

THE EFFECT OF TEMPERATURE INCREASE, HOLDING TIME AND NUMBER OF LAYERS ON CERAMIC SHELLS USING THE INVESTMENT CASTING PROCESS

Tresna Priyana Soemardi¹, Agri Suwandi^{1,3*}, Gandjar Kiswanto¹, Widjajalaksmi Kusumaningsih²

¹*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*

²*Department of Medical Rehabilitation, Faculty of Medicine, Universitas Indonesia, Salemba Raya No. 6, Jakarta Pusat 10430, Indonesia*

³*Department of Mechanical Engineering, Faculty of Engineering, Universitas Pancasila, Srengseng Sawah, Jagakarsa, Jakarta 12640, Indonesia*

(Received: March 2016 / Revised: August 2016 / Accepted: September 2016)

ABSTRACT

This study aimed to determine the effect of using acrylonitrile butadiene styrene in place of conventional wax material on treatment pattern removal in the investment casting process. There are three controllable process variables that can affect treatment pattern removal, which include temperature increase, holding time and the number of layers of ceramic shell that have been considered for comparison. Comparison among the effects of temperature increase, holding time and numbers of ceramic shell layers on the ceramic shell was analyzed using ANOVA. It was found that temperature increase (T_x), holding time (t) and number of layers of ceramic shell (N) contribute significantly to the length of the crack (l) on the ceramic shell. The crack in the ceramic shell's surface was analyzed using scanning electron microscope photos. Less layers number cause the increase of crack length. The combination between temperature upraise and longer holding time cause cracking delay. The experimental is conducted by using 3 (three) variants for each of layers number, temperature and holding time. The layers number is ranging between 7-9 layers. Temperature increase from room temperature until 1300°C. The layers number variant is ranging between 180-300 seconds. It was concluded that a longer holding time will result in a more intact ceramic shell, as longer holding times yield short crack lengths.

Keywords: Acrylonitrile butadiene styrene; Ceramic shell; Holding time; Number of layers; Temperature increase

1. INTRODUCTION

The Investment Casting (IC) process is a method of producing high quality casting product. It is useful for generating complex geometry in casting products, which cannot be achieved through forging or machining processes, which involve excessive material usage (Jafari, et al., 2014). Currently, IC's pattern is made of wax and is coated with refractory material. Dewaxing process is applied before ceramic shell is inserted in to the oven. Afterward the casting process can be conducted. In the past, it was argued that once a foundry used a particular grade of pattern wax, the wax could not be replaced by another grade.

*Corresponding author's email: agrisuwandi@univpancasila.ac.id, Tel. +62-812 9683716
Permalink/DOI: <https://doi.org/10.14716/ijtech.v7i6.3354>

The advantages of IC include: (1) the ability to generate complex and intricate geometry of a casting product; (2) the ability to achieve dimensional control within ± 0.075 mm; (3) the ability to achieve low surface roughness; (4) the pattern wax material can be recycled for the next production; and (5) IC is a net shape process, which does not require additional machining processes (Groover, 2010). A disadvantage of IC is the high tooling cost in producing wax patterns (Singh & Singh, 2015). Therefore, IC is prohibited for low volume production such as prototyping, and customized or specialized component productions. Lead-time range of IC varies between several weeks to months depending on machine shop scheduling and capabilities. Therefore, the toolmaker has to evaluate different mold designs before committing to manufacturing, because design errors or iterations are expensive and time-consuming to amend (Sopcak, 1986). However, IC is still the preferable process for producing biomedical applications, especially for a prostheses component product (Suwandi et al., 2014).

IC is an easily applied precision manufacturing technology, yet in reality the process involves many steps to ensure optimum casting results (Kalpakjian & Schmid, 2008). There are seven steps in the existing IC: (1) wax pattern production; (2) pattern tree production by attaching several patterns to a sprue and coating of pattern tree with thin layers of refractory material; (4) mold production by covering the coated tree with sufficient refractory material in order to make it rigid; (5) mold reposition and preheated process in order to melt down the wax, so it will flow down to the cavity; (6) mold pre-heated process with high temperature; and (7) separation process between sprue and finished casting product. The pattern is used as the core of a mold to be used for casting.

