AN EXPERIMENTAL ANALYSIS OF STRAIN AND STRESS FOR ABS PATTERN DEVELOPED BY PORTABLE FDM MACHINE USED IN DIRECT INVESTMENT CASTING

M. S. Shukri[1], O. M. F. Marwah[1], M. Ibrahim[1], S. Sharif [2] and E. J. Mohamad[3]
[1]Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
[2]Faculty of Mechanical Engineering, University of Technology, Malaysia, Skudai, Johor, Malaysia
[3]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, Malaysia
Email: shazwanshuk@gmail.com

ABSTRACT

Fewer reports regarding the portable FDM machine has encourage the study about the capability of the machine to be used as sacrificial master pattern in investment casting for small production of castings. This study presents an analysis of cracking on ceramic shell during burnout process to determine the maximum value of the hoop stress towards pattern itself and also hoop stress on ceramic shell. There are two types of the internal pattern structure whereby hollow and square in which built from portable Fused Deposition Modeling (FDM) technique with same thickness of ceramic shell. Strain gauge is viable tool in which was attached on patterns and ceramic shells to determine the maximum value of hoop stress during experimental burnout process. This experimental were conducted with variant temperature starting from 30°C until 150°C with increment of 5°C per minute. Moreover, experimental result shows that ABS P400 material strain was increased when subjected to increment of temperature and pressure. This phenomenon happened due to the different value of Coefficient Thermal Expansion (CTE) between the patterns and ceramic shell. In addition, experimental results show that the maximum hoops stress is higher on the square internal structure compared to the hollow internal structure. The hollow pattern experienced 40 % amount of reduction of strain compared to the square pattern. The observation was made that glass transition temperature, Tg between 70°C to 110°C. It was observed that the shell cracking happened on ceramic shell.

Keywords: direct investment casting, fused deposition modeling, rapid prototyping.

INTRODUCTION

Rapid Prototyping (RP) approaches were initially formed with polymeric material to design models chiefly utilized for evaluation assessment with the valuable impact of perception. Past few decades the manufacturing process undergoes evolution, especially in the metal casting production process, and today's one of the most viable manufacturing route for metal casting parts in small to medium production were RP's technique. The concept of addition of layer by layer by using materials such as plastic, wax or paper fall in 'Additive process' category which vary from machine process (milling, turning, drilling, grinding and etc.) which fall in 'Subtractive process'[1]. Most of the RP techniques developed such as Stereolithography (SL), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Three Dimensional Printing (3DP), Fused Deposition Modeling (FDM) and Multijet modeling (MJM) are in additive fabrication process [2-3]. The idea of RP to develop prototype as sacrificial master pattern for Investment Casting (IC) was dated back in 1989 [4]. The block mould was used in IC, and the concept is to build the RP parts that obliged additional finishing. Nowadays, the application of RP in IC was driven by prospects of reducing tooling cost and production lead times [5].

IC has emerged at the leading edge in the casting process for manufacturing of intricate parts whereby better dimensional accuracy is requisite. Utilization of RP patterns is crucial advancements in IC process. The downside of conventional wax process essentially required die making for processing the patterns, which needed lots of time and cost, by elimination of this step, the process of IC using RP patterns become instantaneous and a cost effective [6]. The direct conversions of 3-D CAD data into RP pattern results in deterioration of development time, chances of costly mistakes, minimizes the sustaining engineering changes and extend the product life time by adding necessary features and eliminating redundant features early in the design [6-7].

During the burnout process, the shell acts as stress towards pattern due to the expansion of the pattern when heat was applied. Therefore, the shell cracking occurred when the stress-strain of pattern is greater than shell resistance. From the Hooke's Law, the ceramic shell stress in the elastic deformation regime is proportional to the ceramic shell strain [8]. The consequence to this phenomenon is thicker shell induced greater shell stresses towards pattern. In addition, another criterion which is vital in determining the collapsibility of the pattern itself is the web build internal pattern structure. If the shell rupture temperature is lower than the pattern buckling temperature and the resin glass transition temperature, the cracking of the ceramic shell will occurs [9]. Besides that, the glass transition temperature (Tg) and Modulus of Rupture (MOR) is a relationship that significant for every polymer materials. By using polymer materials as sacrificial pattern, the Tg is a reference to understand how the shell cracking occurs during the burnout process [9-10]. There will be a certain point of temperature when the pattern expands vigorously and reached above Tg with stress is above than MOR of ceramic shell, the shell will crack and failed. This occurrence is related to prediction of cracking in the ceramic shell.

