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Fabrication of a high precision silicone rubber mold for replicating wax patterns of cylinder heads

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New products must be more quickly and cheaply developed, manufactured and introduced to the market due to the pressure of global competition. This work demonstrates a technique for producing accurate wax patterns made from a high precision silicone rubber mold. Silicone rubber mold is cut into five components, which is the minimum number of components for assembling the silicone rubber mold. The advantages of this silicone rubber mold include savings in assembly time, reduction of human error while assembling the silicone rubber mold and good assembly precision. The shrinkage of critical dimensions can be controlled within 2.19%. Results reported here can speed up the velocity in the development of a new cylinder head in the motorcycle industry.

Keywords: Cylinder head, Rapid prototyping, Rapid tooling, Silicone rubber mold, Wax patterns, Shrinkage

New market realities need faster product development and reduce time to market. They also require higher quality, cost reduction and greater efficiencies. To reduce the product development time and reduce the cost of manufacturing, rapid prototyping (RP)[1] has been developed, which offers the potential to completely revolutionize the process of manufacture. However, the features of the prototype do not usually meet the need of the end product with the required material. Rapid tooling (RT) technologies are then developed. RT is regarded as a nature extension of RP since it is the technology that uses RP technologies and applies them to the manufacturing of tool inserts[2]. Since the importance of RT goes far beyond component performance testing, RT is regarded as an important method of reducing the cost and time to the market in the development of a new product. Several RT technologies are commonly available in industry now. For the purpose of the classification, RT is divided into soft and hard tooling and also indirect and direct tooling. Soft tooling is easier to work with than tooling steels because these tools are created from materials such as epoxy-based composites with aluminium particles, silicone rubber or low-melting-point alloys. It is well known that RT is capable of replacing conventional steel tooling, saving the cost and time in the manufacturing process[3,4]. Indirect soft tooling is used more frequently in the development of new products than direct tooling because it is fast, simple and cost-effective. It is a well-known fact that the silicone rubber mold is employed frequently because it owns flexible and elastic characteristics so that parts with sophisticated geometry can be fabricated[5].

In the past, traditional process of optimizing cylinder head was based on building a series of physical prototypes and performing a series of different experiments and tests, which was time-consuming[6]. Traditionally, cylinder heads are manufactured by investment casting process. Thus, manufacturing wax patterns with high dimensional accuracy is also an important issue. In addition, it was difficult to build physical prototypes during the early stage of the design. In order to overcome the above stated problems, a cost-effective method to develop a new cylinder head was proposed. Cylinder head designed was first fabricated by RP machine. The focus of this work is to develop a silicone rubber mold with the minimum number of components for replicating wax patterns with high dimensional accuracy. Wax patterns were replicated from this silicone rubber mold. Surface roughnesses of wax patterns were measured using a white-light interferometry (WLI). Critical dimensions of the wax patterns replicated were measured using a digital vernier calliper. Geometrical features of cylinder head

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on the shrinkage of critical dimensions were analyzed. Advantages of this silicone rubber mold were discussed.

Experiment Procedure

The study flow chart of this work is shown in Fig. 1. The first step in the process is to design a new cylinder head using the Pro/ENGINEER software. The three-dimensional (3D) model designed was sliced with a thickness of 0.2 mm along Z axis into a series of two-dimensional slice models. Series of slice models were combined together by RP machine (Solider 5600; Cubital, Inc.) to fabricate a 3D physical model. A core is needed for making silicone rubber mold because there is an internal cavity inside the cylinder head. Low carbon steel was used as the core materials. A core was machined by a precision computer numerical control turning machine, as shown in Fig. 2.

Figure 3 shows the schematic illustration of fabrication process for a silicone rubber mold in detail[7]. Silicone rubber was used as the elastomeric mold material. Base compound (KE-1310ST; ShinEtsu, Inc.) and hardener (CAT-1310S; ShinEtsu, Inc) were mixed thoroughly to make silicone rubber mold. The amounts of base compound and hardener were calculated by multiplying the desired volume of the silicon rubber mold to be made by the density of silicone rubber (1.07 g/cm^3 at 23°C). Typical properties of silicone rubber are summarized in Table 1. The curing agent and silicone rubber in weight ratio of 10:1 was mixed thoroughly with a stirrer. The Shore A hardness of silicone rubber mold fabricated is about 40. The properties of the silicone rubber mold such as durability and mold life are significantly affected by the relative amounts of curing agent and silicone rubber. Thus, calculating the weight of base and curing agent precisely is crucial before mixing. To reduce human error, a user-friendly man-machine interface was developed using Visual Basic program. A vacuum machine was used for generating a vacuum atmosphere, which provides a function of degassing process to remove the air bubbles derived from the mixing process of the silicone rubber and hardener. Depending on the extent of air bubbles in the mixture, the degassing process can range from 25 to 60 min. After degassing process, the pressure inside the vacuum machine was changed by breaking vacuum atmosphere. Thus, a silicone

