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Analysis for diving regulator applying local heating mechanism of vapor chamber in insert molding process ☆

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ABSTRACT

This paper aims to use the local heating mechanism, along with the excellent thermal performance of vapor chamber, to analyze and enhance the strength of products formed after insert molding process. In the insert molding process, the metal insert is firstly placed into the mold, and then formed into an embedded plastic product named diving regulator by injection molding. These results indicate that, the product formed by the local heating mechanism of vapor chamber can reduce the weld line efficiency and achieve high strength, which passed the standard of 15.82 N-m torque test, with a yield rate up to 100%.

1. Introduction

Plastic products are widely applied despite of their comparative disadvantages in material strength, electrical and thermal conductivity, and glossiness, as compared to metal. Driven by the demands on the functionality and appearance design, the optimal option of the designers is assembly and molding of parts of different materials (metal and plastic). In traditional processing procedure, the plastic parts and metal inserts are formed separately, and then assembled by secondary processing. Such manufacturing process can assemble parts of different dimensions or shapes, but also lead to longer manufacturing time and higher cost.

Insert molding process is a simplified molding method that eliminates secondary processing and assembly. In this process, the metal inserts are firstly formed, and placed in the mold during injection molding (the metal inserts can be designed into a grooved pattern, allowing them to be connected closely with the plastics), and then the mold is closed for injection molding. Thus, the products can be formed in a single molding process, helping to shorten the processing time and reduce the possible human error arising from several procedures.

Although insert molding process can greatly improve the assembly and manufacturing procedure, the joining of two materials is the main problem yet to be solved. When the metal inserts are placed in the mold for injection molding, a weld line may be formed from the plastics after bypassing the inserts. Traditionally, the inserts are placed in the mold at room temperature, but the temperature of inserts is lower than that of the mold (the temperature of inserts cannot rise sharply within a very short period) when the filling is conducted after mold sealing. Once the plastics are filled, the temperature of plastics bypassing one side of the inserts may decline more quickly than that of plastics contacting the temperature side of the mold wall, so a weld line may be formed when meeting again after bypassing the inserts.

The strength at the position of weld line is generally lower than that at the region of plastics [1–3]; moreover, the metal inserts are generally located at the stress region when the product is utilized. Hence, the rupture of plastics often occurs from the weld line at the rear of the metal inserts, leading to damage of products. Some studies [4–7] indicated that, during the injection molding process, the defect of weld line could be resolved by adjusting the mold temperature. The key is to rapidly and uniformly increase the temperature of inserts before the plastics enter into the mold cavity.

Studies have proved that the vapor chamber can be used to eliminate the weld line of plastic injection molding [8]. Given a vacuum chamber with inner wall of microstructure, the vapor chamber allows the evaporated heat of thermal superconducting medium to be distributed rapidly and uniformly to the low-temperature area for condensation, when the source of heat is conducted to the evaporation region. Then, the evaporated heat is re-circulated to the source of heat through the capillary structure within the chamber. This procedure is repeated in the vapor chamber [9]. Both the vapor chamber and heat pipe have the same passive operating principle and theoretical framework, without need of additional energy consumption. Moreover, the vapor chamber is free from the influence of the gravity. However, the heat pipe has a one-dimensional linear heat transfer mode [10,11], while the vapor chamber has a two-dimensional heat transfer mode. Thus, the vapor chamber enables the heat to be distributed rapidly and uniformly onto a surface [12]. With the vapor chamber and heating mechanism, the

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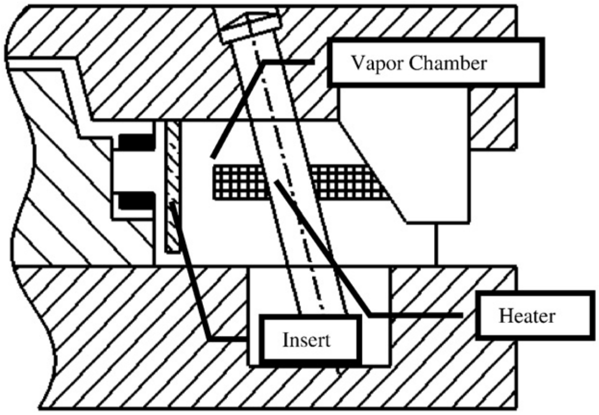

Fig. 1. Local heating mechanism of vapor chamber applying insert molding product.