Moreover, from previous study stated that, during the pattern in burnout process, it shows that the inner structural webbed pattern expands more than the outer ceramic shell. Consequently, contact pressure existed between the ceramic shell and the epoxy pattern. The inner epoxy pattern tendency to compressive load and the outer ceramic shell is tends to tensile load that forming a hoop stress or circumferential stress [11].

Diversification of techniques in RP has been explored to minimize space thoroughly and able to generate diverse solutions in IC process. Intensification of RP technique currently pays attention to portable Fused Deposition Modeling (FDM) machine technique. FDM considered as the cheapest among different types of 3D-Printers available in the market. Nevertheless, less reports regarding the FDM pattern printed by the portable FDM printer as well as its capability to be used as a sacrificial pattern in IC to generate metal cast parts. This research is to study the stress developed by the RP pattern act as a sacrificial pattern in the IC process during the burnout process whereby, temperature and stress are the main keys to be watched.

MATERIALS AND METHODS

Introduction of ABS P400

The usage of wax in conventional IC process is instantly when consumed the materials like Expanded Polystyrene (EPS) and polyurethane as well as materials from Stereotitography (SLA) [12]. Neverthelesss, wax pattern is not satisfactory and it is unable to sustain the high pressure on the ceramic shell due to the low strength of materials [10]. Moreover, casting wax patterns in the conventional IC process is less favorable compared to the materials produced from the RP process. Materials such as Acrylic, ABS, polyurethane, powder and other materials fabricated from the RP process have a higher strength and produced good quality surface as well as high dimensional accuracy.

The material that has been selected for this experimental type was ABS P400. ABS is a thermoplastic group in a combination of monomers of Acrylonitrile, Butadiene and Styrene. Besides that, ABS basic molecule consists of three plastic to form composite group characteristics. The wide range of using ABS materials as sacrificial pattern has been attracted reseacher due to the high impact strength, large temperature range, good dimensional stability, good chemical resistance, ability to prevent the flow of electricity and easily to process [7]. Other than that, ABS has mechanical properties that are strong and hard even at temperatures as low as -40 ° C. Moreover, it also has a high thermal resistance even at fluctuated temperatures. Next, the glass transition temperature (Tg) is at 110 ℃ and ABS has a coefficient of thermal expansion (CTE) of 10.08 x 10^{-5} [13].

Internal pattern structure built layout

In this paper, a new internal structure for investment casting for portable Fused Deposition Modeling (FDM) was designed and compared between one open and one closed half cylindrical shape. Firstly, the new internal structure pattern was design with hollow and square 90° styles. The hollow and square models were built with the diameter of 50 mm and have same dimension for the pattern itself. Figure-1 (a) & (b) shows the hollow and square model structure open ended. This built style has been chosen for easier the examination of collapsibility behavior during the burnout processes. The hollow model built with none internal web structure but with only a wall surrounding, due to the weaker point at wall in which don't have a support structure, it will easily collapse on that stage if and only if the ABS P400 not expanding much after the glass region temperature (Tg). Besides that, Figure-1 (b) shows the internal web structure built whereby design with constant square 90° structure at internal. The reason behind this is due to the square 90° tends to weaker during the burnout process whereby, the weaker point located in the middle in which the melting process takes place.

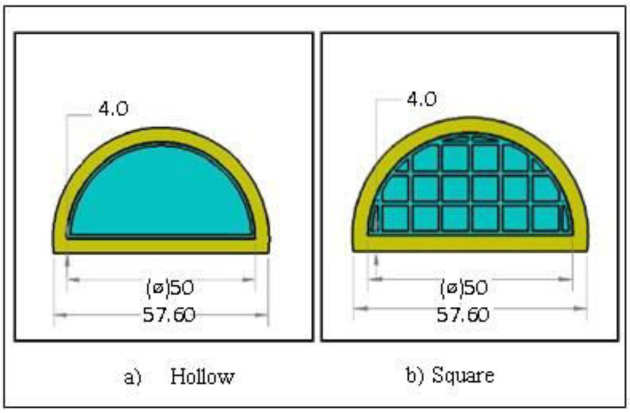

Figure-1. Hollow and square internal web pattern structure.

