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Quality Parts of Portable FDM Machine used in Direct Investment Casting

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***Abstract*—Nowadays an application of Additive Manufacturing (AM) has been employed in Investment Casting (IC) for the direct casting process (DIC). The DIC was designed to assess the performance of portable Fused Deposition Modeling (FDM) fabricated acrylonitrile butadiene styrene (ABS) pattern material as the sacrificial pattern for IC process. Increasing demands on AM's technique has raised the fabrication of portable FDM printers. However, the quality level of pattern made from the portable FDM printer is still not been categorized. In this study, it focus on comparison in between sacrificial pattern of FDM ABS fabrication with the final product of IC. There were three different inner structure patterns of FDM ABS which are hollow, square and polygon were used as a benchmark. The analysis results identified that hollow internal structure shows the highest percentages in dimensional accuracy and flatness during pattern fabrication. In addition, FDM ABS square internal structure shows the lower percentages in dimension accuracy and highest flatness but inversely result after the investment process was done.**

Keyword-Additive Manufacturing, Fused Deposition Modeling, Investment Casting, Direct Investment casting

I. INTRODUCTION

Investment casting (IC) is one of the route in producing near net shape of metal product that proficient of providing a lower cost fabrication when involving lower volume production. IC capable in producing good surface finish and the relative ease of producing components with internal cavities and good castability with a large variety of alloys are some of the advantages which justify its preference to other processes [1]. Development of casting process has taken the advantages of technologies from year to year and made it to be the most modern and versatile for metal casting process. Previous method has employed a wax as the sacrificial pattern material in producing master pattern in which it can reduce the cost. However, method of conventional wax patterns may result in longer processing of new pattern preparation that related to over 70% of the total lead time [2]. The high overall cost was account for the need of particular equipment, inexpensive refractory and binder materials as well as cost of mould making. The high tooling cost for making the wax pattern using injection moulding method may not suitable for fabrication low volume production, thus it usually utilized for mass production [3].

It was found that employment of IC using Additive Manufacturing (AM) routes has various rate of success. The advantages of AM is it can reduce the lead time of patterns, moulds, and prototypes, and due to its ability it has attracted some manufacturing enterprises to use AM methods to fabricate intricacy patterns. Within few years there are variety development of AM system such as Stereolithography (SL), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), Ballistic Particle Manufacturing (BPM), and Three Dimensional Printing were distributed and enhanced its performances. Furthermore, most of the commercialized AM techniques have been utilized in producing the IC patterns with various successes (high end 3D printer machine). Nevertheless, there are less reports involving portable or home user 3D printer machine used for IC process.

Nowadays, AM materials were used as master or sacrificial patterns for IC process, particularly in small volume production as well as to generate complexity parts. With the invention of the AM technology, sacrificial or master pattern can be produced in shorter fabrication time. One of the major benefits is it does not require any skilful and experiences worker to produce the sacrificial pattern. Moreover, there was a limited research on the product of FDM pattern printed by the portable FDM printer. Contemporary, there are varieties of portable machines in the market, however there is none validate data on equality of the quality of each of these portable machines. Besides that, portable FDM is considered to be the economical among different types of 3D printers that available in the market. Fabricating the pattern with cheap, easily available components and easily anywhere are significant towards portable 3D printer [4].

This study was conducted due to less research regarding the pattern printed by portable FDM machine whereby the pattern is diffuse into the IC process as a master pattern for metal casting of alloys. Furthermore, this research is to study the quality part by using RP as a sacrificial pattern for the IC process. It is obligatory to study about the dimension accuracy and flatness between the portable FDM ABS master patterns and final aluminum products whereby comparison can be made simpler. It is significant to know the quality of the IC products since the IC always in critical parts of metal fabrication. Such as AM used as sacrificial pattern, the shrinkage occurs when direct investment casting (DIC) conducted. The major cause of accuracy of the product of IC process is the shrinkage of the final metal casting [5]. Benchmarking study was adopted to make comparison between printed parts and the metal parts after casting process.

