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Optimisation of subtractive rapid prototyping process parameters using response surface methodology

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Abstract. Subtractive rapid prototyping machine is the most suitable tool to manufacture a polymer based prosthetic part because it is able to achieve a low surface roughness value for a complex and customised part. Many investigations have been conducted to explain the relation among the surface roughness value, the material rate removal, and the subtractive rapid prototyping process parameters. It is important to find the optimum process parameters in order to achieve the most efficient and productive process. However, none of the research found in the literature optimises the subtractive rapid prototyping process parameters in fabricating polycarbonate part. Therefore, this research aims to find the optimum process parameters to achieve the lowest arithmetic average of surface roughness value of the polycarbonate part in maximum material removal rate. In this research, the response surface methodology is implemented to optimised feed rate, step-over, and depth of cut of the subtractive rapid prototyping process. This research finds the feed rate, step-over, and depth of cut values that can be used to achieve the best result in manufacturing of polycarbonate material.

1. Introduction

Polycarbonate material has been applied for various prosthetic products due to the fact that it is strong, tough, and transparent thermoplastic material. A prosthetic product is mostly an intricate product and customized for each patient. As a result, the feasible process to fabricate the product is by using rapid prototyping. Rapid prototyping process can be performed by using subtractive or additive methods. Subtractive rapid prototyping is carried out by implementing high speed milling process to cut the raw material in order to produce the part. Meanwhile, additive rapid prototyping carried out by depositing materials layer by layer to build the shape of the part. For a certain type of prosthetic parts such as a socket of prosthetic leg that require a specific surface roughness and dimensional accuracy, the subtractive rapid prototyping is preferable to be implemented. The main purpose of subtractive rapid prototyping is to achieve the required minimum surface roughness and dimensional error in the maximum material rate removal. Therefore, the optimisation of subtractive rapid prototyping process parameters in fabricating polycarbonate materials is considered as a significant problem and needs to be tackled. This paper only describes the optimisation of subtractive rapid prototyping processes to achieve the maximum material removal rate and the minimum surface roughness. The novelty of this research lies in optimising the subtractive rapid prototyping process parameters to achieve the

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maximum material removal rate and half of the arithmetic average of surface roughness value resulted by using additive rapid prototyping process.

2. Literature review

Limited research found in the literature discussed rapid prototyping process of polycarbonate. The possibility to fabricate a thin fin of polycarbonate material by using subtractive rapid prototyping is investigated by Nieminem, I., et. Al [1]. However, they did not investigate the influence of the depth of cut and step-over on the surface roughness and the dimensional error of the polycarbonate material.

Other researchers conduct an investigation on the influence of high speed milling process parameters on metal materials. The research by Albertí, M., et. al., Vivancos, J., Urbanski, J.P., Oktem, H., et al., The, J.S., et. al., Ma, W., et.al., Zeroudi, N. and Fontaine, M., and Shimana, K., et. al. show that material removal rate, surface roughness, and dimension error of a material are affected by physical and mechanical characteristics of the material, depth of cut, step-over, feed rate, cutting speed, cut type, interpolation type, tool holder type, physical and mechanical characteristics of the tool, vibration, controller of the machine, and computer aided manufacturing software [2, 3, 4, 5, 6, 7, 8, 9].

Suteja, T.J. develops several models to show the influence of the depth of cut, feed rate, and step-over on the vertical and horizontal surface roughness, vertical length error, horizontal length error, and depth error of polycarbonate material in subtractive rapid prototyping [10, 11]. The models show that the vertical surface roughness is positively affected by the feed rate, the step-over, and the depth of cut. The parameter that has the most influence on the vertical surface roughness is the step-over. In addition, the depth of cut and the interaction between the step-over and the depth of cut has a positive influence on the horizontal surface roughness.

The expected surface roughness values to optimize the process parameters are determined based on literature review. As the additive rapid prototyping can also be used to fabricate a product made of polycarbonate, then a review of previous research is conducted to investigate the achieved surface roughness of part fabricated by using an additive rapid prototyping.

Ippolito, R., et. al. compared five methods of additive rapid prototyping [12]. According to Ippolito, R., et. al., the achieved arithmetic average of surface roughness of additive rapid prototyping process is varied in the range between 0.001 to 0.025 mm. In addition, the parallel arithmetic average of surface roughness is lower than the perpendicular feed rate direction.

Fox, J.C., et. al., conduct experiments performed on Laser Powder Bed Fusion type of additive rapid prototyping with the EOS M2701 system using the commercially available Stainless Steel powder [13]. According to their research, the value of arithmetic average of surface roughness increases as overhang angle decreases. The minimum and maximum surface roughness values achieved by using the additive rapid prototyping process are 0.015 to 0.045 mm respectively.

