

COLLAPSIBILITY OF PMMA BASED MATERIAL IN DIRECT INVESTMENT CASTING

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ABSTRACT: Over recent years, the rapid growth of Additive manufacturing (AM) has benefits the Direct Investment Casting (DIC) process for intricate design in which significantly reduces the cost when associated with low volume production. Nevertheless, ceramic shells cracking has been recognized as critical problem when involved direct casting in which leads to incomplete collapsibility. Therefore, this study presents a numerical and experimental on poly(methyl) methacrylate (PMMA) pattern collapsibility for investment casting process and the stress analysis study on the ceramic shells. Study revealed that there were significant average of 5.8 % reduction of stress between square and polygon patterns. This study was conducted to examine the collapsibility of AM materials in the IC process.

KEYWORDS: *Additive Manufacturing; PMMA; 3D Printer; Investment Casting; Polyjet*

1.0 INTRODUCTION

Investment casting (IC) process is a metal casting techniques in which capable to provide an economical means of mass production components with complex features such as thin walls, undercut

contours and inaccessible spaces which are difficult using conventional machining methods [1]. IC is one of the manufacturing routes that able to produce a precise dimension, complex shapes and high quality casting with good surface finishing on variety of alloys which leads to higher demand in the industries of casting [2]. IC is a process in which the molten metal was poured into the ceramic mould. The ceramic mould was created by using wax pattern that covered by several layer of ceramic slurry. The ceramic mould with the wax inside was melted during the dewaxing process. Then the moulds were preheated and molten metal was poured into the ceramic mould to fill the cavity inside. Molten metal was allowed to be cool and solidified inside room temperature and the time mostly depends on the material of the molten metal. One of the important processes in the IC is the making of ceramic shell mould. The thickness of the ceramic shell mould significantly affects the permeability. Low permeability of ceramic shell tends to crack because of the unreleased gases of the mould-metal reaction [3].

However, producing a wax pattern for the IC process consume a lot of time from the overall processes [4]. The higher tooling costs for conventional IC process becomes a drawback when small numbers of castings are required. By employing Additive Manufacturing (AM) techniques in the IC process, it relatively reduced the cost and time whereas AM shortens the development time of a new product design through the capability of quickly fabricate the 3D physical objects. Besides that, most AM techniques able to fabricate the complex geometries and varieties of materials [5]. Li [6] had created a complex foam patterns in IC whereas he developed it to predict the possible crack formation of ceramic shell during rigid polymer pattern removal in the IC process. The author concluded that complex geometry of foam pattern tends to be more vulnerable to shell cracking as more stress concentration region were present. Based on Hague [7], the author observed the shell cracking at temperature below the glass transition temperature of the epoxy material, nevertheless the author not observed buckling of hollow SL patterns in his burnout experiments. In some cases, the present of residual ash inside the mould tends to cause defects in the final castings products [5, 15-16].

Diversification of techniques in AM has been explored to minimize the gap and able to generate diverse solutions in IC process. Intensification of AM technique currently pays attention to portable Polyjet machine technique. Polyjet considered as one of the best portable 3D-Printers compared to Industrial poly jetting technique. Nevertheless, less reports regarding the Polyjet pattern printed by the portable Polyjet printer as well as its capability to be used as a sacrificial pattern in IC to generate metal cast parts.

2.0 METHODOLOGY

An experimental has been conducted to investigate the collapsibility of the PMMA based material in direct investment casting process by implementing the strain gauge as the medium of interpreting the data.

2.1 Raw Material

The material used in this study is poly methyl methacrylate (PMMA) which also known as clear plastic acrylic. PMMA has high mechanical strength, high Young's modulus and low elongation at break [8]. It is one of the hardest thermoplastics and highly scratch resistant. The characteristic of PMMA was highly transparent material with excellent resistance to ultraviolet radiation and weathering. This is the strong reason it can be colored, molded, cut, drilled and formed. Through these properties, it is ideal for many applications including airplane windshields, skylights, automobile taillights and outdoor signs. By implementing the PMMA material (liquid forms) using 3D Polyjet machine, it can produce the complex geometry shapes as required.

2.2 Full Strain Gauge Setup

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 semi-cylinder. Figure 1 shows that the locations of strain gauge were attached on the PMMA patterns.

The strain gauge significantly attached on the ceramic shell for analyzing the strain changed on the shell surface due to reaction of temperature changes. 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. 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°C per minute's increment starting from 30°C until 150°C.