II. METHODOLOGY

A. Fabrication Technique of Portable FDM Pattern

The sacrificial pattern for IC process has been made using the specific Odyssey X2 machine. As a matter of fact that most of the available portable 3D printer process at the present time are based on the extrusion filament process in which inheritance by high end FDM machines. This process is most common and recognizable in the 3D printer process. The most common materials for entry level FDM are Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA). Besides that, other materials also are available such as flex and conductive ABS in which comes with variety of colours. The process begins with directly feed the polymer material into the extruder which is in the form of filament. The extruder uses a torque and a pinch system to feed and retract the precise amount of filament. Then, the filament passes through extruder and flows directly to the heater block whereas this block will heat the filament according to significant temperature. The semi molten filament is forced out through the heated nozzle at a small diameter. Next, the small filament diameter deposited at the top bed platform forming the layer upon layer in the XYZ. This process is continuing whereby the molten polymer deposited layer upon layer until full solid prototype completed. In addition, a supports are built along the way providing overhanging geometry materials to withstand the building process. However, with only one nozzle working, it is challenging to provide efficiency supports. Thus, as the system has advanced to integrate dual extrusion head nozzle, the issue become less important. With the improvement in dual extrusion, a combination of colours can be made significantly thus providing a colourful end product and ease of removal support materials.

By using ABS P400 material as sacrificial pattern to be employed in IC process, the early design proposed was significantly affected the end product quality. This is due to material properties of ABS P400 that are high impact strength, large temperature range, good dimensional stability, good chemical resistance, ability to prevent the flow of electricity and easily to process. Many researchers interested to study about the potential of using ABS material as a master pattern due to the extensive scope [6]. Figure 1 shows the schematic of common FDM machine.

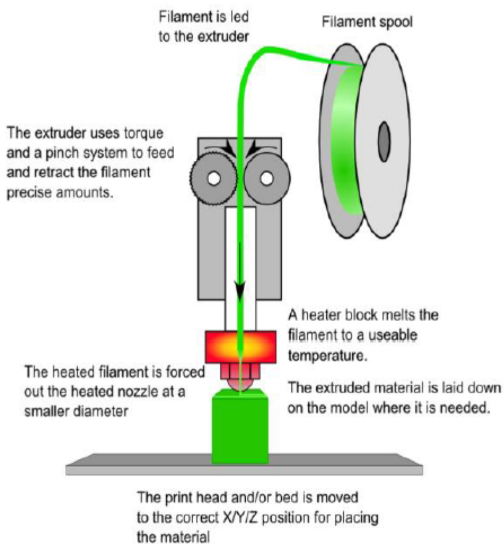

Fig. 1. Schematic of Fused Deposition Modeling

B. Internal Structures of Sacrificial Patterns

This study related to the AM process and IC process before the analysis of the casting part quality, in which related to the dimensional accuracy and flatness. Firstly, there were several types of pattern have been recognized and shortlist for the selections and all the product divided into two types in which is the technical drawing of the product and the parts that are already produced. Next, the shape chosen is half cylindrical for the analysis of this study. The reason behind this is to enhance the probability of flatness occurs in the pattern. For the portable FDM machine, Odyssey X2 machine was used to fabricate the master pattern of ABS with half cylindrical shape with different internal structures. The internal structures selected were hollow, square and polygon as shown in Figure 2. There were 9 specimens for each patterns tested for this study.

The internal structure was intended to permit simple evacuation of the molten AM material during the burnout process from the ceramic mould. Hence, the structure should sufficiently solid to give the support, yet sufficiently frail to collapse early underneath the expansion and permit complete drainage. In imperative for a structured design to be appropriate for IC process it should be developed in accordance with the following criteria stated by [7] such as be robust to support the part during building, strong enough to support the general handling of the part, weak enough to collapse under the influence of its own expansion as well as allows complete drainage.