The purpose of this research is particularly for investigating the subtractive rapid prototyping of a polycarbonate prosthetic product. He, Y., et al. implemented Scanning Printing Polishing Casting to fabricate a prosthetic product [14]. Based on their research, the fabrication method can achieve a low arithmetic average of surface roughness (maximum 0.002 mm) and require low cost. However, the method requires more complex process and longer time.

Udroiu, R., et. al., investigate the surface quality for a polymer-based additive rapid prototyping [15]. The additive rapid prototyping machine used is EDEN 350 using PolyJet technology. Based on the result, the arithmetic average of surface roughness values for the PolyJet material jetting process with matte finish were in the range of 0.0005 to 0.015 mm. For the glossy finish, the arithmetic average of surface roughness values in the range of 0.0005 to 0.010 mm. Though PolyJet technology can achieve lower surface roughness, the cost of the process is still high.

The widely used additive rapid prototyping technology is Fused Deposition Modelling because the cost of the technology decreases into feasible price. The research by Kaji, F., et. al. proposes a model of surface roughness in Fused Deposition Modelling especially for the geometry of the cusp profile [16]. The result of the research shows that the layer thickness generally has a deep effect on the surface roughness. The minimum surface roughness value, which is achieved by using 0.125 mm layer thickness, is 0.015 mm.

Based on the literature review, the aim of this research is to optimize the process parameters in subtractive rapid prototyping to achieve the half of the arithmetic average of surface roughness values of the Fused Deposition Modelling, which is maximum of 0.0075 mm (7.5 μm), in the maximum material rate removal of polycarbonate material.

3. Methodology

Response Surface Methodology is implemented in this research to develop several mathematical models and validate the models. The shape and the dimensions of the polycarbonate material specimen fabricated by using the subtractive rapid prototyping process are shown in Fig. 1. Roland MDX 40 is used as the subtractive rapid prototyping machine. The machine is assisted by CAM Modela Player 4.0 software to generate the tool path from the STL format model. A carbide solid square end mill with 5 mm diameter is used as the cutting tool. In order to move the cutting tool, the software uses zigzag cut type.

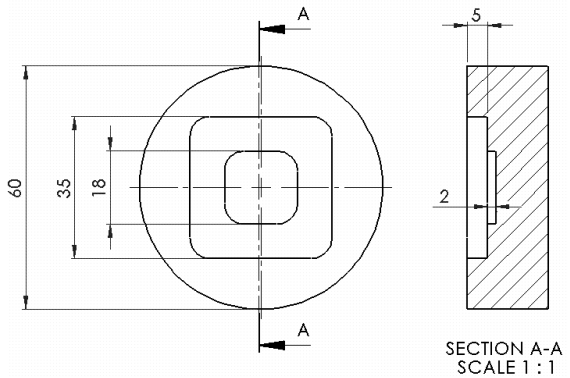

Figure 1. The specimen (in mm).

Different parameter values for roughing and finishing processes are determined based on the tools catalogue and interview with the expert. Table 1 shows the roughing parameter value of the subtractive rapid prototyping. Three levels of value for depth of cut, feed rate, and step-over are designed for finishing process. The value of each level for each parameter as shown in Table 2 is determined based on the machine specification, literature study, and the preliminary experiment. The subtractive rapid prototyping is performed under dry operating condition. The spindle for finishing process is 10000 rpm and the entry speed for finishing process is 4 mm/s. The polycarbonate material is assumed to be always homogeneous. Then, the cutting temperature is assumed to be always constant. Finally, the tool wear is assumed to occur after performing three roughing and finishing processes.

Table 1. Parameter value for roughing.

Feed Rate	: 12 mm/s
Entry Speed	: 4 mm/s
Spindle Speed	: 8500 rpm
Depth of Cut	: 0.37 mm
Step-over	: 1 mm

Table 2. Parameter value for finishing.

	Low	Middle	High
Depth of Cut [mm]	0.1	0.235	0.37
Feed Rate [mm/s]	12	14.5	17
Step-over [mm]	0.3	0.65	1

Material rate removal and arithmetic average of surface roughness are investigated in this research as the responses. To calculate the material rate removal, the time needed to fabricate the specimen is

measured by using a stopwatch. The arithmetic average of surface roughness is measured by using Mitutoyo SJ 210 with 0.01 μm of accuracy at Industrial Metrology Laboratory of University of Surabaya. Two direction of arithmetic average of surface roughness measurement is conducted, which are horizontal and vertical directions. After the measurement process, the measured data is analyzed by using MINITAB release 14 software.