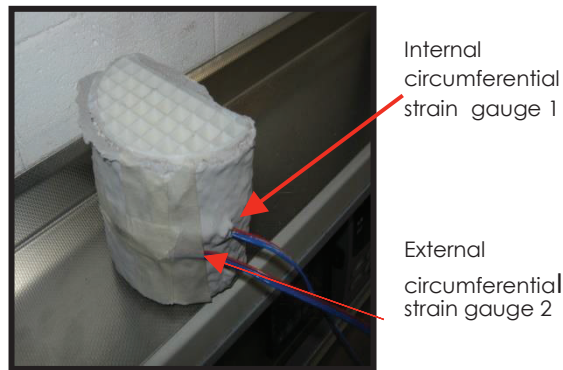


Figure 1: Location of Strain Gauge on Ceramic Shells

2.3 Simulation of PMMA Based Material

Finite Element Method (FEM) is known as simulation analysis technique in which can analyzed the object into certain number of regions by divided it. FEM is a based numerical simulation of the thermal stresses generated during the pattern burnout process. For the efficient simulation, an equivalent force technique developed for the Finite Element Analysis (FEA). The FEA results are useful to developer of computer aided design engineering tools for the design of the pattern internal web structures. The study involved a numerical study of collapsibility internal pattern and stress analysis on ceramic shell. The type of analysis used to conduct this study was static structural analysis in total deformation (collapsibility pattern). The input parameters of this simulation are based on the real of experimental result in which includes the thickness of the ceramic mould, temperatures, coefficient thermal expansion and elastic

modulus [12]. Table 1 shows the mechanical and thermal properties for both PMMA materials as well as ceramic shells mould.

Table 1: Mechanical and Thermal Properties of PMMA and Ceramic Shells

Entry	Parameters	PMMA	Ceramic shell mould
1	Elastic modulus	2930 Mpa	3411 Mpa
2	Tensile strength	65.5 Mpa	4.5 Mpa
3	Density	1180 Kg/m ³	1920 Kg/m ³
4	Specific heat	1450 J/Kg	650 J/Kg
5	Poisson ratio	0.37 N/A	0.24 N/A
6	Coefficient thermal expansion	$7.35 \times 10^{-5} \text{K}^{-1}$	$2 \times 10^{-6} \text{K}^{-1}$
7	Thickness	1 mm	6 mm

^aAll parameters were carried out maximum at 700°C for square and polygon patterns according to these parameters.

^bThe total deformation of the patterns indicates the allowable stress on the patterns can withstand during burnout process.

^cThe total weight of the ceramic mould is same (320 g) however, the weight between patterns is different.

3.0 RESULT AND DISCUSSION

This section briefly discuss about the finding in this study in which includes the data from experimental and simulation.

3.1 Total Deformation

Deformation of acrylic (PMMA) material can be seen from the finite element analysis result as shown in Figure 2 and Figure 3. The red marking area shows the deformations are at maximum while the blue marking shows the area with the minimum deformation during the burnout process. The deformation is changing with respect of temperature. Besides, it could be identified that the ceramic shell would not crack as the deformation rate was at the minimum level.

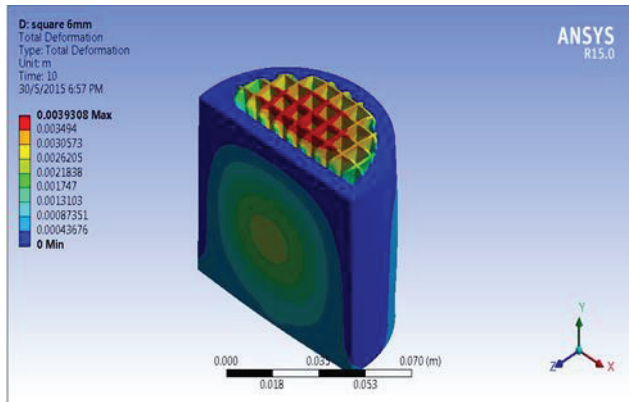


Figure 2: The Result of Total Deformation for Square Model at 700 °C

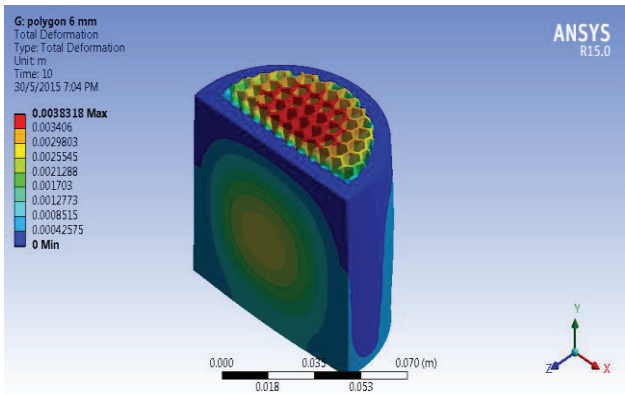


Figure 3: The Result of Total Deformation for Polygon Model at 700 °C

From the overall results, they have similarity in which ceramic shell expands and acrylic (PMMA) pattern collapse first at the top as showing in red zone. When the temperature increased, the internal patterns expand upward and downward then collapse at maximum displacement. It can be said that the square model is the best model in terms of internal mould cleanliness due to the highest displacement of total deformation and the possibility of shell not to crack at 6 mm shell thickness. It was found that the highest maximum displacement on the square which is $3.931e^{-3}$ m followed by the polygon which is $3.832e^{-3}$ m.