In pattern production, Sopcak (Sopcak, 1986) stated that wax is most commonly used for a pattern because it is easy to deform, harden, and melt down at a low temperature. Despite the advantages of wax application, it also has deficiencies or material weaknesses. For example, wax application requires special equipment such as a wax injector to manufacture the pattern. Not only are wax injectors expensive, but they also require special care in their use and maintenance (Sopcak, 1986). Gebelin and Jolly (2003) and Sopcak (1986) explain that machine wax injectors require several factors for consideration prior to use including: (1) the flow of wax; (2) solidification time or cooling the wax; (3) shrinkage of wax; and (4) whether to heat the wax into the mold or from the mold into wax. All of these factors influence wax behavior and pattern quality. Moreover, Yarlaga and Hock (2003) explain that the wax injection process results in the decline of dimensional accuracy from about 0.2% to 0.4% as well as a low quality pattern and ceramic shell. Rather than using a wax injector machine, a mold can be made beforehand (Yarlaga & Hock, 2003). There are two material types that can be used to make a mold: polyurethane and silicone.

Foggia and D'Addona (2013) explain that the IC process is especially complicated at the time of pattern creation. There are three processes for producing patterns in IC, which include: (1) making a mold for wax; (2) performing the injection of wax into the mold wax with a wax injector engine; and (3) carrying out the assembly of the wax pattern with gating system parts as well as part of the core if used. In this study, the pattern will be made using rapid prototyping (RP) technology due to its accuracy, speed and ease of use (Chua et al., 2003; Cooper, 2001; Yongnian et al., 2009). The type of RP used in manufacturing the process pattern is Fused Deposition Modeling (FDM), which replaces the wax material with acrylonitrile butadiene styrene (ABS) material. With the use of FDM, pattern-making becomes easier and faster (Soemardi et al., 2016).

Many researchers have studied the correlation between temperature increase of pattern removal as well as holding time and the ceramic shell using wax material for the pattern. Gebelin and Jolly (2003) explained that the value length of cracks increased linearly as the temperature

increase of pattern removal, if the increases in value of the temperature suddenly. The research found cracking of the ceramic shell in thin layers of the ceramic wall (Wang et al., 2010) and short time of the holding time (Foggia & D'Addona, 2013). Moreover, Pattnaik et al. (2012) determined that thermal shock can cause the ceramic shell to crack.

While these studies have explained the influence of temperature on ceramic shell quality using wax pattern materials, few studies have examined the relationship between temperature increase and ceramic shell quality using an ABS pattern (Lee et al., 2004). This report presents a comprehensive study on ABS pattern removal and crack shape formation for three interval ranges of temperature increase with three levels of variation of holding time and number of layers of ceramic shell in the investment casting process. ANOVA statistical analysis was used to discover the relationship among temperature increase (T_x), holding time (t) and number of layers of ceramic shell (N). The crack formation was observed for each shape of the crack. The observation was performed by noticing its presence and by comparing crack lengths (l).

2. EXPERIMENTAL SETUP

This study constitutes part of a series of research studies regarding the process of making biomedical products, particularly knee joint prostheses. This research can determine the criteria for fast, easy precision in the manufacturing process, which can eventually result in the implementation of laboratory scale production (Suwandi et al., 2014). The research stages of this study were conducted to obtain the best method of pattern removal results with ABS material from the FDM process for the IC process. The pattern was produced on a Stratasys Uprint Plus FDM Machine in ABS-P430 material. Figure 1 shows the flow chart of the experiments that were performed by using multiple machines and tools in IC processing. The first step was implementation of the selected designs to create a pattern for the IC process. The main parameters that must be considered in an initial setup of FDM include: (1) resolution of the layers; (2) model interior; (3) support fill; (4) STL file unit; and (5) reference axis used for printing (Singh et al., 2016).