4. Results and discussion

The design of the first order experiment are shown in Table 3. The first order experiment involves all two level factors using 2^3 factorial design with additional 5 center points. The result of the first order experiment is showed in Table 3. RaVer is vertical arithmetic average of surface roughness [μm], RaHor is horizontal arithmetic average of surface roughness [μm], and MRR is material rate removal [mm^3/s].

Table 3. First order experiment results.

Std Order	Run Order	Feed Rate [mm/s]	Step-over [mm]	Depth of Cut [mm]	RaHor [μm]	RaVer [μm]	MRR [mm^3/s]
11	1	14.50	0.65	0.235	3.13	7.25	1.221673
13	2	14.50	0.65	0.235	3.22	7.83	1.220947
2	3	17.00	0.30	0.100	2.53	4.46	0.266056
12	4	14.50	0.65	0.235	3.18	8.65	1.222763
7	5	12.00	1.00	0.370	4.88	12.39	2.607133
9	6	14.50	0.65	0.235	2.89	7.83	1.220637
3	7	12.00	1.00	0.100	3.64	12.01	0.704914
5	8	12.00	0.30	0.370	3.00	4.70	0.801036
10	9	14.50	0.65	0.235	3.55	8.33	1.217333
6	10	17.00	0.30	0.370	4.18	4.59	0.983487
1	11	12.00	0.30	0.100	2.81	3.60	0.215947
4	12	17.00	1.00	0.100	4.30	12.08	0.868179
8	13	17.00	1.00	0.370	4.49	12.01	3.213400

Based on the result of the validation step, the first order models are not adequate as a linear regression model. For that reason, the second order experiment for material removal rate, vertical arithmetic average of surface roughness, and horizontal arithmetic average of surface roughness must be conducted. The central composite design is used to determine the number of the second order experiment run. The design and result of the second order experiment is shown in Table 4.

By using the experiment result shown in Table 4, the prediction model of material removal rate, vertical arithmetic average of surface roughness, and horizontal arithmetic average of surface roughness are shown in Eq. 1, Eq. 2, and Eq. 3.

$$\begin{aligned} MRR = {} & 0.462 - 0.0260 \times F - 0.901 \times S - 2.833 \times D - 0.00067 \times F^2 - 0.162 \times S^2 - 0.345 \times D^2 \\ & + 0.0761 \times F \times S + 0.2129 \times F \times D + 7.804 \times S \times D \end{aligned} \quad (1)$$

$$\begin{aligned} Ra_{hor} = {} & 2.61 + 0.007 \times F - 0.41 \times S + 1.31 \times D + 0.0038 \times F^2 + 1.450 \times S^2 + 12.46 \times D^2 \\ & - 0.067 \times F \times S - 0.485 \times F \times D + 3.73 \times S \times D \end{aligned} \quad (2)$$

$$\begin{aligned} Ra_{ver} = {} & -8.9 + 0.88 \times F + 17.65 \times S + 6.4 \times D - 0.0146 \times F^2 + 3.34 \times S^2 + 13.9 \times D^2 \\ & - 0.521 \times F \times S - 0.59 \times F \times D - 4.10 \times S \times D \end{aligned} \quad (3)$$

where F is feed rate [mm/s], S is step-over [mm], and D is depth of cut [mm]. According to the result of the validation step for the second order experiment, the developed equations can be used as the best prediction model.

The aim of this research is to determine the feed rate, step over, and depth of cut in subtractive rapid prototyping to achieve the maximum material rate removal of polycarbonate material and the arithmetic average of surface roughness less than or equal to 7.5 μm. The multiple response optimizer based on desirability approach is used to maximize the material rate removal and minimize the horizontal and vertical arithmetic average of surface roughness [17]. The result shows that the optimum condition achieved when the feed rate, step-over, and depth of cut are set in 18.70 mm/s, 0.54 mm, and 0.46 mm respectively. The maximum material removal rate achieved by implementing these parameters is 2.3672 mm^3/s. The achieved horizontal and vertical arithmetic averages of surface roughness are 3.5842 μm and 7.4867 μm respectively.

Table 4. Second order experiment results.