Fig. 3. Insert molding product.

inserts can be heated up quickly after being placed into the mold, thus increasing greatly the strength of weld line for injection molding process.

This paper proposes a local heating mechanism of vapor chamber. As shown in Fig. 1, the mold is a moveable slider, at inner side of which a heating rod is installed; a vapor chamber is mounted at the joint of the frontal edge of the slider and the mold wall. When the inserts are placed in the mold and the mold is closed, the heated slider will move forward, and contact the vapor chamber, so that the inserts are heated up rapidly and quickly with the vapor chamber. When the plastics are used for filling, the temperature of inserts corresponds to the temperature of external mold temperature. When the mold is opened after completion of filling for packing and cooling, the heated slider will move back. Then, the heating the stopped, and the finished product is pushed out for next process. The dimension of the heating system can be adjusted according to the mold mechanism.

2. Experimental procedure

To find out the efficiency of the heating mechanism, the heating mechanism is mounted onto the mold of a submersible regulator for testing. Diving regulator (see Fig. 2) is an important diving equipment of SCUBA (Self Contained Underwater Breathing Apparatus) diving [13], which can convert the air in a compressed tank into breathable air of ambient pressure, depending on the breathing action of the divers. As the regulator is connected to a high-pressure tube, the connector as shown in Fig. 3 of the regulator is usually made of stainless steel due to usage safety and operating environment (it is used in seawater, thus, corrosion-resisting products must be used).

During the manufacturing process, the metal joint is manually placed into the mold, and then the mold is closed for injection molding, so that the molded metal joint is embedded into the product as shown in Fig. 4. The regulator must pass torque test. The torque wrench and force application schemes are shown in Fig. 5. A regulator is packaged and delivered only after passing 128.82 N-m torque tests (torque wrench applied to metal joint). Due to the special features of diving environment, some manufacturers may conduct thermal cycling test and then 15.82 N-m torque test before the regulators are shipped. The parameters and conditions of thermal cycling test differ slightly depending on the specific requirements of the manufacturers.

Fig. 2. Diving regulator.

Fig. 4. Diving regulator with metal joint.

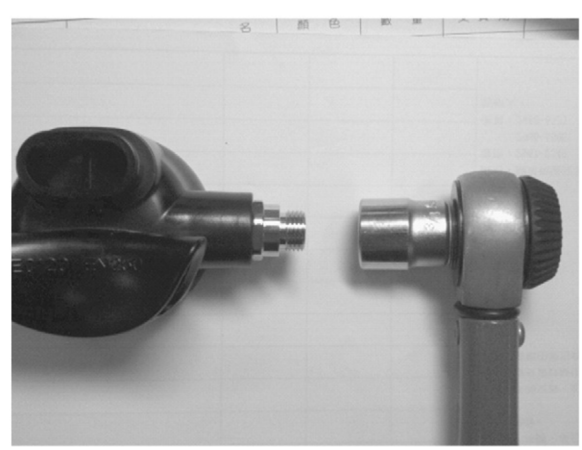

Fig. 5. Torque testing device.