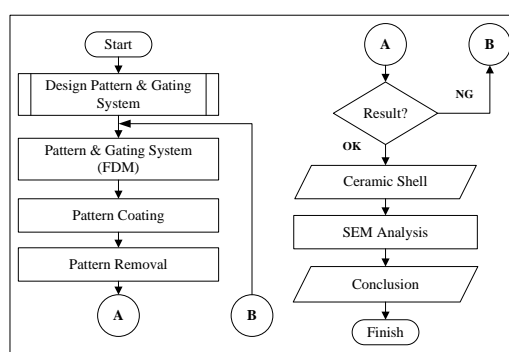


Figure 1 Flow chart of the experimental

The second step was to prepare equipment for the coating process in the manufacturing of a ceramic shell including weights, container and mixer. This was done in a two-stage process of making slurry as well as resurfacing the work pattern repeatedly to get the optimal ceramic shell. The ceramic material for casting mold as a coating pattern is divided into three types: (1) adhesive materials; (2) a filler; and (3) material of cement. The material forming the ceramic shell derives from a mixture of several materials. Liquid-based adhesive material, which is commonly called the slurry, consists of a mix of materials: zircon silicate flour, colloidal silica, Deep Foamer (DF) and Wetting Agent (WA). Solid-based coating material consists of multigrain zircon flour and flour with a big grains of different grades. Investment or ceramic coating on the pattern was conducted by dipping and then drying the mold (Pattnaik et al.,

2012). The most important consideration in this process is the viscosity and stickiness of the slurry, because the type of pattern material used in this study has a polymer that contains oil on its surface. Thus, the slurry should have a viscosity that is greater than wax coating material. To achieve this, the slurry must be made as an adhesive and the coating pattern must be made using several types of sand.

The third step is the pattern removal, patterns made previously were dried beforehand. At this step, the experiment is divided into three parameter variations: temperature increase, holding time (Feng et al., 2016) and number of layers of the ceramic shell. After the entire step was completed, the cracks and the structure of the resulting ceramic shell were observed and analyzed using a scanning electron microscope (SEM).

2.1. Pattern Making

Currently, the manufacturing of patterns mostly uses materials made of wax. Some disadvantages of these existing processes include requiring a mold and injector machine in the manufacture of patterns and the melting process pattern, which is separate from the process of hardening the shells of ceramic, which can result in a long process and high investment costs (Lee et al., 2004). The advantage of using an FDM process is that it can produce a more optimal pattern and can shorten the process of IC with a minimal investment cost.

The model used in this study is a component of the knee joint prostheses— the femoral and tibia stem (Figure 2). The time to make patterns of femoral is three hours, while the pattern components of the tibia take 47 minutes to produce. The use of the volume of the material used in the manufacture of patterns is “sparse-high density” for model interior style (Faes et al., 2016). The pattern uses a shell model, which allows for easy pattern removal in a short amount of time.

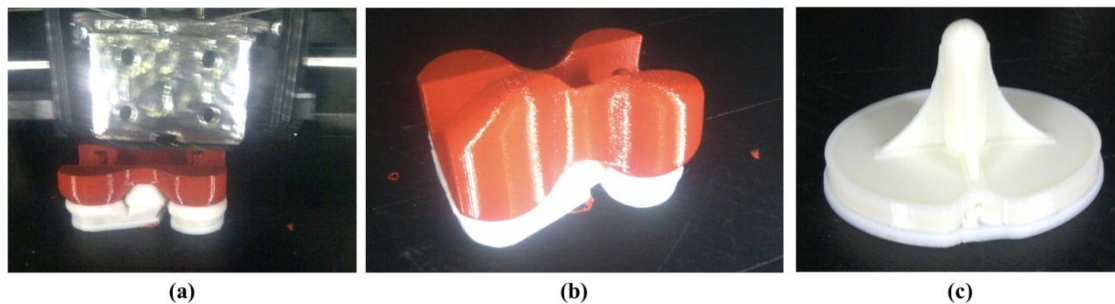


Figure 2 Pattern; (a) FDM process; (b) femoral; (c) tibia stem

2.2. Preparation of Ceramic Materials

To prepare ceramic materials, solid zircon silicate flour was mixed with a liquid colloidal silica composition in a ratio of 3:1 using a simple mixer. Furthermore, mixing the DF and WA alternately into the mixer containing material previously without dismissing mixed with 1% of the material composition of zircon silicate flour. The solution was stirred until the liquid had thickened and was then used as adhesives in the pattern. Slurry dries easily, and thus must be continuously stirred if it is to be used for any other pattern.