Std Order	Run Order	Feed Rate [mm/s]	Step Over [mm]	Depth of Cut [mm]	RaHor [μm]	RaVer [μm]	MRR [mm^3/s]
18	1	14.5000	0.65000	0.235000	3.64	8.20	1.33510
19	2	14.5000	0.65000	0.235000	3.36	8.73	1.22121
10	3	18.7045	0.65000	0.235000	2.80	7.76	1.47727
15	4	14.5000	0.65000	0.235000	2.74	7.57	1.22204
20	5	14.5000	0.65000	0.235000	2.72	9.67	1.22152
13	6	14.5000	0.65000	0.007958	3.33	9.53	0.04138
14	7	14.5000	0.65000	0.462042	3.90	9.08	2.40249
5	8	12.0000	0.30000	0.370000	3.71	5.05	0.79896
11	9	14.5000	0.06137	0.235000	2.35	0.88	0.11581
8	10	17.0000	1.00000	0.370000	4.29	13.21	3.21431
6	11	17.0000	0.30000	0.370000	3.51	5.38	0.98372
2	12	17.0000	0.30000	0.100000	3.10	4.88	0.26597
9	13	10.2955	0.65000	0.235000	3.28	8.90	0.97840
7	14	12.0000	1.00000	0.370000	5.03	13.72	2.61059
12	15	14.5000	1.23863	0.235000	4.60	18.61	2.25131
4	16	17.0000	1.00000	0.100000	3.48	12.50	0.86892
3	17	12.0000	1.00000	0.100000	3,26	13,20	0.70532
16	18	14.5000	0.65000	0.235000	2,94	7,41	1.21149
1	19	12.0000	0.30000	0.100000	2,95	2,77	0.21595
17	20	14.5000	0.65000	0.235000	3,42	8,76	1.22183

5. Conclusions

The goal of this research is to optimize the subtractive rapid prototyping parameters for polycarbonate material by implementing the response surface methodology in order to achieve the maximum material rate removal of polycarbonate material and achieve the horizontal and vertical arithmetic average of surface roughness less than or equal to 7.5 μm at the same time. The optimized feed rate, step over, and depth of cut for the subtractive rapid prototyping are found to be 18.70 mm/s, 0.54 mm, and 0.46 mm respectively. By implementing these parameters, the achieved material removal rate is 2.3672 mm^3/s and the maximum achieved vertical arithmetic average of surface roughness is 7.4867 μm.

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Preface

Welcome Remarks,
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It is a great pleasure to welcome all of you to Bali and to the International Conference on Informatics, Technology, and Engineering 2019 (InCITE 2019) held by the Faculty of Engineering, University of Surabaya (UBAYA) in collaboration with The University of Adelaide, Australia and Sirindhorn International Institute of Technology (Thammasat University), Thailand. The first InCITE has been successfully held in Bali, Indonesia in 2017. We are very delighted to host the second InCITE here in Bali, Indonesia again.

There are more than 75 presentations in this conference. We welcome leading experts not only from Indonesia, but also from different parts of the world. The experts will share the knowledge and experiences in the fields of informatics, technology, science, and engineering. The main theme of this conference is **Enhancing Engineering Innovation Towards A Greener Future** in response to several world challenges including sustainable development, global convergence of information and communications technologies, climate change and global warming as well as the depletion of unrenewable natural resources. We hope this conference will provide you a good opportunity to get to know each other better and consolidate bonds of friendship and mutual trust.

We would like to express our sincere gratitude to the Keynote and Plenary speakers, International Scientific Committee, Steering Committee, and Organising Committee for their huge efforts to make this conference successful.

Thank you all for your support and attendance at InCITE 2019. Please enjoy the conference and Bali !

Asst. Prof. Djuwari, Ph.D.

Preface

Welcome Remarks,
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Welcome to Bali, Indonesia to all delegates and presenters. It is my pleasure and privilege to welcome all of you to the 2nd (second) International Conference on Informatics, Technology, and Engineering 2019 (InCITE 2019) held by the Faculty of Engineering, University of Surabaya (UBAYA) in collaboration with The University of Adelaide, Australia and Sirindhorn International Institute of Technology (Thammasat University), Thailand.

InCITE 2019 has received more than 75 papers to be presented in this conference. All papers represent four following parallel clusters: Green Design and Innovation, Green Manufacturing and Green Processes, Power System and Green Energy Management, and The Role of IT in Innovation Enhancement. Each cluster supports the main theme of the conference, which is **Enhancing Engineering Innovation Towards A Greener Future.** The engineering innovation is the key to increase our awareness in maintaining the sustainable growth and development in the world.

The Organising Committee of InCITE 2019 would like to express our sincere gratitude for the tremendous supports and contributions from many parties. The supports from The Faculty of Engineering of UBAYA, keynote and plenary speakers, our International Scientific Committee, the Steering and Organising Committees are really acknowledged.

The last but not the least, thank you for your supports, enjoy the conference and we hope through this meeting all of you can extend your networks and collaborations.

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