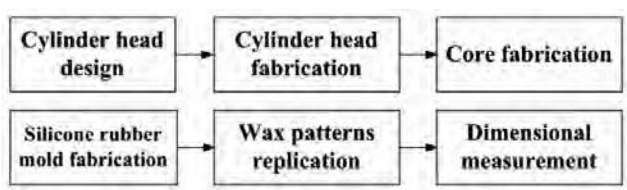

Fig. 1—Flow chart of this work

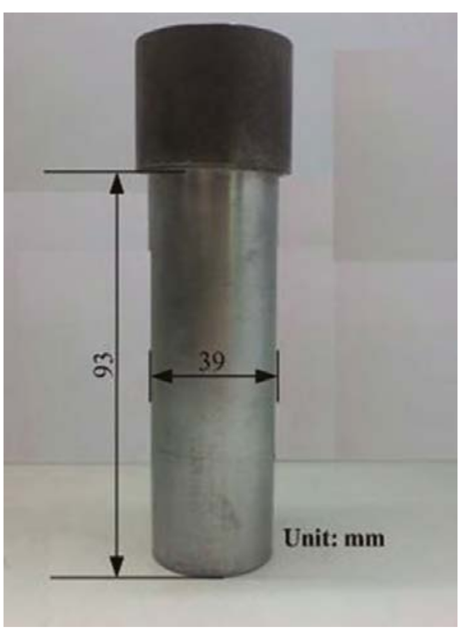

Fig. 2—Core for making silicone rubber mold

Table 1—Typical properties of silicone rubber

Color	Translucent
Viscosity (Pa-s)	75
Tensile strength (MPa)	5.86
Tear strength (kN/m)	21.875
Elongation (%)	340
Density (g/cm^3)	1.07
Mix ratio by weigh	10:01
Melting point (°C)	280
Cure conditions (h/°C)	24/23

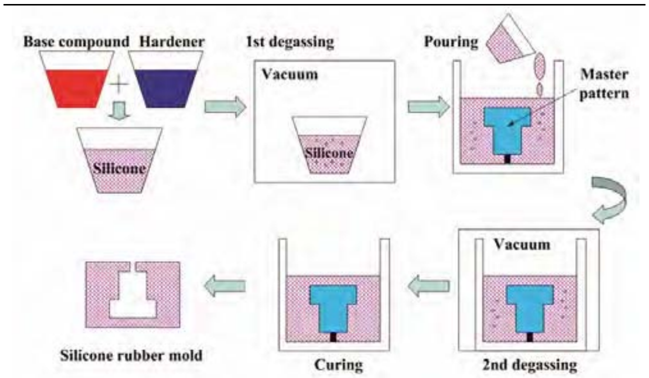

Fig. 3—Schematic illustration of fabrication process for a silicone rubber mold using vacuum casting

rubber mold can be fabricated without defects caused by the air bubbles derived from the mixing process. In general, cylinder heads are manufactured by investment casting process consisting of fabrication of wax patterns, ceramic coating, wax removal, drying, metal casting, and surface finishing. In this work, casting wax (k512; Kato, Inc.) was applied to fabricate wax patterns. The cast wax was melted at 90°C in an oven first. Then the temperature of molten wax was maintained at 70°C before pouring into silicone rubber mold. To increase the yield rate of wax patterns, a convection oven (DH400; Deng Yag, Inc.) was used to preheat the silicone rubber mold before pouring the molten wax. Five critical dimensions of the wax patterns replicated were measured using an electronic digital vernier calliper (S11006; Mitutoyo, Inc). Surface roughnesses of wax patterns fabricated were measured using a WLI (7502; Chroma, Inc.). The measurement position of wax patterns for surface roughnesses evaluation is the surface of the cylinder guide, which is an important part of a cylinder head. The sampling area was chosen to be 50 μm × 50 μm. The arithmetic average roughness value (R_a) was used to quantify the surface finish. R_a values represent the average displacement of the peaks and valleys measured with respect to a mean line.