2.3. Ceramic Coating Process

Each step in the coating process requires ± 4 hours of drying time. The coating process is a covering process which is intended to make ceramic shell. The material to make the ceramic shell is consist of multigrain flour and multigrain. The multi flour has a function as foundation and the multigrain sand has a function as the next layers. The slurry is applied at the patter as a coating for the pattern together with the mutli grain. The application is started with slurry-multigrain flour-slurry-multigrain sand-slurry-multigrain sand. Multiple application is

conducted to form layers in the pattern. The cast was left to dry in the open air without exposure to direct sunlight.

2.4. Pattern Removal

Feng et al. (2016), explained that all polymer-based material has highly flammability properties including ABS material and heat may affect a polymer in two ways: (1) the polymer softens and melts eventually; the chains' kinetic energy exceeds intermolecular forces and the polymer becomes a highly viscous liquid mass but without any change in its chemical structure; and (2) chains break or changes in the chemical structure of chains occur. Many macromolecular substances degrade when heated and produce low-molecular weight products. Chains may continue to degrade from polymers down to monomers without any change in their chemical structure; this type of degradation is called depolymerization. The polymerization process is influenced by the type and melting temperature of the material. ABS has a melting temperature above 180°C (Feng et al., 2016), but in this study, the ABS-P430 material used had an unknown melting point (Stratasys, 2014).

In traditional investment casting, the pattern of the mold removal process ceramic by means of melt wax by heating is commonly called the dewaxing process (Sopcak, 1986; Pattnaik et al., 2012). The de-waxing process has been conventionally carried out using autoclave de-waxing, flash fire de-waxing, and more. In most investment casting industries, de-waxing is commonly carried out in industrial autoclaves in which the ceramic shell containing the wax patterns is placed. The ceramic shell is then melted under wet or warm conditions (high temperature and pressure). However, in this study, we replaced the wax pattern material with a pattern made of ABS material. Moreover, we used the burnout method of pattern removal, which involves using an oven to harden the ceramic shell or consolidation pattern. We then varied temperature, holding time and numbers of layers of the ceramic shell to examine the effects of these factors on crack formation.

3. RESULTS AND DISCUSSION

3.1. Length of the Crack

Length of crack is a measurement that can be used to analyze the quality of the ceramic shell in the investment casting process. Crack lengths were measured using two methods— calipers and SEM. To determine the relationship temperature increase (T_x), holding time (t) and numbers of layers of ceramic shell (N) on appearance of the crack, we used ANOVA statistical analysis (Table 1).

Table 1 Variable factor levels and length of crack

Holding Time, t (s)	Numbers of layers of ceramic shell, N (layers)								
	7			8			9		
	Temperature Increase, T_x (°C)			Temperature Increase, T_x (°C)			Temperature Increase, T_x (°C)		
	50	75	100	50	75	100	50	75	100
180	18	26	30	15	25	28	7	14	15
240	14	18	23	15	22	25	5	8	14
300	10	12	15	12	15	18	5	6	10