Figure 4 shows the experimental result of PMMA patterns when subjected to higher heat and buckling happened. This occurrence is to review the collapsibility behavior of patterns when exposed to high

temperature and pressure in the furnace. It can be seen that the PMMA pattern is collapsed inward rather than outward for the open ended highlighted in the red section. Furthermore, the buckling process does not fully take place. It can be seen that, the red section buckling only at the middle part whereby, at the side none buckling happened. This occurrence was setup at temperature ranges 30 °C until 150 °C. Figure 5 shows the collapsibility of square and polygon of PMMA patterns.

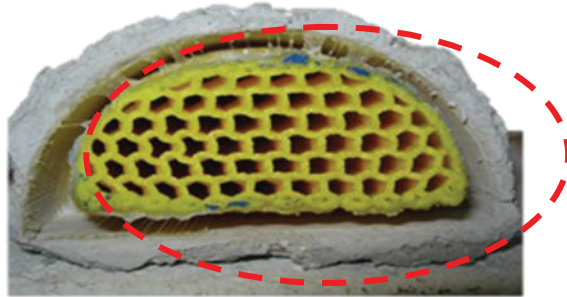


Figure 4: The Result of PMMA Patterns Collapsibility

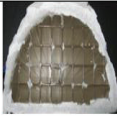



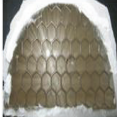


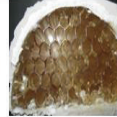
Internal Structure	40 °C	70 °C	110 °C	150 °C
Square	 Original	 Partially buckling	 Buckling	 Buckling
Polygon	 Original	 Partially buckling	 Buckling	 Buckling

Figure 5: The Collapsibility of Square and Polygon Patterns

Furthermore, the 6mm ceramic thickness has been selected to be used to investigate the collapsibility behavior of the internal patterns such as shell cracking, epoxy softening and internal structure buckling. The different style of the internal structure enable the pattern to collapse and buckle inwards under the influence of heat, rather than cracking the ceramic shell as a result of expanding outward.

As shown in Figure 5, during early stage of the burnout process at 40 °C, PMMA patterns subsequently exhibits none buckling behavior. However, continuous heating of the AM shows that the internal structures exhibits partially buckling and the color of PMMA materials change to yellowish at 70 °C. When increasing the temperature to the 110 °C, the AM patterns tend to undergoes partially buckling and buckling for different internal structures. The internal structures became wavy and started to bend considerably when heated at the range of glass transition temperature. Furthermore, at 110 °C the internal structures started to deform in the middle and side of the patterns. The color of the PMMA material at 110 °C started to change to brown. Moreover, with further increasing the temperature at 150 °C most of the AM patterns tends to collapse, buckling and deform. Nevertheless, it can be seen that, square pattern of ABS material hardly collapse inwardly and this shows that the pattern has higher stress inside the pattern although when physical inspection on the square pattern shows it become wavy. At 150 °C most of the patterns become fragile for PMMA material.

3.2 Analysis of Shell Cracking

The collapsibility was set to be the measurements of the weight loss of PMMA pattern as the temperature is increased. Under the influence of heat, whether the shell will crack or not it depends on material factor and geometry of the shell pattern construction [9]. Cracking occurred when the stress induced in the ceramic shell is greater than the Modulus of Rupture (MOR) of the shell material [9].

When it comes to analysis of ceramic shells, it was found that the square pattern has higher equivalent stress compare to polygon pattern. When the particles of any substances are experience heat from the surrounding, it's changed the state from solid to plastic. The phenomenon was stated that, square shell received more amount of strain when temperature was increased. The highest increased of temperature for square shell happened between temperature of 60 °C until 120 °C. During this phase, the shell tends to achieve the ultimate stress due to pressure contact between the pattern and shell in which the pattern expanded as well as shell too. However, the tendency of ceramic shell material shall reduce the expansion of pattern inside due

to its non-thermal conductive. This occurrence is believed to be a strong bond between the ceramic shells materials to hold the pattern expansion.