Results and Discussion

Figure 4 shows the cylinder head fabricated by RP machine. The cylinder head fabricated required further processing because of their relatively poor surface roughness, which results from the layered structure inherent in the building method[8,9]. In this work, the hand finishing was used to improve the stair-step surface texture inherently in the master pattern models fabricated[10,11]. Figure 5 shows the silicone rubber mold of a cylinder head. Blue lines indicate the path for cutting the silicone rubber mold. A silicone rubber was chosen as the material of an elastomeric mold because of its high elasticity and low surface energy. Figure 6 shows the details about paths for cutting the silicone rubber mold.

In general, the fewer the number of silicone rubber components means a good assembly precision. It is evident from Fig. 7 that silicone rubber mold are composed by only five components. Figure 8 shows the assembly of silicone rubber mold. The advantages of this silicon rubber mold include good assembly precision, savings in assembly time and reduction of human error while assembling the silicone rubber mold.

After assembling the silicone rubber mold, wax patterns were then replicated and successfully removed from the silicone rubber mold, as shown in Fig. 9. To slow down the solidification rate of liquid wax, silicone rubber mold was preheated to 70°C in a convection oven. The freezing time of wax patterns is about six hours. The use of silicone rubber mold is to fabricate wax patterns without the use of traditional tooling. The elastomeric mold of a high elasticity enables wax patterns to be released without damage or breakage. Wax patterns fabricated can be used for optimizing the casting design in terms of process and gating parameter, which reduces the time and cost required to develop a new cylinder head. Figure 10 shows the surface roughness of wax pattern produced from silicone rubber mold. The average roughness is about 217 nm. This result shows that the surface finish of the wax pattern replicated from silicone

Fig. 4—Cylinder head fabricated by RP machine

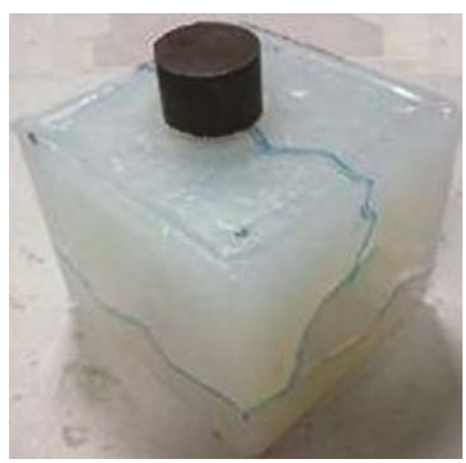

Fig. 5—Silicone rubber mold of a cylinder head (Blue lines indicate the path for cutting the silicone rubber mold)