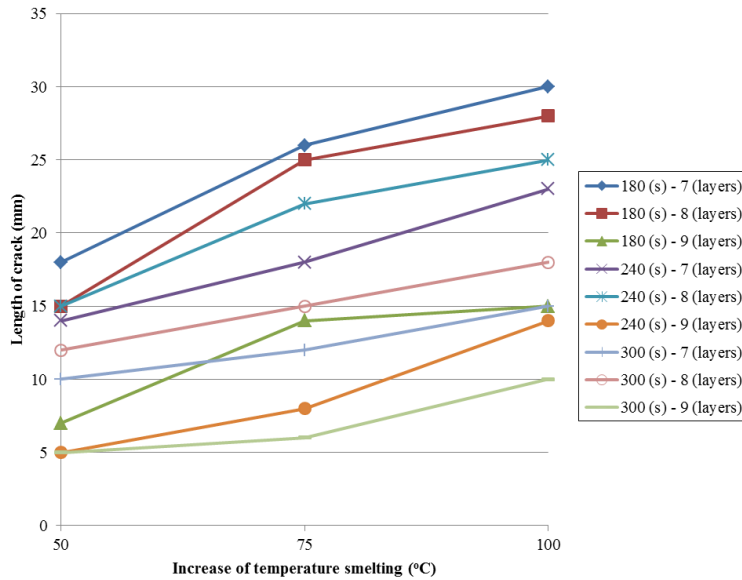


Figure 3 Comparison of length of the crack and number of layers of ceramic shell in three interval ranges of temperature smelting increases

Figure 3 shows the correlation between pattern removal parameters and length of the crack. The graph illustrates that length of the crack increases as the temperature increases. As selection number of ceramic shell layers increases, crack length decreases. Moreover, longer holding times are associated with shorter crack lengths.

Figure 4 shows the residual plots for the length of the cracks (*l*) calculated using statistical software. The simplest way to determine the most influential factors affecting length of the crack (*l*) is by obtaining the idea of the Main Effect Plot for length of the crack, as shown in Figure 4. The plot shows that good ceramic shell quality can be achieved by increasing holding time and decreasing temperature smelting.

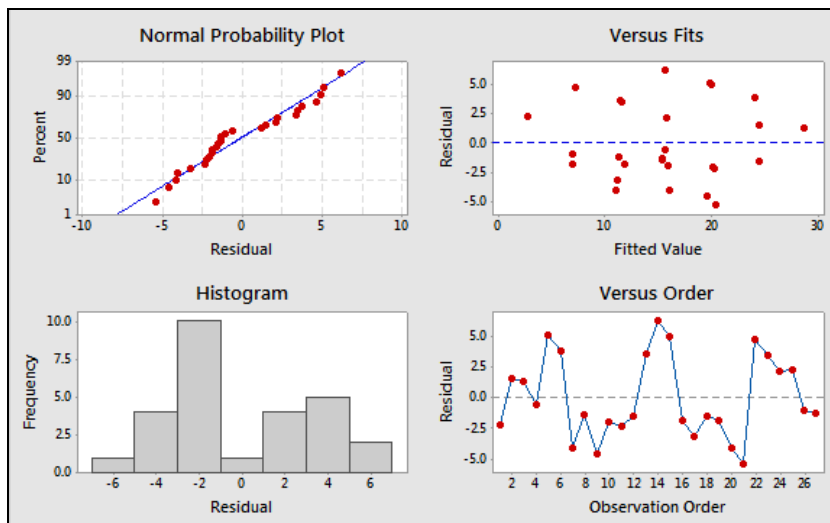


Figure 4 Residual Plots for length of the cracks (*l*)

General regression analysis was used to comprehend the relationship of increase of temperature smelting, holding time and numbers of ceramic shell layers with respect to length of cracks. The length of the crack data was calculated using statistical software. The observed value (*F*) of the

experiment was 26.87 while the critical value at significant level 0.05, taken from the Table of Percentage Points of F Distribution (Mountgomery, 2013), was $F_{0.05, 5, 21} = 2.68$. The critical value $F_{0.05, 5, 21} = 2.68$ is less than the observed value $F = 26.87$ while the P value from the data calculation was 0.000, which is less than the significant level of 0.05. Both the F and P values provide statistical support to reject the null hypothesis. This implies that at least one of the independent parameters of temperature increase (T_x), holding time (t) and numbers of layers of ceramic shell (N) contribute significantly to the quality of the ceramic shell.