From Figure-2 (a) & (b) shows that the two types of internal patterns in which hollow and square built style that have one opened ended and one closed together wrapped with the 4 mm of ceramic shell thickness. This is vary constructed styles from the previous Quickcast 2.0 for external layout in which in this paper it was built with half cylinder compared to the full cylinder style [14].

Application of strain gauge

For the experimental parts, the usage of strain gauge is vital due to its ability to detect the presence of strain changed due to external pressure and temperature in the furnace. The cylindrical geometry of ceramic shell makes it possible to assume it as a thick cylinder. The difference between a thin cylinder and a thick cylinder is

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that a thick cylinder has a stress in the radial direction as well as a circumferential stress and longitudinal stress [14].

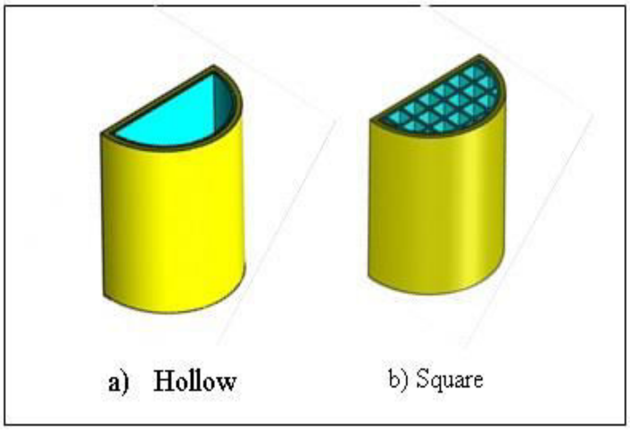


Figure-2. Half cylinder built style for hollow and square internal pattern structure.

In addition, radial stress has only a radial crippling effect on the wall of the ceramic shell and it is not the main criteria for defining the failure of a thick cylinder. For hollow and square models, strain gauges are installed in longitudinal and circumferential directions. Therefore, the magnitude of the strains in both directions is the comparative criteria for two structures. A Figure-3 show that the location of strain gauges was installed on the pattern itself, whereby hollow and square internal web structure. The strain gauge was installed for detecting the circumferential stress on the pattern itself.

Figure-3. The location of strain gauge attached on pattern for both hollow and square internal web structures.

Besides that, the strain gauge also was attached on the ceramic shell for analyzing the strain changes on the shell surface. Furthermore, it is important to detect the strain changed on the shell due to cracking behavior of the ceramic shell when subjected to high stress and temperature. Figure-4 shows that the location of strain gauge attached for analyzing the cracking of ceramic shell.

The testing sample was placed in the controlled temperature furnace for ensuring that the temperature can be adjusted within time. The strain gauge was used with the help of data logger for collecting the responded data. Due to the sensitivity of the strain gauge towards pressure and temperature, the data was taken every 5 times for 5°C per minute's increments starting from 30°C until 150°C.

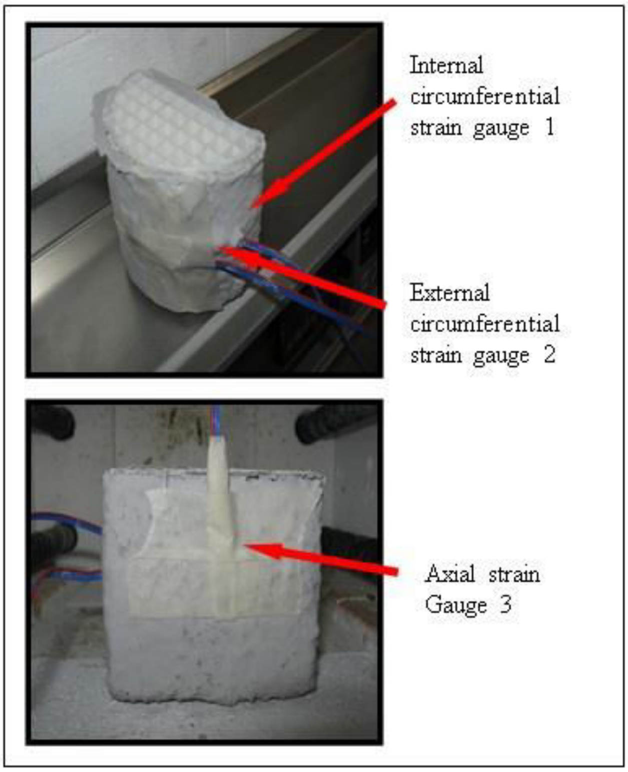


Figure-4. The location of strain gauge attached on ceramic shell.

