An Experimental Study of Weld Line in Rapid Heat Cycle Molding

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Rapid Heat Cycle Molding is a new environmental-friendly technology to access high surface quality of plastic products. In this paper, the influence of processing parameters of this technology on weld line of High density polyethylene (HDPE) plastics has been investigated using the orthogonal experiment method. Weld line is evaluated by dE(Euclidean distance). All the parameters influencing weld line have been respectively discussed, while the result shows that heating temperature is the most important factor in the process of forming weld line. From this point of view, the influence of heating temperature on weld line is then further studied from a micro prospective.

Keywords: *weld line, Rapid Heat Cycle Molding, processing parameters, orthogonal experiment, heating temperature*

Injection-molded products are widely used nowadays while their development trend is to be low-cost, environmental-friendly with high performance. High stability and performance of molding process and process equipment are required due to their usage in industry [1,2]. Rapid Heat Cycle Molding (RHCM) technology is a new promising “green” injection technology, which can improve the surface quality of products and eliminate weld line without secondary polluting processes, such as spraying and electroplating [3].

“Weld line” refers to the three-dimensional regions generated by the difference of injection-molded parts. It is formed when the two shares of the molten plastic in contact [4]. Weld line has got more and more attention of researchers in injection molding in recent years. Malguarnera and Mielewski [5, 6] analyzed the forming process and shape of the weld line in traditional injection molding, which laid the foundation for the formation mechanism of weld line. Fellahi [7] studied the structure of weld line with the mixture of HDPE/PA6, and found that the organizational structure of the weld zone and the main organizational structure of the part are completely different. Zhou and Li [8] proposed a way to avoid weld line and improve weld line strength from the aspect of the molding process, mold design and product design based on the characteristics of the initial meeting node. Subsequently, they presented another prediction method with back-propagation network to evaluate weld lines [9]. Xie and Ziegmann [10] studied the weld line tensile strength on micro tensile sample based on different gate dimensions and processing parameters. Liu [11] used Taguchi experimental methods to study the impact of processing parameters on weld line of PS plastics in traditional injection molding, the results showed that melt temperature had the greatest impact on weld line, while mold temperature, packing pressure and injection speed followed. In conclusion, the above researches have obtained better understanding of the formation, performance and control of weld line in traditional injection molding. However, the RHCM technology has rarely involved by former work. The research of the impact of processing parameters on weld line will provide a great practical significance in improving the appearance quality and mechanical properties of RHCM parts.

In this paper, HDPE is used to study the influences of various processing parameters. Weld line is evaluated by *dE*(Euclidean distance). The parameters influencing weld line have been respectively discussed based on the orthogonal experiment method. Furthermore, the most important process parameter on weld line is researched from a micro perspective. The research results obtained in this paper are valuable to guide the engineering applications.

Experiment part

In this paper, orthogonal experiment and SEM microscopic experiment are introduced to study the impacts of processing parameters on weld line in RHCM. The material and equipment used in this experiment are shown as follows.

Product and Equipment

A RHCM product has been prepared for this experiment, which is shown in figure 1. This product is produced using a set of electric heating mold (as shown in fig.2,3).

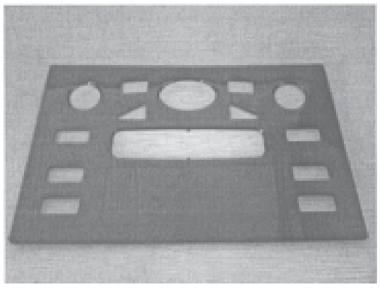

Fig.1. The RHCM product

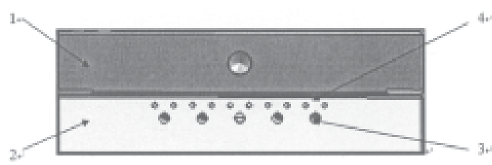

Fig.2. The structure of RHCM mold

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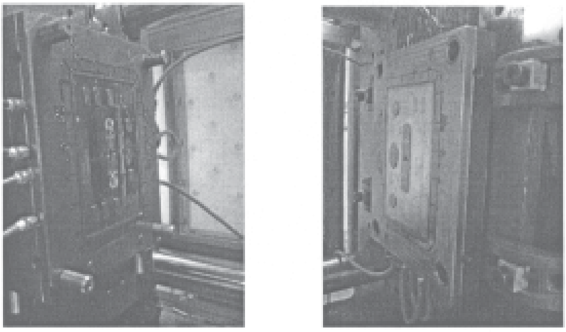

(a) Movable mold part (b) Fixed mold part

Fig.3. RHCM for the experiment

Figure 2 shows a part of rapid heat cycle mold with electrical heating, where the size of the fixed mold plate and movable mold plate are 450x350 x 55.6mm, 450 x 350 x 60mm, respectively. Compared with the traditional injection molding, the main difference is that a row of electric heating rods has been designed around the mold cavity in the RHCM mold. The fixed mold plate and the movable mold plate are made of SP400, which has excellent thermal stability and thermal transmission to ensure that the heat generated by the heating rods can be delivered to the cavity surface rapidly and the heat dissipation of the midway can be reduced.