3.2. The Crack Formation

In the pattern removal process, crack formation greatly affects ceramic shell quality, as the size of cracks can almost span the length of the small ceramic shell. By using SEM photos, it is clearly visible that cracks have formed on the ceramic shell surfaces.

In the experiment for the tibia steam model using the burnout method, the oven was heated to 100°C, and the ceramic shell was then placed in the oven. The ceramic shell was held for 180 s at a temperature of 50°C, and the temperature was then gradually increased in 50°C intervals. Each temperature interval was held for five minutes so that the temperature inside the mold would remain stable. Patterns began to burn at a temperature of 500°C. Figure 5a shows the cracks that appear when the temperature reaches 550°C, but the pattern has not been removed. Figure 5b represents a failing and the pattern has removed. Figure 5c demonstrates a good ceramic shell, as there are no cracks on the surface of ceramic shell and the pattern has been removed with only ash of the ABS pattern left behind.

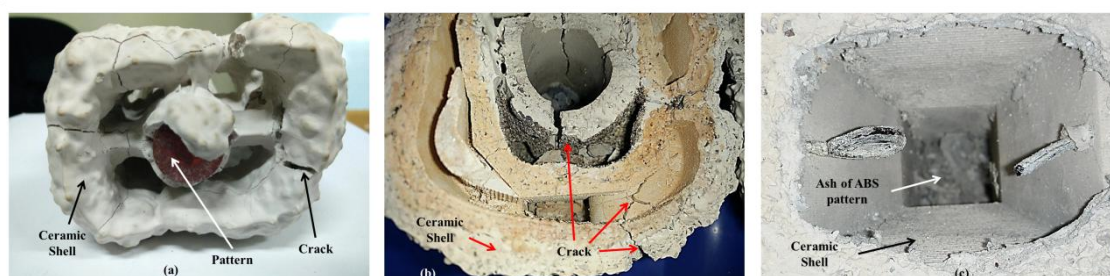


Figure 5 Result of ceramic shell: (a) cracks appear; (b) failed result; (c) good result

However, the ceramic shell was placed into the oven when the oven reached room temperature. Then, the oven was turned on until the temperature reached 75°C and a holding temperature of 75°C within 240 s of holding time. Patterns began to burn at a temperature of 500°C but cracks did not occur at a temperature of 500°C. However, the shell did begin to crack when the temperature reached 1300°C.

The SEM photographs shown in Figure 6 show cracks in the ceramic shell across 50°C temperature increases. Figure 6i demonstrates good results in comparisons to other figure, due to less appearance of crack in the surface. Figure 6i is a result of the combination between 300 s holding time and 9 layer. Figures 6a, 6b, and 6d show cracking on the surface with a length between 18-25 mm, due to the combination of shorter holding time and less layer. The cracking due to the combination of shorter holding time and less layer also appears in Figures 6c, 6e, 6f, 6g, 6h. A certain level of layers in ceramic thickness results in cracks that can lead to rupture of the entire ceramic shell which cannot be used, as evidenced in Figure 6b. Another factor that can lead to cracking of the ceramic shell is the thickness of the plastic-based material used to make the pattern—in this case, ABS. Upon increases in heat, certain plastic-based materials can result in deformation of the existing dimensions of the ceramic shell. In this study, such factors are not considered, but should be explored in future work.