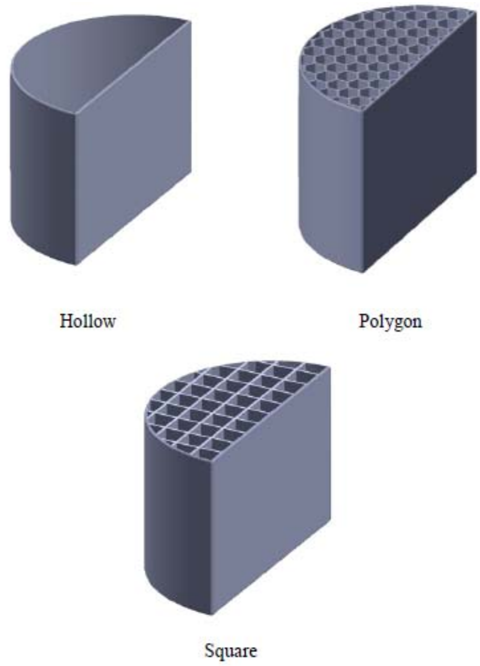

Fig. 2. Internal pattern design structure of ABS P400

C. Coating of Ceramic Shell on Patterns

In the first place, the IC started by coating the pattern layer by layer until the desired thickness of the shell formed is 6mm. This process is about to mixing of slurry and shell mould making. Then shell mould coated overall surface of the pattern. The ceramic shell mould technique involves dipping the entire cluster into ceramic slurry, draining it, and then coating it with fine ceramic sand. After drying, this process is repeated again and again until an adequate, self-supporting shell is formed. First of all mix the slurry which contains the 2kg of mulgrain flour slowly into a container of 2kg colloidal silicate. The mulgrain flour gradually added into the colloidal silicate until the desired viscosity of the slurry is obtained. Before applying the first layer of ceramic slurry on the ABS P400 pattern, the patterns were brushed with the release agent that acts as glue to the body of the pattern. The ceramic slurry mixture only can be used after reaching its viscosity in the range 8 second by using the Zahn cup 5. The patterns were coated by a combination of slurry, Zircon Sand as well as Hi-alumina Sand whereby the finest grains are chosen. This step is done by hanging and dried the pattern coated for about 8 hours for every step.

D. Burnout and Pouring Alloy Metal

Next, the stage which is eliminated and the pre-heating of RP pattern is about the certain temperature that is suitable for the ABS material to burn out completely. Firing at a certain temperature is allowed whereby 600 ℃ to 900 ℃ is done to remove all residues ash of the FDM ABS pattern inside the moulds. This leaves ceramic shell cavities of the desired shape. After that, the ceramic shell moulds were arranged in the sand tub for the pouring of the molten aluminum process. Before pouring happened, it is essential to make a hole on the sand tube to put shells after firing process. Moreover, the firing process takes about 60 minutes. This is a critical stage in the mould making procedures because the wax in runner and the FDM ABS pattern will expand during melting and there is a possibility of the shell moulds to crack. Subsequently, the crucible furnace melting system will be used for melting the aluminum alloy LM6. For the pouring process, the molten LM6 at certain temperature poured in the ceramic shell cavities slowly. The pouring temperature measured using hand held digital thermometer. Lastly, knockout process will be done after the metal has cooled and solidified. The ceramic shell is broken off using hammers and chisel. The shells are easily broken because it is brittle after the heating and casting process. Figure 3 shows the burnout and pouring of alloy metal.

Burnout of pattern material Pouring of Alloy metal into the mould

Fig. 3. Burnout of pattern and pouring alloy metal

III. RESULT AND DISCUSSION

The measurement of dimensional accuracy and flatness were taken and tabulated the data. Meanwhile, for the dimension accuracy and flatness testing, the apparatus were used such as Flexible Measuring machine (FMM) model and QM-Measure 353 Mitutoyo. All this apparatus must be handled with care to ensure the data collected was accurate. From the dimension measured by using the machine, percentage error data gained by few calculations. The equation related for calculation to get the precise data was shown in Equation (1).

$$\frac{|Dimension\ \ of\ FDM\ Pattern\ -Dimension\ \ of\ drawing\ |}{Dimension\ \ of\ drawing}\ x\ 100 \quad (1)$$

Whereby;

Dimension of FDM ABS pattern = mm

Dimension of drawing = mm

Some previous researcher discussed the internal structure of different models produced by the AM routes has played an important role in determining internal structure, particularly in the IC process [8]. Figure 4 shows the percentage errors in dimensional comparison among different internal structure of FDM ABS. Based on Figure 4, the graph shows that the shrinkage between CAD drawing to the FDM pattern printed. Negative sign of means shows that the decrement of dimension because of shrinkage. The graph in which shows highest mean value is FDM ABS pattern with hollow internal structure followed by square and polygon. It shows that the hollow shrink more among three different internal structures of the patterns. FDM ABS with hollow internal structure graph shows the error in dimension was skewed right. Most of the errors were between -1.5% and -0.7%. Referring to the standard deviation of the graph, highest value was from FDM ABS polygon followed by hollow and square internal structure patterns.