The injection molding machine is Haitian MA3800, which has the maximum clamping force of 3800KN, the biggest melt volume of 1239cm^3, and the maximum injection pressure of 182Mpa. This machine is suitable for plastic molding with demanding precision requirements.

The electric heating controller is MTS-32II, which uses a three-phase and five-wire system supplied by 380V power. It can provide a single maximum output power of 6.5KW, temperature control range of 0-399.9°C, time control accuracy of 10ms, and maximum controllable loop digital of 24.

Electric heating rods (type I and type II) in this experiment are the high-density single-end electric-heating tubes or electric tubes. The parameters of type I include voltage/power of 220V/270W, diameter of 4mm, and length of 450mm while type II rods are with voltage/power of 220V/210W, diameter of 4mm, and length of 134mm.

To observe the morphology of weld line, a Scanning Electron Microscope (SEM) Hitachi S-4700 is utlilized. The accelerating voltage is 15KV. The sample with vacuum spraying metal processing is placed on a slide.

Identification of weld line

Weld line can be identified by the colour difference between weld line area and its nearby area [12]. The steps for distinguishing weld line the are as follows˙: firstly, product photos are taken by a digital camera and loaded in Photoshop software; secondly, some 1.5×0.5cm^2 regions contained weld line are intercepted by Photoshop and then loaded in Matlab software; Thirdly, the RGB values are red by Matlab and converted into CIE System Lab values. The conversion mode of dE is as follows.

a. Dimensionless form of RGB values

Integer RGB values in the range of [0÷255] are converted to floating-point values in the range of [0, 1] with below equations.

$$R_N=R/255,\ G_N=G/255,\ B_N=B/255 \quad (1)$$

b. The linearization of RGB values

$$R_L = R_N^{2.2},\ G_L = G_N^{2.2},\ B_L = B_N^{2.2} \quad (2)$$

c. Converting RGB values to XYZ values of system CIE

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = A * \begin{pmatrix} R_L \\ G_L \\ B_L \end{pmatrix}, \text{ where } A = \begin{pmatrix} 0.4298 & 0.3967 & 0.1377 \\ 0.2142 & 0.7141 & 0.0718 \\ 0.0146 & 0.0903 & 0.7199 \end{pmatrix} \quad (3)$$

d. Converting XYZ values to lab values of system CIE

$$L = \begin{cases} 903.3 * (Y/Y_0), for 0 \le Y/Y_0 \le 0.008856 \\ 116 * (Y/Y_0)^{1/3}, for Y/Y_0 \ge 0.00856 \end{cases} \quad (4)$$

If (X/X_0), (Y/Y_0) and (Z/Z_0) are greater than 0.008856,

$$a = 500 * \left[(X/X_0)^{1/3} - (Y/Y_0)^{1/3}\right]$$

$$b = 200 * \left[(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}\right] \quad (5)$$

where X_0, Y_0 and Z_0 are the coordinates of the reference point. The values are 0.9642, 1.0 and 0.8249 respectively in the Matlab RGB color coordinate system. *dE* represents the measure of the color difference in the CIE system, which is the Euclidean distance of two colors. The value is calculated as follows:

$$dE = \left[(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2\right]^{1/2} \quad (6)$$

Because NBS values are with the same sense of the values of system CIE (dE), NBS values could be used to characterize the visibility of weld line. Relationships between NBS value and human vision colour are shown in table 1 [12].

The above method is utilized to identify weld line in this paper.