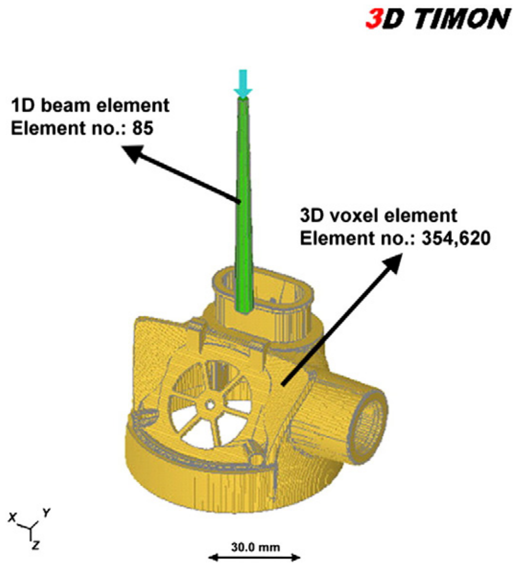

Fig. 6. Grid element.

This experiment includes three parts. The first part is to test the thermal performance and temperature uniformity of vapor chamber. The size of the vapor chamber used in this study is 50 mm × 50 mm × 4 mm. First, thermal performance test is conducted to measure the temperature uniformity of vapor chamber, and confirm the equivalent heat conductivity under different temperatures. The second part is to test the regulator. The inserts are heated up less than three heating temperatures, and the regulator is tested by five groups of torques. The number of damaged inserts at different heating temperatures is recorded to compare the effects of the heating system on the strength of product. The third part is the torque test on the regulator. First, thermal cycling test is conducted on the products that are not damaged in the previous test; then, torque test is conducted by five groups of torques. Similarly, the number of damaged parts is recorded for data comparison.

In the experiment, twenty samples are prepared for each heating temperature, and the damage conditions are recorded. The heating temperatures are 25 **°C**, 40 **°C** and 90 **°C** (Type1, Type2 and Type3), respectively. The torque wrenches are 11.3 N-m, 12.43 N-m, 13.56 N-m, 14.69 N-m and 15.82 N-m, respectively. The regulators have to pass the torque test at 15.82 N-m in order to meet the requirement for shipping.

Table 1
Molding condition.

Melt temperature (°C)	270
Mold temperature (°C)	80
Filling time (s)	1.2
Packing time (s)	10
Packing pressure (MPa)	60
Cooling time (s)	30

To confirm the forming position of the weld line, this study used 3D TIMON for numerical simulation. Fig. 6 shows the grid graph, and Fig. 7 shows the partial enlarged view of the weld line formed nearby the insert. It is observed that the weld line is rightly formed at the position of the insert. The regulator is made of PC and ABS, the mold is made of S45C, and the male, female cores and slider made of ASSAB 718. The forming conditions of the regulator are listed in Table 1.

3. Results and discussion

3.1. Performance test of the vapor chamber

Fig. 8 shows the framework of thermal performance test of vapor chamber. Wang [14] inputted different heat fluxes with simulated source of heat and through dimensional analysis, and obtained the equivalent heat transfer coefficient of vapor chamber, as shown in Eq. (1). Table 2 lists the equivalent heat transfer coefficient of vapor chamber at different heat fluxes.

$$k_{eff} = 46.1 \cdot (L_{vc} \cdot W_{vc})^{0.15} \cdot (t_{vc})^{0.24} \cdot (q_{in})^{0.28} \quad (1)$$

3.2. Torque test of the regulator

Fig. 9 shows the mold installed on the injection molding machine. After completion of molding, the regulator is fabricated at three different heating temperatures (25 **°C**, 40 **°C** and 90 **°C**); Fig. 10 depicts the damage condition at the position of weld line.

Table 3 lists the number of damaged regulator in five groups of torque test. The results indicate that, two out of twenty Type1 products cannot pass 15.82 N-m torque test (damaged at 13.56 N-m and 14.69 N-m torque tests), representing a rate of 10%; all Type2 and