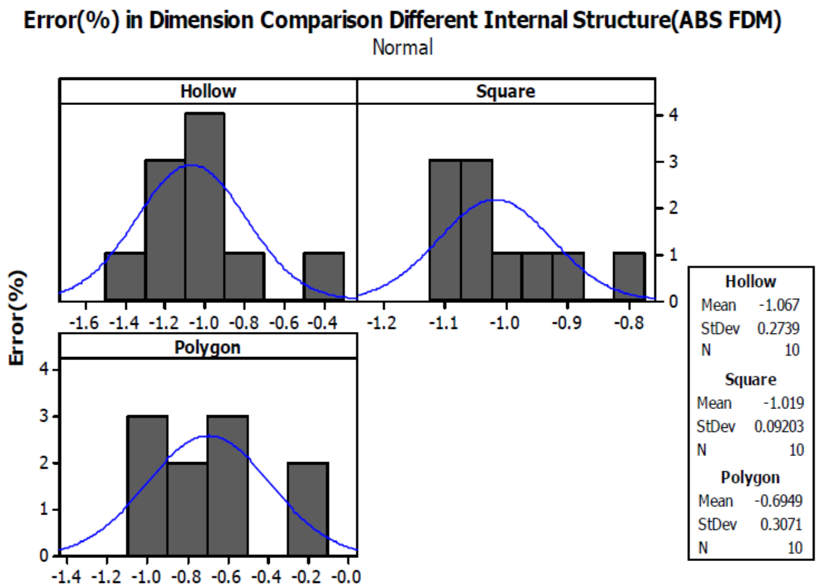

Fig. 4. Percentage errors in dimensional comparison among different internal structures of FDM ABS

As can be seen in Figure 5, it shows the flatness comparison between different internal structures of FDM ABS. Based on the Figure 5, the FDM pattern with square internal structure shows the lowest flatness which was 0.0525µm. Meanwhile the highest flatness is FDM pattern with hollow internal structure which was 0.23µm.There is slightly different value between the highest and the lowest data. This is probably cause by the effect of the inner structure.

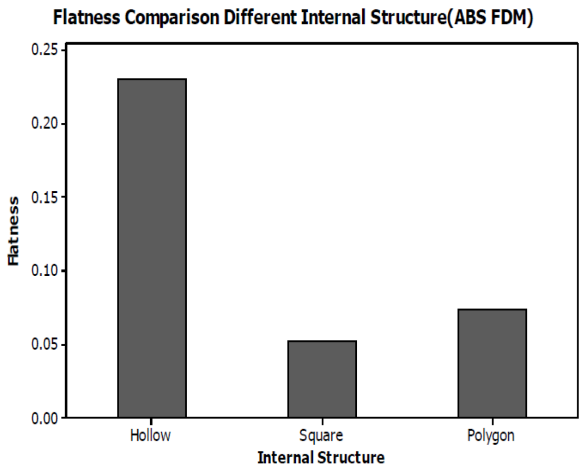

Fig. 5. The flatness comparison between different internal structures of FDM ABS.

For the product LM6 alloy calculation, the equation related for calculation to obtain the precise data was shown in Equation (2),

$$\frac{|Dimension\ \ of\ LM6 - Dimension\ \ of\ FDM\ pattern\ |}{Dimension\ \ of\ FDM\ pattern}\ x\ 100 \tag{2}$$

Whereby;

Dimension of product LM6 = mm

Dimension of FDM ABS pattern = mm

Moreover, Figure 6 shows the percentage errors in dimension comparison of IC process from different internal structures FDM ABS. Based on Figure 6, the graph shows the shrinkage from FDM ABS pattern to IC product (LM6). Negative sign of means shows that the decrement of dimension due to the shrinkage. The graph which shows highest mean value was IC product pattern with square internal structure followed by polygon and hollow. It shows that the square shrink more among three internal structures. Referring to the standard deviation of the graph, highest value was from IC product pattern with square internal structure followed by polygon and hollow. Next, for the graph of IC product pattern with polygon internal structure, there was split to the right which in between 0% to 1%.