Orthogonal experimental method, which is an effective statistical method to solve the problem of multi-factors, is applied to this multi-factor, multi-level problem with random errors. The primary and secondary relationships can be reached based on the factors of weld line and their interaction. The optimum process condition or the optimum combination based on the results of orthogonal experimental analysis [13] can be found out using range method. Range method is a commonly used for the analysis of the experimental results, which is easy to

Table1

RELATIONSHIPS BETWEEN NBS VALUE AND HUMAN VISION COLOR

NBS value	Human vision color
0~1.5	Almost uniform
1.5~3	Slightly different
3~6	Different
6~12	Obviously different
12~	Different color

Level	Heating temperature /°C (Factor A)	Melt temperature/°C (Factor B)	Injection pressure /Mpa (Factor C)	Injection speed /% (Factor D)	Holding pressure /Mpa (Factor E)
1	80	200	30	20	20
2	90	210	35	25	25
3	100	220	40	30	30
4	110	230	45	35	35

Table 2
TEST FACTORS IN FOUR LEVELS

understand, practical, and a small amount of calculation.

The heating temperature, melt temperature, injection pressure, injection speed, holding pressure and their interactions on weld line are investigated in this experiment. The optimum combination of the parameters that affects weld line is obtained next, which can guide engineering applications.

The factor level of the experiment and each factor is set according to HDPE process setting range, which ensures that the products did not appear flash, fill gaps and other defects. It is difficult to guarantee the quality of products when the heating temperature exceeds 110°C, which would generate serious flash. Therefore, 110°C is set to the highest value of the heating temperature. Factors in four levels are shown as table 2.

L16 (5^4) orthogonal experiment is done based on the above setting of 5 factors in 4 levels. The identification of weld line has been mentioned as before The value of *dE* and range analysis [14] can be then obtained.

Results and discussions

The Impact of Processing Parameters on Weld Line of RHCM Parts

Figure 4 shows the influence level of each factor on weld line. Range size $R_A>R_D>R_E>R_C>R_B$, which means the relationship among the parameters' impact on weld line is heating temperature > injection speed > holding pressure > injection pressure > melt temperature.

From figure 4, the impact trends of the parameters can be analyzed as below.

Effect of heating temperature on weld line

Weld line of traditional injection molding(heating temperature 50°C) and that of RHCM(heating temperature: 110°C) are compared in picture 3. It can be observed from the experimental results that dE is 2.2734 under the heating temperature of 50°C, and dE is 0.1841 under 110°C. Therefore, heating temperature has a pronounced influence on weld line. Increasing the heating temperature could effectively reduce the visibility of weld line. In addition, it is proved that the evaluation principle of weld line could effectively evaluate weld line visibility.

In the curve of factor A in picture 2 weld line appears obviously in traditional injection molding. Weld line is weakened but still visible when the heating temperature raises to 80°C. Weld line is almost invisible when the heating temperature was raised to above 100°C, whereas the value of *dE* is stabilized between 0.2 and 0.3. This is because the lower heating temperature is delivered to the condensate layer formation, when the melt in the process of filling contacts with the cooler mold walls in traditional injection molding. The condensate layer would decrease the liquidity near the cavity surface melts, eventually leading to inconsistent speed of the flow front, the center of the flow speed is the quickest but the flow speed closed to the cavity is slower. Two shares of melt cannot be completely confluence during cooling stage, eventually forming weld line. Therefore, the increasing heating temperature before injecting could effectively reduce the formation of condensate layer and lead the same speed of the flow

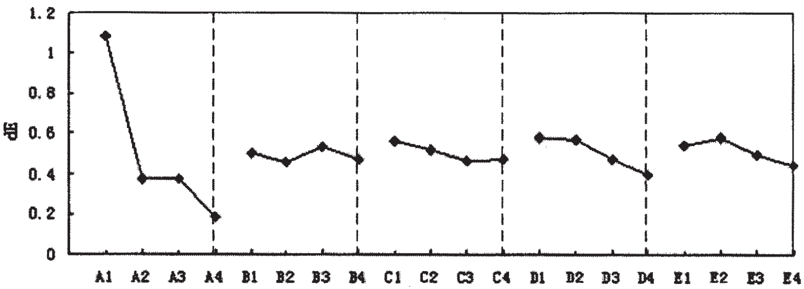

Fig.4 Impact degree of each factor on weld line

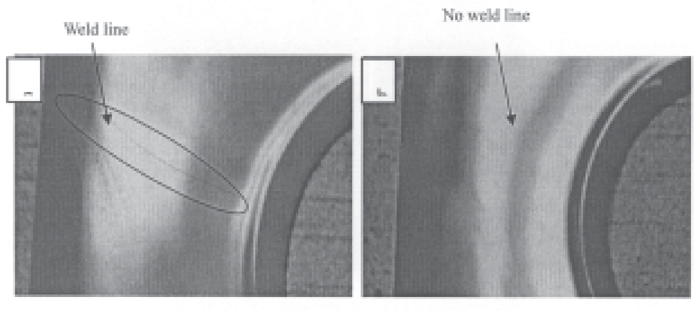

Fig.5 Comparison picture of plastic parts weld line area

front, which could completely confluence during cooling stage. Owing to the above reasons, increasing heating temperature effectively reduces the visibility of weld line.