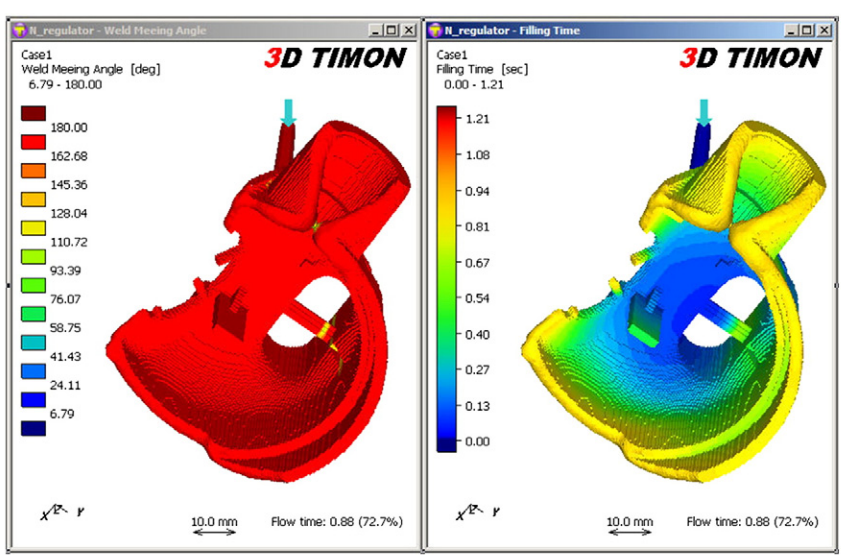

Fig. 7. The position of weld line.

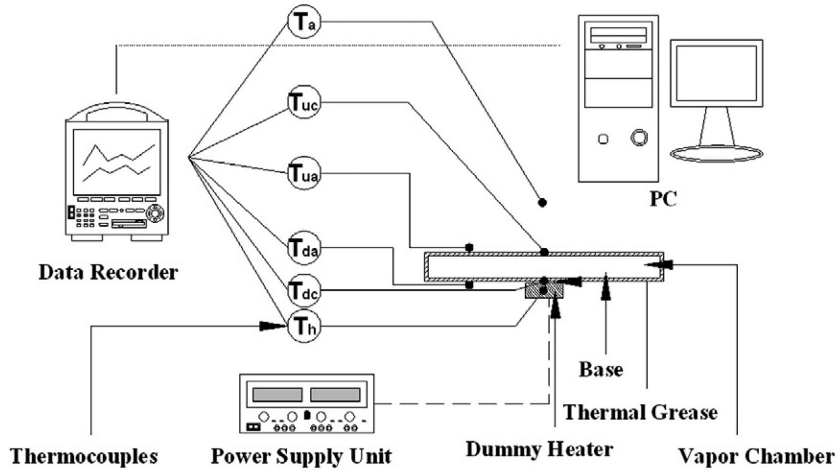

Fig. 8. Experimental apparatus of vapor chamber.

Type3 products can pass 15.82 N-m torque test. The yield is up to 100%.

3.3. Torque test of regulator after the thermal cycling test

These samples from the second part are subject to torque test after thermal cycling test (Type1 are 18, Type2 and Type3 are all 20). Fig. 11 shows the five thermal cycling tests, and Table 4 lists the results of torque test.

The experimental results indicate that, after the thermal cycling test, only six Type1 products can pass 15.82 N-m torque test, with a yield of only 30%; ten Type2 products can pass 15.82 N-m torque test, with a yield of only 50%; all Type3 products can pass the test, with a yield up to 100%.

4. Conclusions

According to the experimental results, after the completion of molding, 10% of Type1 samples did not pass torque test, while all Type2 and Type3 samples passed the test. After thermal cycling test, the residual stress of the plastics began to be released due to temperature change, so the strength of product at the position of weld line was reduced substantially. Only 30% of Type1 products passed the 15.82 N-m torque test after thermal cycling test, followed by 50% of Type2 products and 100% of Type3 products.

This study proved that, among existing insert molding process, the temperature of inserts has impact on the final assembly strength of product. In this paper, the local heating mechanism of vapor chamber can control the molding temperature of inserts; and the assembly strength can be improved significantly if the temperature of inserts

Table 2
Effective thermal conductivity.