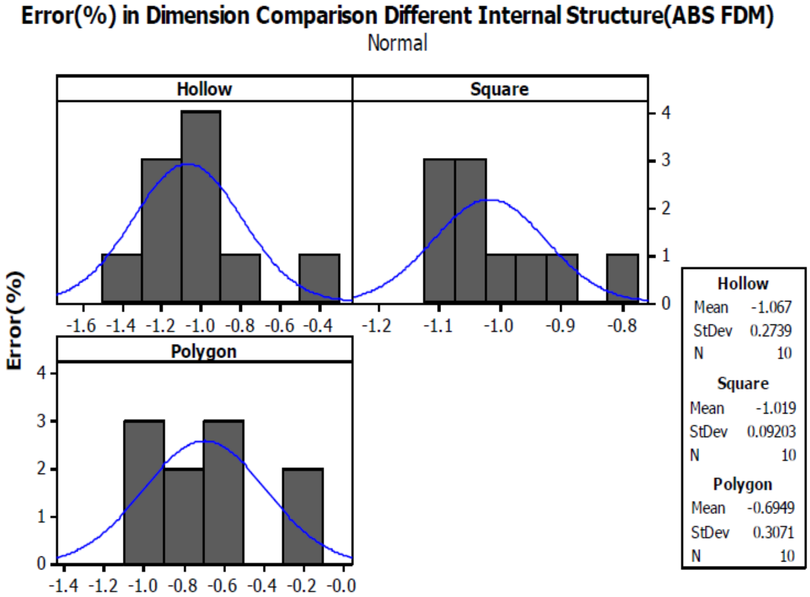

Fig. 6. Percentages error in dimension comparison of IC from different internal structure FDM ABS

Based on the figure 7, for IC product from hollow internal structure (ABS FDM) shows the lowest flatness which was 0.076µm. Meanwhile the highest flatness was FDM pattern with square internal structure which was 0.245µm.There are quite huge different between the highest and the lowest value data. Thus, mainly its cause by the effect of the shrinkage after aluminum cooled and solidified.

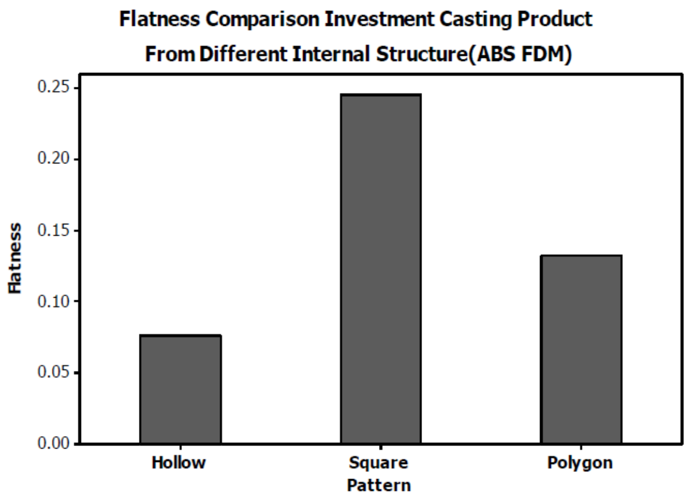

Fig. 7. Flatness comparison investment casting product from different internal structures (ABS FDM).

From this experiment, the effects of internal pattern structure with the quality of FDM ABS are related to the layer by layer process, whereby during the part fabrication of IC process, the early design stage is critical [9-11]. During the IC process, there must be shrinkage defect from master pattern when aligned with the product. Therefore, the effect of the shrinkage must be affected by few factors such as thickness of the shell, fluidity of the molten alloy metals, solidification of alloy metals and etc. As we know, ineffective burnout process will contained the residue ABS pattern in the shell ceramic before aluminum poured into it due to the residual ash not completely burnout. As a result, more locations of the parts would undergo shrink defects due to filling order. To overcome this issue, the ceramic mould should be burnout completely without residue with temperature higher than 600°C and if there is any residue left the manual cleaning using air pressure should be done. The hot metal poured extremely varied locations in the cavity, affecting feeding and heat transfer rates by filling an order supplied into the ceramic shell. The shrinkage effect occurred from drawing pattern until the IC in all internal structure patterns. Basically, these benchmarking of quality evaluation which were the dimensional accuracy and flatness test are influenced by shrinkage defect. Internal structure give the effect when print the FDM pattern. During the printed layer-by-layer process, there was probability that the presence of internal support could cause warping at the wall. It is because of the ABS material are classified as thermoplastic which less harden during high temperature and the ABS plastic easily shrink during the cooling process. Other than that, it is also due to the extrusion nozzle and plane a bit distance during early stage in printing and caused imperfect in the first layer.