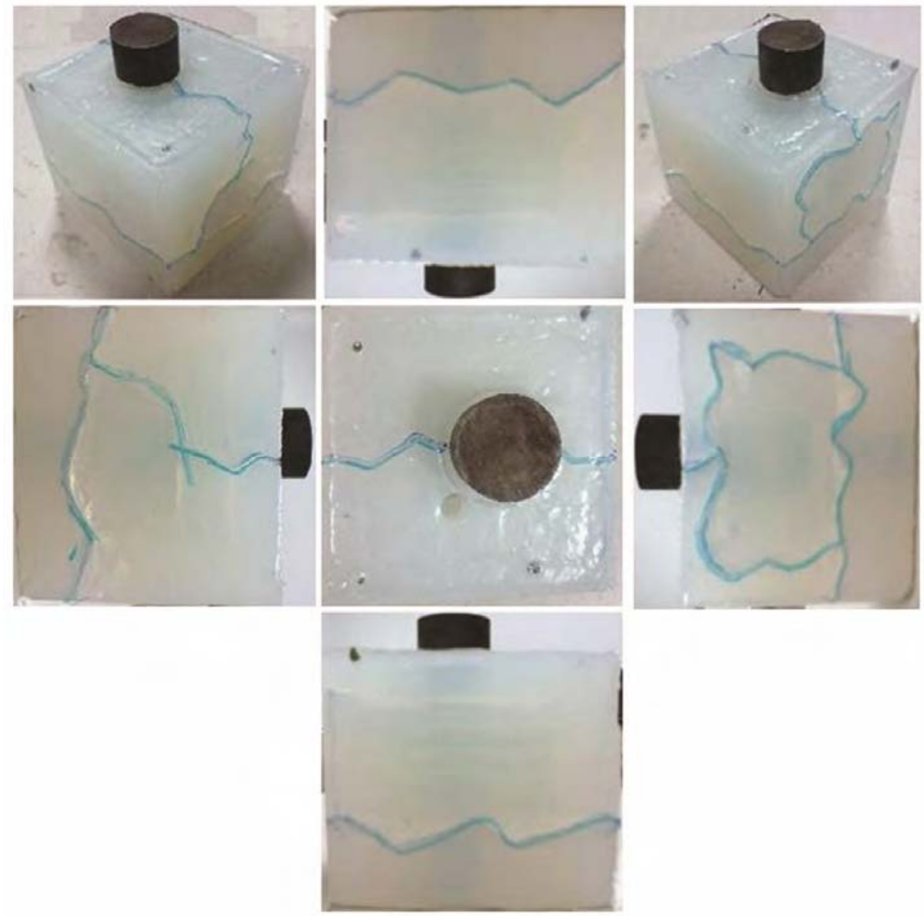

Fig. 6—Details about paths for cutting the silicone rubber mold

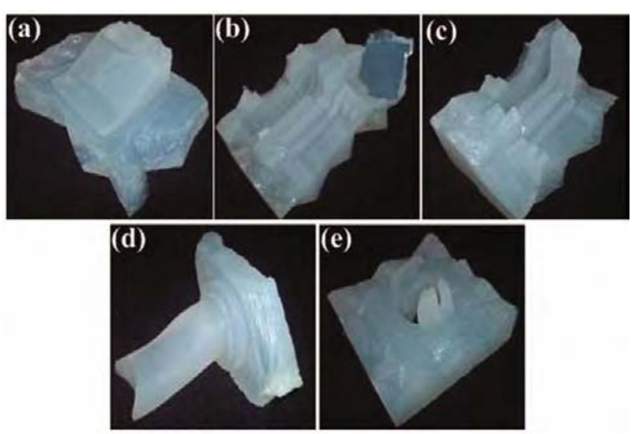

Fig. 7—Five components of silicone rubber mold

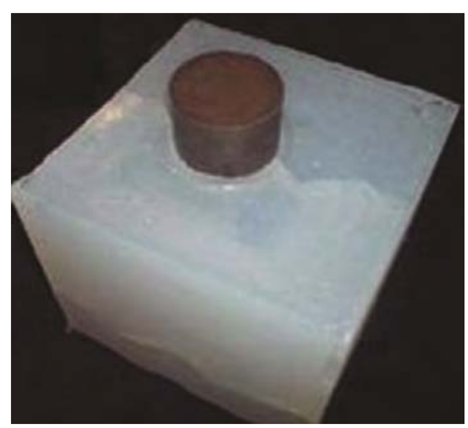

Fig. 8—Assembly of silicone rubber mold

rubber mold is satisfactory for general engineering purpose[12,13]. Figure 11 shows the measurement positions of a cylinder head. Table 2 shows the measurement results of five critical dimensions. It is evident that the thermal shrinkage[14] of length, width, height, diameter, and length of square hole is about 1.12%, 1.07%, 2.19%, 0.47% and 0.86%, respectively. Thermal shrinkage is caused by the temperature difference in the cooling period because of different thicknesses of the cylinder head, which leads to a complicated non-uniform shrinking of critical dimensions. It is clear that the amount of high