Apart from that, for polygon shell tends to yield a little bit stress on ceramic shell. Most of all, the strain was slowly increased within time. Nevertheless, it remains to receive more strain during the burnout process. Up to 140 °C, the shell responded to receive stress. This occurrence was due to the stronger shell to withstand the pressure expanding from the polygon pattern. The Modulus of Rupture (MOR) of the shell must be greater than the expandable material pattern to avoid the shell cracking during the burnout process [10].

From the Figure 6 shown, square pattern yields a higher equivalent stress compare to polygon pattern. This phenomenon is due to the square pattern has slightly higher displacement during the burn out process. However, when the pattern tested with low thickness of ceramic shell (below 6 mm), the cracking of ceramic shells happened due to higher displacement of patterns collapsibility. Thus, it suggested wrapping the patterns with thicker ceramic shell to prevent cracks. The highest stress recorded between temperature of 30 °C to 150 °C were 68.72 Mpa and 67.1 Mpa for square and polygon patterns respectively. There was about 5.8 % reduction of stress when compared between square and polygon patterns. Figure 6 shows the relationship between temperature and equivalent stress of PMMA patterns during the burnout process.

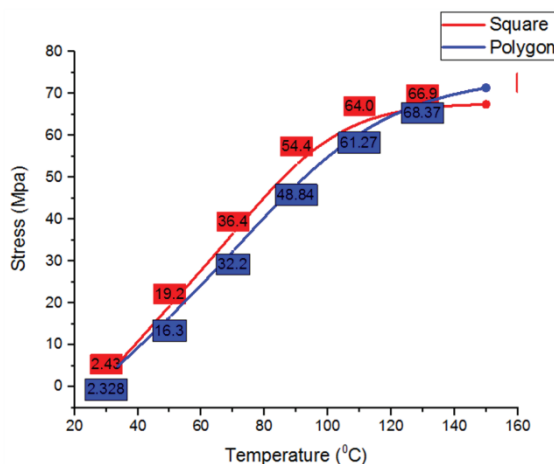


Figure 6: The Equivalent Stress of PMMA Patterns

In contrast, the previous researchers used ABS as sacrificial patterns and it was revealed that the ability of ABS as promising material to be used as substitution of conventional wax [13,14]. Nevertheless, based on the data gained and tested using PMMA material, the PMMA also has tendency to achieve a standard such as ABS material. This can be seen according to the ability of PMMA material to collapse during burnout process, withstand the high pressure and temperature as well as high elasticity. As can be seen in Figure 7, it shows the strain developed during the burnout process of PMMA material whereas it can be seen that internal structure play significant factor in reducing the stress of patterns.

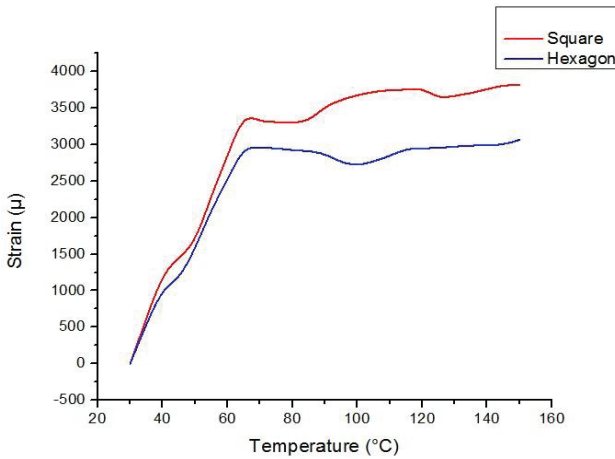


Figure 7: The Strain Developed in PMMA Patterns

4.0 CONCLUSION

The purpose of this research is to study the collapsibility PMMA patterns in the mould and the ceramic shell crack during burnout process in IC. Early study showed that PMMA based material able to be fabricated into sacrificial pattern for Direct Investment Casting. The properties of PMMA based material fulfill the criteria such as ABS and PLA materials. Using the ANSYS simulation, this study revealed that square and polygon patterns were able to withstand the pattern expansion during the burnout process without cracking the ceramic shells. In addition, it also revealed the critical areas of patterns expansion during the burnout process.

The collapsibility between two patterns almost similarly whereas the displacement recorded was $3.931e^{-3}$ m and $3.832e^{-3}$ m for square and polygon respectively. In terms of equivalent stress, square has higher stress compared to polygon which results were 68.72 Mpa and 67.1 Mpa respectively. There were slightly deviation in terms of stress reduction between polygon and square patterns in which about 5.8 %. Besides that, the study revealed square pattern has higher induced strain compared to polygon which were 3777 microstrain and 2767 microstrain respectively.

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