By selecting most appropriate manufacturing control parameters, development of materials with relatively small shrinkage or stress free properties, and stress relief methods are several ways to minimize the effect of shrinkage. In addition, to ensure pattern well precise, the holding time must shortened, however if the holding time too short it will cause distortion when removing it from the mould, as it is too fragile when handled, since the longer holding time will cause more shrinkage take place. Figure 8 shows the shrinkage effect (red section) on the plane surface after the aluminium process for the sacrificial pattern of FDM ABS.

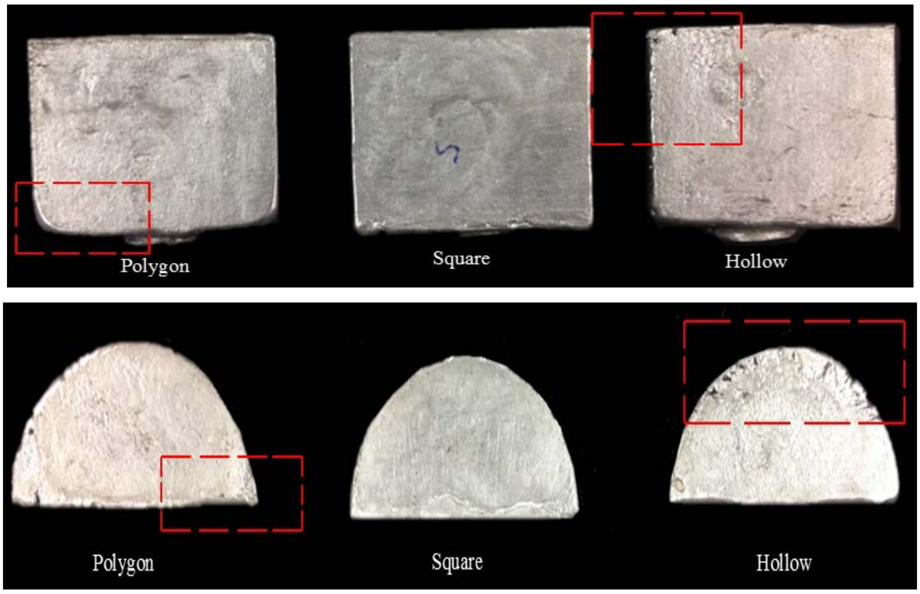

Fig. 8. Shrinkage effect on the plane surface of casting products

IV. Conclusion

In conclusion, this study basically an application of AM process used to cooperate with IC process involving evaluation of the dimensional accuracy and flatness. Furthermore, each single part of inner design structure of FDM ABS tends to effect either on dimension accuracy and flatness. The most significant inner pattern of the FDM ABS pattern in granting response which better in dimension accuracy was square pattern and for the IC product (LM6) shows hollow product. From the analysis, it can conclude that square shows the highest error in dimension accuracy among the three master patterns. It is because the square master pattern produced higher hoop stress during burnout process. From the calculation the average of error in dimension accuracy from drawing CAD until product of IC pattern is -1.2514%. Moreover, to fabricate the pattern of IC from FDM ABS as master pattern the dimension must be increased about 1.2514% of every nominal dimension on CAD drawing. Then, the dimensions will gain as needed. Lastly, the most significant inner pattern of the FDM pattern in granting response which good in flatness was square pattern and for the IC product (LM6) was hollow product. Based on observation, it can conclude that hollow pattern shows the best flatness surface plane. Nevertheless, more findings need to be done in order to utilize the ability of portable FDM ABS whereby it can be distributed as sacrificial pattern for further development of the alloy metal casting parts. This will include the early study of process parameters as well as optimization of shelling strategy for improvement of dimensional accuracy and flatness of sacrificial pattern in IC process.

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