Ceramic shell process

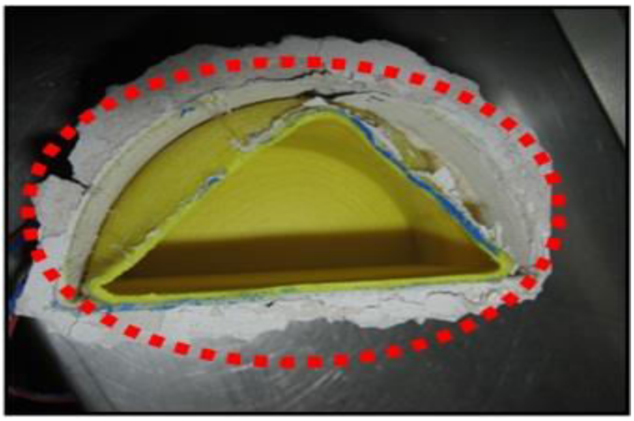
Materials used for slurry preparation is a mixture of 2 kg powdered Mulgrain Flour and 2 kg of liquid Colloidal Silica. These ingredients are mixed into a container and stirred until the viscosity of the mixture reached about 8 seconds using Zahn Cup 5. After the viscosity has reached a desired level, the RP pattern is dipped into primary slurry. For the first layer, the pattern was dipped into the slurry for 20 seconds and then hanging for 40 seconds and left to dry for about half an hour. Due to the unbalanced deposition of ceramic shell layer on the pattern, the pattern was subjected to undergo another dipping process of slurry. For the second layer, the dried product is then dipped into the slurry again for 20 seconds and then hanging for 40 seconds and left to dry about 8 hours. After it fully dried, the pattern was dipped again in mixture of slurry and sprinkled around with the Zircon Sand and left to dry for 8 hours. After that, the next process is dipped the coating pattern into slurry and sprinkled with Hi-alumina grains. These procedures are repeated until a desired thickness of 4 mm achieved.

VOL. 11, NO. 10, MAY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

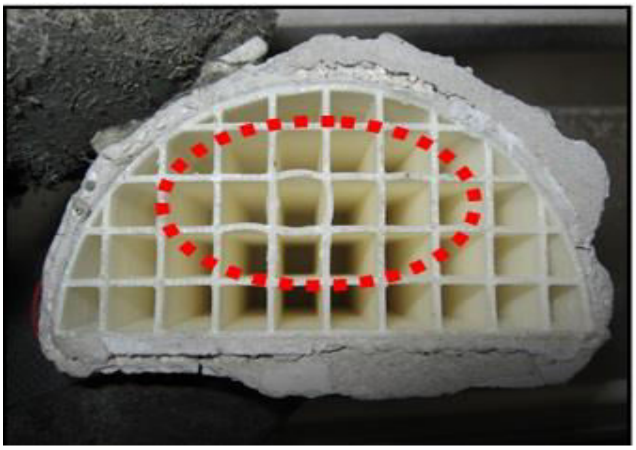
RESULTS AND DISCUSSION

Burnout ability

Many studies have been carried out to understand what happens in the burnout stage, which causes the ceramic shell to crack. Most of the time, this is achievable by a 2D symmetrical FE analysis. Nevertheless, because of the 3D geometry of the hollow and square network it was able to see the weaker point inside structure [15]. Half cylindrical models are used to compare the behavior of the structures during the burnout stage. The shell tends to have more strength against outer pressures; therefore, the results of this model could be applicable for other forms of FDM patterns. Since the material properties of epoxy as a thermoset resin changes with temperature, for simulating the burnout stage, it is essential to have the diagrams of changing the mechanical properties during the heating. Therefore, in this paper it proposed to use FDM ABS as pattern material. Figure-5 shows that the patterns were undergoes burnout process and buckling happened.



a) Hollow



b) Square

Figure-5. Buckling of pattern when subjected to high temperature during burnout process for a) Hollow and b) Square patterns.