Effect of melt temperature on weld line

From the curve of factor B in picture 2, *dE* changes about 0.04 with the increase of melt temperature. Therefore, increasing the melt temperature can reduce the visibility of weld line, but the reduction is very slight. This is because the improvement of the melt temperature changes the fluidity of the melt when the heating temperature is higher, but the melt have been uniformly fused from the confluence of two melt in a better filling environment. Therefore the value of *dE* had remained basically unchanged.

Effect of injection pressure on weld line

From the curve of factor C in picture 2, *dE* changes about 0.2 with the increase of injection pressure. It can be said that injection pressure has little effect on weld line. The reason is that the improvement of the injection pressure changes the fluidity of the melt gradually, and the melt flow resistance of the cavity is smaller under the environment of RHCM. The melt have been uniformly fused from the confluence of two melt in the better filling environment, and the visibility of weld line decreases at the same time.

Effect of injection speed on weld line

From the curve of factor D in picture 2, *dE* exceeds 1 when the injection speed is 5%, and *dE* kept below 0.5 when the injection speed is between 15% and 35%. So injection speed has a greater effect on weld line. This is because the decrease of the injection speed changes the fluidity of the melt, shear stress and the improvement of melt viscosity makes the melt uniformly fusion from the confluence of two melt in the better filling environment. The melt fluidity of the center is poorer than the one closer to the surface of the cavity. Therefore, the visibility of weld line is improved by adjusting the injection speed.

Effect of holding pressure on weld line

From the curve of factor E in picture 2, the holding pressure has little effect on weld line. The effect of holding pressure on weld line is the same as holding pressure, and increasing the holding pressure will gradually decrease the visibility of weld line. *dE* has maintained at a lower range and gradually decreases to 0.3 or less. Weld line is not visible when the value of *dE* is below 0.3. This was because the holding pressure compensated the shrinkage generated in the cooling stage.

The visibility of weld line is as low as possible from the above analysis. The best combinations of processing parameters of weld line are $A_4B_2C_3D_4E_4$ which means heating temperature of 110°C, melt temperature of 210°C, injection pressure of 40Mpa, injection speed of 35%, and holding pressure of 35Mpa. The visibility of weld line is 0.1756 according to the best combinations of processing parameters. Weld line is basically not visible, as shown in figure 6.

Microscopic experiment of weld line

Heating temperature has great influence on weld line. Till now, few research related to the product surface from the microscopic viewpoint has been conducted in RHCM. In this section we will study the influence of heating temperature on weld line in depth through researching the organizational structure of weld line. HDPE is chosen as

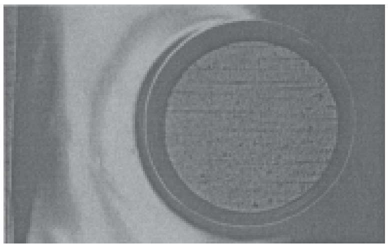

Fig.6 Weld line under the best combinations of processing parameters

the experiment material under six groups of different heating temperatures: room temperature, 70, 80, 90, 100, 110°C. Other processing parameters remain constant. i.e. melt temperature of 210°C, injection pressure of 60Mpa, injection speed of 25% and holding pressure of 30Mpa. The specimen with the size of 3mm x 3mm is cut around weld line region, and the specimen of vacuum spraying metal processing is placed on a slide. The surface of the sample is observed by the equipment.

The surface of the specimen is magnified by 30 times, and the SEM photos are shown below (fig. 7).

The surface topographies of the specimen under different heating temperatures are shown in figure 7. Weld line of figure 7(a) to figure 7(c) is clearer than figure 7(d), in which weld line is barely visible. Weld line in figure e and figure f is basically invisible. So it's concluded that weld line is relatively clear when the heating temperature is lower than 80°C, weld line is barely visible when the heating temperature is 90°C and weld line is basically eliminated with the increase of the heating temperature.