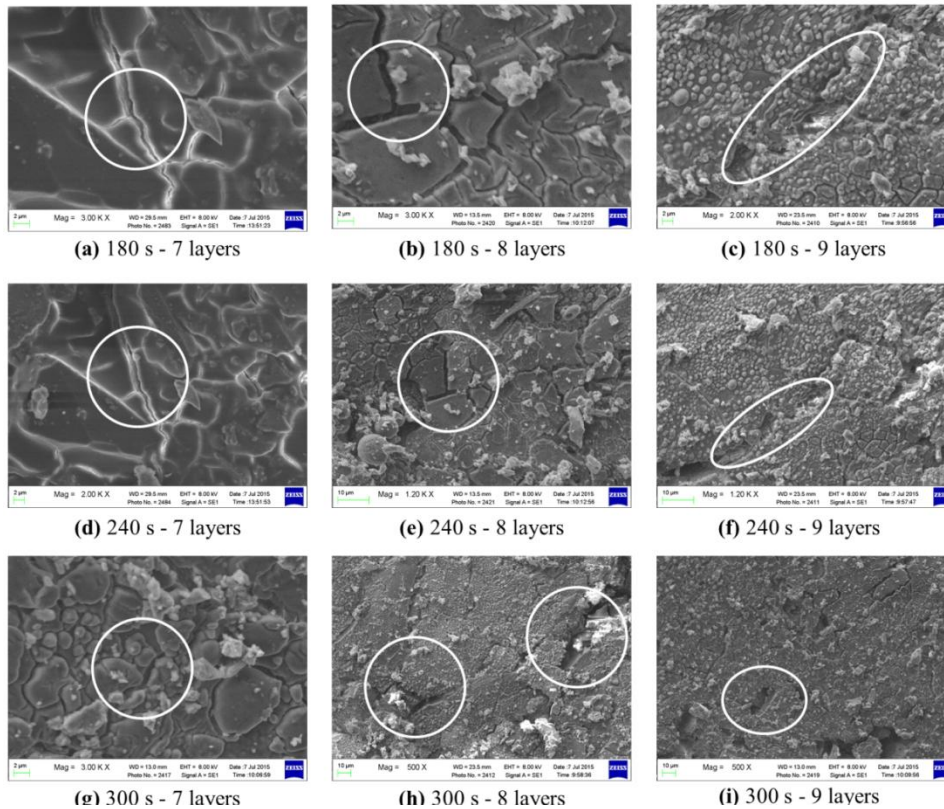


Figure 6 View of cracks for each ceramic shell parameter with 50°C temperature increases

4. CONCLUSION

This study has examined the effects of pattern removal parameters and holding time on crack length and crack formation in the ceramic shell. The making of ceramic shells using the ABS material pattern was performed with three variations including temperature increase, holding time, and number of ceramic shell layers in three intervals. Both lengths and formation of the crack were analyzed. By statistical method, it was found that temperature increase (T_x) and holding time (t) contribute significantly to the length of the crack. Longer holding times and a large number of layers yield better quality ceramic shells.

Crack formation occurred during the pattern removal process. Cracks often formed on the side of the arch-shaped sample as shown in Figure 5a and 5b, which indicates that the curved part of the pattern is the critical area in the emergence of cracks. To prevent this, layers can be added on the curved side of the shell. Moreover, instances of cracks can be decreased with a longer holding time and a larger number of layers.

Though increasing the number of layers yields shorter crack lengths, such an increase could produce a good quality ceramic shell and a good casting product. Though the occurrence of cracks in the ceramic shell can still happen, they remain within tolerable limits, where the crack has a length less than 10 mm and does not cut into the core pattern.

The implementation of integrated ceramic shell in the prosthetic product will reduce the cracking and further machining process after IC. The integrated ceramic shell can be achieved by giving multiple coating in the form of layer to the pattern, ABS material application to make pattern, and arranging the selected operational IC parameter (Temperature, holding time and layers). Lower temperature melting point, longer holding time and the more coating layer will delay the cracking formation.

5. ACKNOWLEDGEMENT

The authors are grateful for the main financial support from research grant Hibah Pascasarjana 2015 by Directorate of Research and Community Services, Universitas Indonesia (DRPM-UI) with Contract No. 1756/UN2.R12/HKP.05.00/2015.

