fitness function for the GA. The input process parameter values in each chromosome are used in the fitness function and the fitness value for each chromosome is computed.

Surface roughness (Z) = $1167.276 + 1347.281 \times X_1 + 141.465 \times X_2 - 9.933 \times X_3 - 4649.567 \times X_4 + 0.021 \times X_3^2 - 4.770 \times X_1 \times X_3 + 23512.090 \times X_1 \times X_4 - 0.493 \times X_2 \times X_3 - 989.508 \times X_2 \times X_4$

$$\text{Porosity}(Y) = -5.85298 + 353.71408 \times X_1 - 35.23580 \times X_2 - 0.051890 \times X_3 + 306.30239 \times X_4 - 580.30875 \times X_1^2 + 31.66310 \times X_2^2 - 77.24794 \times X_1 \times X_2 - 304.96094 \times X_2 \times X_4$$

X1 – Slice thickness X2 – Road width X3 - Liquefier temperature X4 – Air gap

The GA parameters selected for this problem are

Population Size	400
Number of Generations	500
Crossover Probability	0.95
Mutation Probability	0.05
Crossover mechanism	SBX

GA results

The optimal input parameters for minimum porosity and surface roughness predicted using genetic algorithm with mathematical model as the fitness function is shown in table 4 and table 5.

Slice thickness	Road Width	Air Gap	Liquefier Temperature	Porosity
0.179 mm	0.734 mm	-0.01 mm	289.6 ° C	4.012 %

Table 4.0 Optimal input parameters for minimal porosity

Slice thickness	Road Width	Air Gap	Liquefier Temperature	Surface roughness
0.252 mm	0.316 mm	-0.01 mm	268.6 ° C	24.23 µm

Table 5.0 Optimal input parameters for minimum surface roughness

Validation

Experiments have been conducted using specific combination of values of process parameters obtained from Genetic algorithm on FDM 2000 machine. The responses such as surface roughness and porosity were measured and calculated. These values were compared with that of GA results and they were found to be within their accuracy limits as shown in table 6.

Response	Predicted(GA)	Experimental	Accuracy (%)
Porosity (%)	4.012	4.231	94.82
Surface Roughness (µm)	24.23	25.32	95.69

Table 6.0 Validation results for mathematical model

Conclusion

This work identified four important process parameters such as slice thickness, road width, liquefier temperature and air gap that had significant effect on porosity and surface roughness of the parts produced by FDM. It could be observed that surface roughness increased with increase in road width and air gap and decreased with increase in slice thickness.

The road width is found to be the most effective parameter affecting the surface quality and porosity of the part produced. Increase in road width and temperature reduces the porosity. The regression statistics proved that the mathematical models developed have a high precision. Hence, those models could be used to predict the surface quality in terms of porosity and surface roughness within the range of various significant process parameters with 95 % confidence level. The developed GA could be used to predict the optimal process (input) parameters as well as the output responses accurately.

References

[1] Anitha R., Arunachalam S. and Radhakrishnan P. (2001), ‘Critical parameters influencing the quality of prototypes in fused deposition modelling’, Journal of Materials Processing Technology, Vol.118, pp.385-388.

[2] Arumaikkannu G., Gowri S. and Muralikrishna S. (2004), ‘Modeling of RP-FDM using response surface methodology to predict the influence of process parameters on porosity’, Journal of Manufacturing Technology Today, Vol.3, No.3, pp.3-6.

[3] Berins (1991), ‘Plastics engineering hand book of the plastics industry’, Fifth edition, Chapman and Hall, New York, NY.

[4] Bharath Vasudevarao, Dharam Prakash Natarajan and Mark Henderson (2000), ‘Sensitivity of RP surface finish to process parameter variation’, in: Solid Freeform Fabrication Proceedings, pp. 251-258.

[5] Neil Hopkinson and Phil Dickens (2001), ‘Rapid prototyping for direct manufacture’, Rapid Prototyping Journal, Vol.7, No.4, pp.197-202

[6] Pulak M. Pandey, Venkata Reddy N. and Sanjay G. (2003), ‘Improvement of surface finish by stair case machining in fused deposition modeling’, Journal of Materials Processing Technology, Vol.132, issue 1-3, pp.323-331.

[7] Richard H. Crawford (1993), ‘Computer aspects of solid freeform fabrication: geometry, process control and design’, Proceedings of 4th Solid Freeform Fabrication Symposium, The University of Texas at Austin, Austin, TX, pp.102-112.

[8] Xue Yan and Gu P. (1996), ‘A review of rapid prototyping technologies and systems’, Computer-Aided Design, Vol.28, No.4, pp.307-318.