This occurrence happened to view the collapsibility behavior of patterns when exposed to high temperature and pressure in the furnace. It can be seen that the hollow pattern was collapsed inward rather than outward for the open ended highlighted in the red section. While for the square internal web pattern, the buckling process does not fully takes place. It can be seen that, the red section buckling only at the middle part whereby, at the side none buckling happened. When investment castings shell with a FDM epoxy pattern inside furnace oven during the burnout process, it is subjected to high temperature rise, thermal expansion, and large strains [14, 16]. Since the difference of the CTEs of epoxy and investment ceramic is more than one order of magnitude, the epoxy pattern can exert considerable stress on the ceramic shell. During the pattern burnout process, the inner epoxy pattern expands more than the outer ceramic shell. As a result, there exists contact pressure between the ceramic shell and epoxy pattern. The inner epoxy pattern is subjected to a compressive load, and the outer ceramic shell is subjected to a tensile load [9,10].

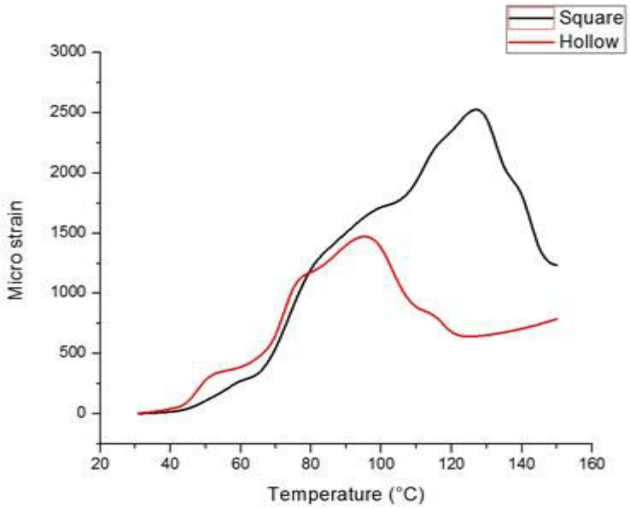


Figure-6. Internal circumferential strain on hollow and square patterns.

Strain and stress analysis

Some previous researcher discussed the internal structure of different models produced by the RP routes has played an important role in determining internal structure, particularly in the IC process [16]. When subjected to temperatures in stages, each internal structure yield von misses, equivalent stress, equivalent strain and deformation of difference values. The resulting internal structure also determines the damage and fractures in shells under the influence of temperature changes. The result of two types of internal circumferential stress for both internal web structures which strain was spotted on pattern was stated in Figure-6.

As can be seen from the graph above, according to collapsibility behavior, hollow patterns tend to collapse easier compared to square pattern. This phenomenon shown in Figure 6 concluded that, square pattern tends to experience more strain changes compared to hollow pattern. This is due to the inner built structure of both types of ABS pattern. For the square, the design built was 90^0 internal shapes along together with supports which enable it to collapse easier. Nevertheless, during the experimental process, the square pattern less collapsed even though it passed glass region temperature (Tg). It continued to gain stress from the expansion of pattern from the rise of temperature of 30^0 C until 130^0 C. The strain only started to reduce when passed the temperature of 130^0 C until 150^0 C. This shows that, the square pattern is hardly collapsed due to its strong build structure. According to the principle of CTE, during this phase, the pattern is most likely undergoes phase changed from solid to rubbery like. There is a limit when the maximum of temperature can be achieved by the materials pattern before it collapsed [17].

For the hollow pattern, it tends to expands from beginning of 30 ^{0}C until it reached 100 ^{0}C which is before the glass transition temperature (Tg). This phenomenon can be acceptable for most of the resin / polymer material whereby, the pattern should be collapsed before the glass transition temperature (Tg). Nevertheless, the pattern started to gain more pressure and caused expansion of the material. If this occurrence is continue, the cracking of shell may takes place during the burnout process.