6. REFERENCES

- Chua, C.K., Leong, K.F., Lim, C.S., 2003. *Rapid Prototyping: Principles and Applications*. 2^{ed.}, World Scientific Publishing Co. Pte. Ltd., Singapore
- Cooper, K.G., 2001. *Rapid Prototyping Technology: Selection and Application*. Marcel Dekker, Inc., New York
- Faes, M., Ferraris, E., Moens, D., 2016. Influence of Inter-layers Cooling Time on the Quasi-static Properties of ABS Components Produced via Fused Deposition Modelling. *Procedia CIRP*, Volume 42, pp. 748–753
- Feng, J., Carpanese, C., Fina, A., 2016. Thermal Decomposition Investigation of ABS Containing Lewis-acid Type Metal Salts. *Polymer Degradation and Stability*, Volume 129, pp. 319–327
- Foggia, M.D., D'Addona, D., 2013. Identification of Critical Key Parameters and their Impact to Zero-defect Manufacturing in the Investment Casting Process. *Procedia CIRP*, Volume 12, pp. 264–269
- Gebelin, J.C., Jolly, M.R., 2003. Modelling of the Investment Casting Process. *Journal of Materials Processing Technology*, Volume 135(2-3), pp. 291–300
- Groover, M.P., 2010. *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*. 4th ed., John Wiley & Sons, Inc., USA
- Jafari, H., Idris, M.H., Ourdjini, A., 2014. An Alternative Approach in Ceramic Shell Investment Casting of AZ91D Magnesium Alloy: In Situ Melting Technique. *Journal of Materials Processing Technology*, Volume 214(4), pp. 988–997
- Kalpakjian, S., Schmid, S., 2008. *Manufacturing Processes for Engineering Materials*, fifth ed., Pearson Education Incorporation, New York
- Lee, C.W., Chua, C.K., Cheah, C.M., Tan, L.H., Feng, C., 2004. Rapid Investment Casting: Direct and Indirect Approaches via Fused Deposition Modelling. *The International Journal of Advanced Manufacturing Technology*, Volume 23(1), pp. 93–101
- Mountgomery, D.C., 2013. *Design and Analysis of Experiments*. 8th ed., John Wiley & Sons Inc., Arizona
- Pattnaik, S., Karunakar, D.B., Jha, P.K., 2012. Developments in Investment Casting Process—A Review. *Journal of Materials Processing Technology*, Volume 212(11), pp. 2332–2348
- Singh, R., Singh, S., Fraternali, F., 2016. Development of In-house Composite Wire Based Feed Stock Filaments of Fused Deposition Modelling for Wear-resistant Materials and Structures. *Composites Part B: Engineering*, Volume 98, pp. 244–249
- Singh, S., Singh, R., 2015. Wear Modelling of Al-Al₂O₃ Functionally Graded Material Prepared by FDM Assisted Investment Castings using Dimensionless Analysis. *Journal of Manufacturing Processes*, Volume 20(3), pp. 507–514
- Soemardi, T.P., Suwandi, A., Kiswanto, G., Kusumaningsih, W., 2016. Development of Pattern Smelting Method with ABS Material in Investment Casting Process. *ARPN Journal of Engineering and Applied Sciences*, Volume 11(16), pp. 10023–10027
- Sopcak, J.E., 1986. *Handbook of Lost Wax or Investment Casting*. Gem Guides Book Co., California.
- Stratasys, 2014. *Fdm-technology: Stratasys Ltd.*, Available online at: <http://www.stratasys.com/> Accessed on 14 November 2014

- Suwandi, A., Kiswanto, G., Kusumaningsih, W., Soemardi, T.P., 2014. Research–Design & Development of Fast Customized Manufacturing for Prostheses TKR Based on Rapid Prototyping. *Advanced Materials Research*, Volume 980, pp. 243–247
- Wang, S., Miranda, A.G., Shih, C., 2010. A Study of Investment Casting with Plastic Patterns. *Materials and Manufacturing Processes*, Volume 25(12), pp. 1482–1488
- Yarlagadda, P.K.D.V., Hock, T. S., 2003. Statistical Analysis on Accuracy of Wax Patterns Used in Investment Casting process. *Journal of Materials Processing Technology*, Volume 138(1-3), pp. 75–81
- Yongnian, Y., Shengjie, L., Renji, Z., Feng, L., Rendong, W., Qingping, L., Zhuo, X., Xiaohong, W., 2009. Rapid Prototyping and Manufacturing Technology: Principle, Representative Technics, Applications, and Development Trends. *Tsinghua Science and Technology*, Volume 14(1), pp. 1–12