Heat Flux (W/cm^2)	Keff (W/mk)
10	396.2
20	481.0
30	538.9
40	584.1
50	621.7

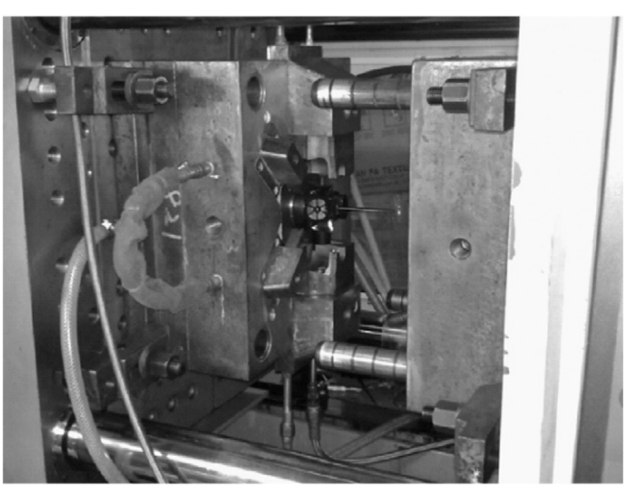

Fig. 9. Diving regulator in injection mold.

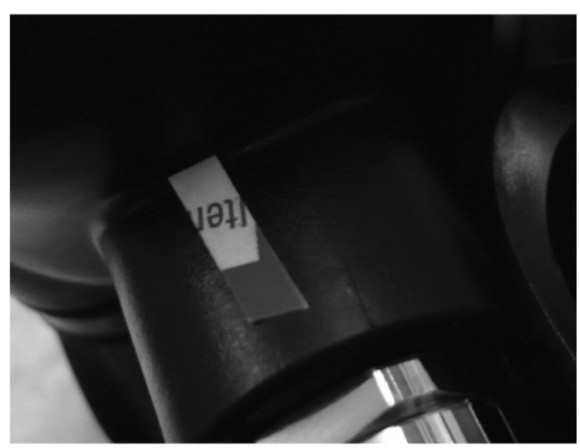

Fig. 10. The weld line of diving regulator.

Table 3
Torque test (failed part no.).

	Type1	Type2	Type3
	25 °C	40 °C	90 °C
12.43 N-m Amount of failed part	0	0	0
13.56 N-m Amount of failed part	1	0	0
14.69 N-m Amount of failed part	1	0	0
15.82 N-m Amount of failed part	0	0	0
Amount of passed part	18	20	20
Defective Rate	10%	0%	0%

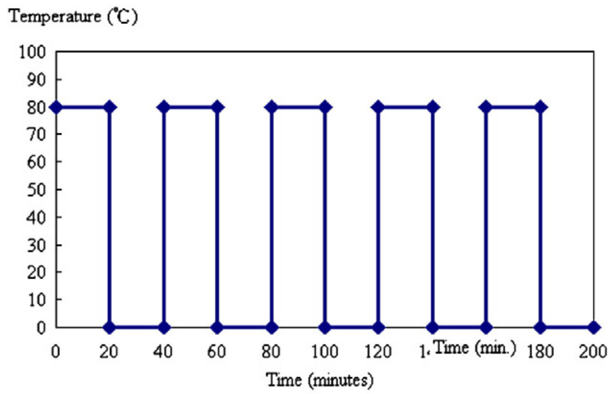

Fig. 11. Relationship of temperature with time at cooling-heating cycle test.

Table 4
Torque test.

	Type1	Type2	Type3
	25 °C	40 °C	90 °C
12.43 N-m Amount of failed part	3	2	0
13.56 N-m Amount of failed part	7	5	0
14.69 N-m Amount of failed part	2	3	0
15.82 N-m Amount of failed part	0	0	0
Amount of passed part	6	10	20
Defective Rate	70%	50%	0%

prior to filling can be increased over the mold temperature, thus allowing the local heating mechanism to improve the weld line in the insert molding process.

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