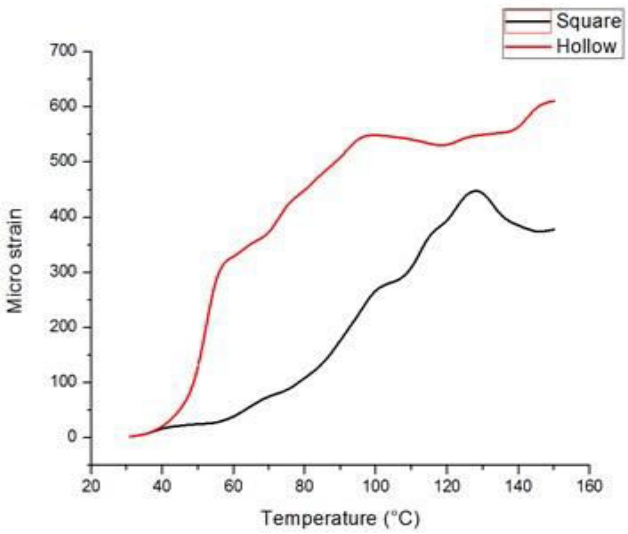


Figure-7. External circumferential strain on hollow and square patterns ceramic shell.

Another finding that achieved through this experiment is the analysis of shell strain-stress during the burnout process for ceramic shell. For this analysis, it is needed to identify the cause of expansion of shell and cracking prediction of shell itself. Figure-7 shows that the external circumferential stress on shell for both hollow and square patterns.

When the particles of any substances are experience heat from the surrounding, it changed the state whether from solid to plastic or etc. From the Figure-7 shown, it was stated that, hollow shell received more amount of stress when temperature increased. This is absolutely due to organization of built internal layout whereby none support system for pattern is provided. The highest increased of temperature for hollow shell happened between temperature 30 ^{0}C until 60 ^{0}C. During this phase, the shell tends to achieve its ultimate stress due to pressure contact between the pattern and shell in which the pattern expanded as well as shell too.

Apart from that, however, for square shell it tends to yield a little bit stress on ceramic shell. Most of all, the strain was slowly increased within time. Nevertheless, it remaining to received more strain during the burnout process. Up reaching 130 °C, the shell still received strain, but was less compared to the hollow shell. This occurrence happened due to the stronger shell to withstand the pressure expanding from the square pattern. It was said that, the Modulus of Rupture (MOR) of the shell must be greater than the expandable material pattern to avoid the shell cracking during the burnout [14]. Table-1 shows the comparison results of both hollow and square internal pattern structures in terms of strain.

Table-1. The strain comparison results of Hollow and square structures.

Structures	Internal gauge 1 (maximum strain)	External gauge 2 (maximum strain)
Type of analysis	Experimental	Experimental
Hollow	1520 µ	555 µ
Square	2552 µ	456 µ
Percentage reduction	40 %	18 %

As can be seen in Table-1, it shows the comparison of the maximum strain for both internal pattern structures and external ceramic shells. There was about 40 % reduction of strain between hollow and square patterns whereby, hollow pattern tend to receive less strain and stress rather than square pattern. Therefore, it enhances its ability to collapse easily. However, for the external ceramic shell, the square pattern has better ability due to less absorption of strain changes during the burnout process. This different between both patterns was 18 % of reduction.

CONCLUSIONS

Direct RP patterns of portable FDM ABS material, has validated its ability to be used in IC process. It was found that both two types of internal patterns possessed the capability to endure the pressure of patterns during burnout processes. The experiment is fundamentally an application of RP route used to infuse with investment casting for tooling cost reduction. The benchmark is essential in this experiment for evaluation of weakness, strength as well as improvement from previous RP's technique. The strain analysis of hollow pattern performed better compared to square pattern in terms of expansion of pattern during burnout process, whereby, hollow pattern collapsed before the glass transition temperature (Tg) 110 °C. Furthermore, the strain and pressure difference on each internal structure depends on the type of internal structure of the material. However, in terms of shell strain and stress, square pattern tends to gain less strain match to hollow pattern, which are 456 microstrain and 555 microstrain, respectively. This behaviour can be understandable in terms of shell cracking, whereby, less strain happened to the shell considered to reduce the stress on the shell itself. By doing so, the shell can withstand the high pressure expansion of the pattern and will collapsed within time. Besides that, there is 40 % significant of reduction when compared hollow and square patterns in terms of strain. Even so, more investigation need to carry on to recognize the pattern collapsibility behaviour by implementing new built structure, new parameters thickness of ceramic shell, as well as new materials for RP sacrificial patterns.

ACKNOWLEDGEMENTS

The authors wish to thank Ministry of Education Malaysia for funded Fundamental Research Grant Scheme (FRGS) Vot1423 and Faculty of Mechanical & Manufacturing Engineering in Universiti Tun Hussein Onn Malaysia (UTHM) for facilitating and financial support to this research programmed.

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