Fig. 9—Wax patterns made from silicone rubber mold

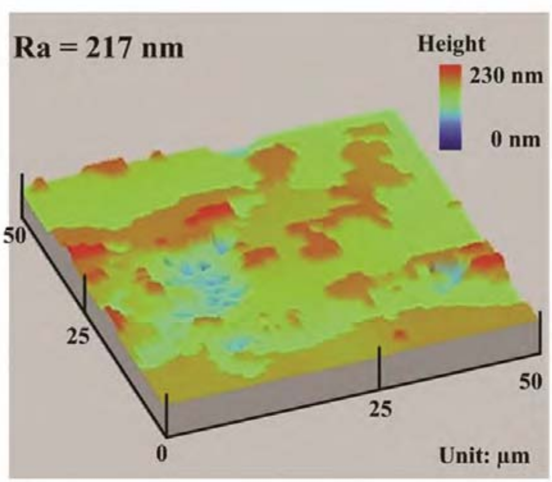

Fig. 10—Surface roughness of wax pattern produced from silicone rubber mold

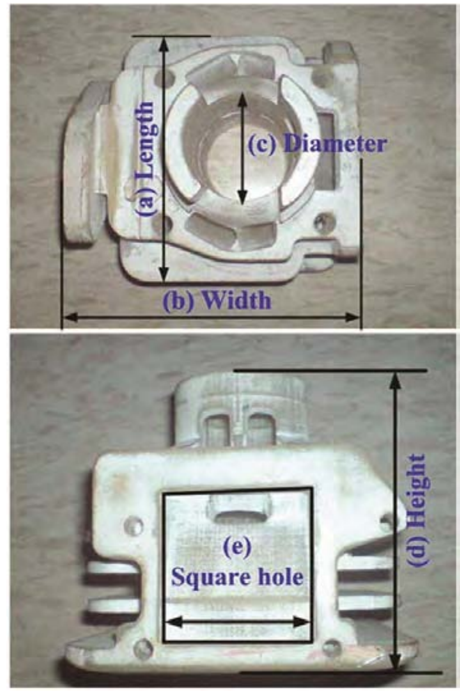

Fig. 11—Measurement positions of a cylinder head

Table 2—Measurement results of five critical dimensions

	Rapid prototyping (mm)	Wax pattern (mm)
Number of measurement	**(a) Length**	
1	101.86	100.73
2	101.79	100.65
3	101.78	100.62
Average	101.81	100.67
Shrinkage (%)	1.12	
Number of measurement	**(b) Width**	
1	109.62	108.33
2	109.52	108.07
3	109.65	108.27
Average	109.6	108.43
Shrinkage (%)	1.07	
Number of measurement	**(c) Diameter**	
1	38.05	38.01
2	37.94	37.85
3	38.2	37.78
Average	38.06	37.88
Shrinkage (%)	0.47	
Number of measurement	**(d) Height**	
1	92.07	89.24
2	92.06	90.52
3	92.02	90.32
Average	92.05	90.03
Shrinkage (%)	2.19	
Number of measurement	**(e) Length of square hole**	
1	41.86	41.01
2	41.75	41.72
3	41.72	41.54
Average	41.78	41.42
Shrinkage (%)	0.86	

shrinkage is relatively high, up to 2.19%, due to a thicker thickness of this section. To reduce the thermal shrinkage, a decrease in melt temperature of wax is an alternative choice because the accuracy of wax pattern produced is affected by melt temperature of wax[15]. In this work, geometrical features of cylinder head on the shrinkage of critical dimensions can be controlled within 2.19%. This information can be applied to the critical dimensions compensation for enhancing the dimensional accuracy of a cylinder head designed.

Wax injection tool machined by computer numerical control (CNC) machine for replicating wax patterns of cylinder head is a traditional method. A major contribution of this work is to fabricate a silicone rubber mold for developing a new cylinder head, which is the minimum number of components for replicating wax patterns. In general, the total working time for fabricating a wax injection tool using CNC machining is about seven days. However, the fabrication time of that using RT is drastically reduced to only two days. This means that a time saving of 71.42 % can be achieved. In addition, the advantage of this silicone rubber mold for replicating wax patterns is low manufacturing cost compared with the technology proposed by Rezavand and Behravesh[15]. Another contribution of this work is to investigate the shrinkage of critical dimensions of a cylinder head. As described above, this means that this technique can be accepted for developing sophisticated geometry over a shorter period of time and at lower cost in the motorcycle industry because the cylinder head is one of the most complicated and challenging parts of motorcycle engine in terms of narrow dimensional and geometrical tolerances.

Conclusions

A technique to manufacture wax patterns of cylinder head with high precision dimensions for investment casting has been presented. This technique provides some advantages in the early stages of engine design to save time and cost in the manufacturing process. Only five components have been cut when the silicone rubber mold was fabricated, which is the minimum number of components for replicating wax patterns. Surface finish of the wax pattern replicated from silicone rubber mold is satisfactory for wax patterns needed for investment casting. The shrinkage of critical dimensions can be controlled within 2.19%. Results reported here can speed up the velocity in the development of a new cylinder head in the motorcycle industry.

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