In figure 7, the number of grains is also changed with the heating temperature. Factors of crystallization effect can be categorized into internal and external factors. Internal factors include the regularity of the molecular chain structure and flexibility, while external factors include temperature, pressure, and concentration. And one of the most important factors of the external factors is temperature. The crystallization effect includes nucleation and the growth of grain. The polymer is difficult to form a crystal nucleus when the polymer temperature is greater than the melting point T_m, but the grain does not grow and the crystallization rate is zero when the temperature is lower than the glass transition temperature T_g. The temperature of polymers is between the melting point and glass transition temperature, and there is a linear relationship between the changes in the grain size and the time. Consequently the polymer chain will not be frozen. The macromolecule is still orderly arranged and promoted the growth of grain if we increase the heating temperature above the glass transition temperature in filling and holding pressure stage. The surface of the specimen is magnified by 4000 times, and the SEM photos are shown as follows.

The surface topographies of the specimen under a different heating temperature are shown in figure 8. Weld line is the most obvious when the heating temperature was 80°C, then weakens with the increase of heating temperature. Weld line is essentially invisible when the heating temperature is 110°C. There is no fusion on both sides of melt before cooling stage. Weld line of product surface is not only wide, but also deep because of the gradually cooling of the melt when the heating temperature is 80°C. The surface of the product is smooth. The melt has been fully integrated, and there is not basically apparent weld line when the heating temperature is 110°C.

In figure 9, *dE* decreases when heating temperature is increasing, but a peak point exists in 80°C. There is bad combination layer with 5 to 10μm in length on both sides of weld line when weld line is more discernible. The condensing layer is generated in the filling stage when the

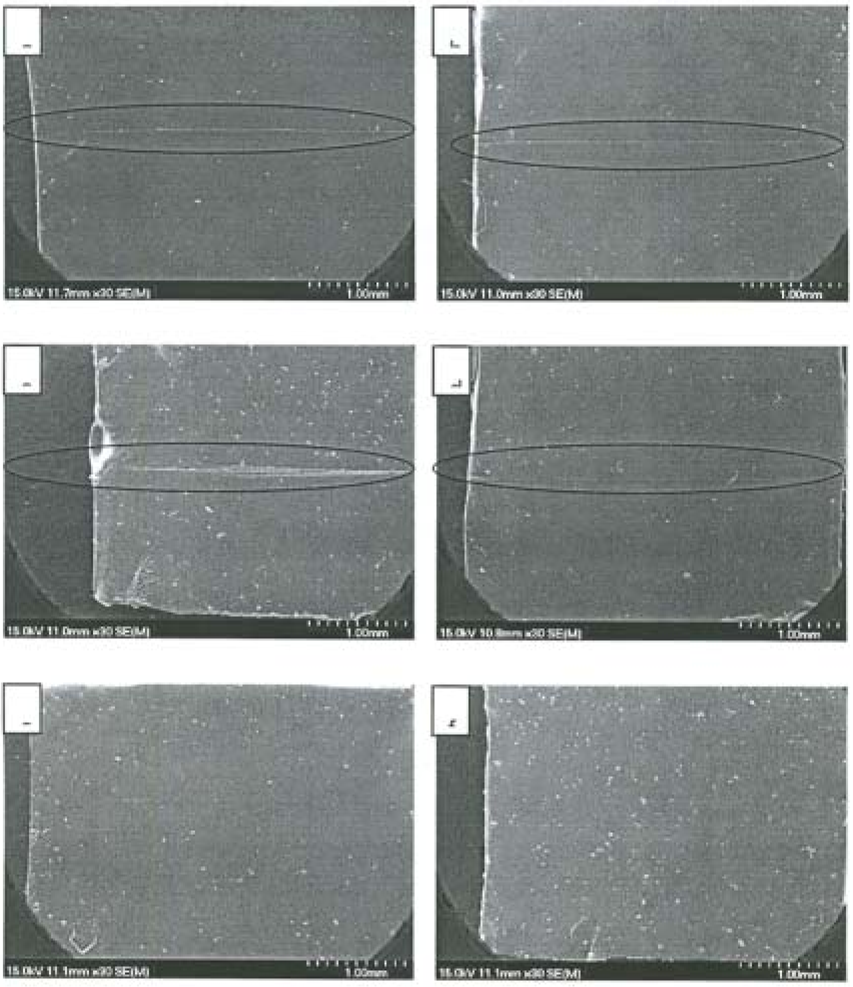

Fig.7. SEM photos of parts in different heating temperature˙30 times (a)Room temperature, (b) Heating temperature 70°C, (c) Heating temperature 80°C, (d) Heating temperature 90°C, (e) Heating temperature 100°C, (f) Heating temperature 110°C

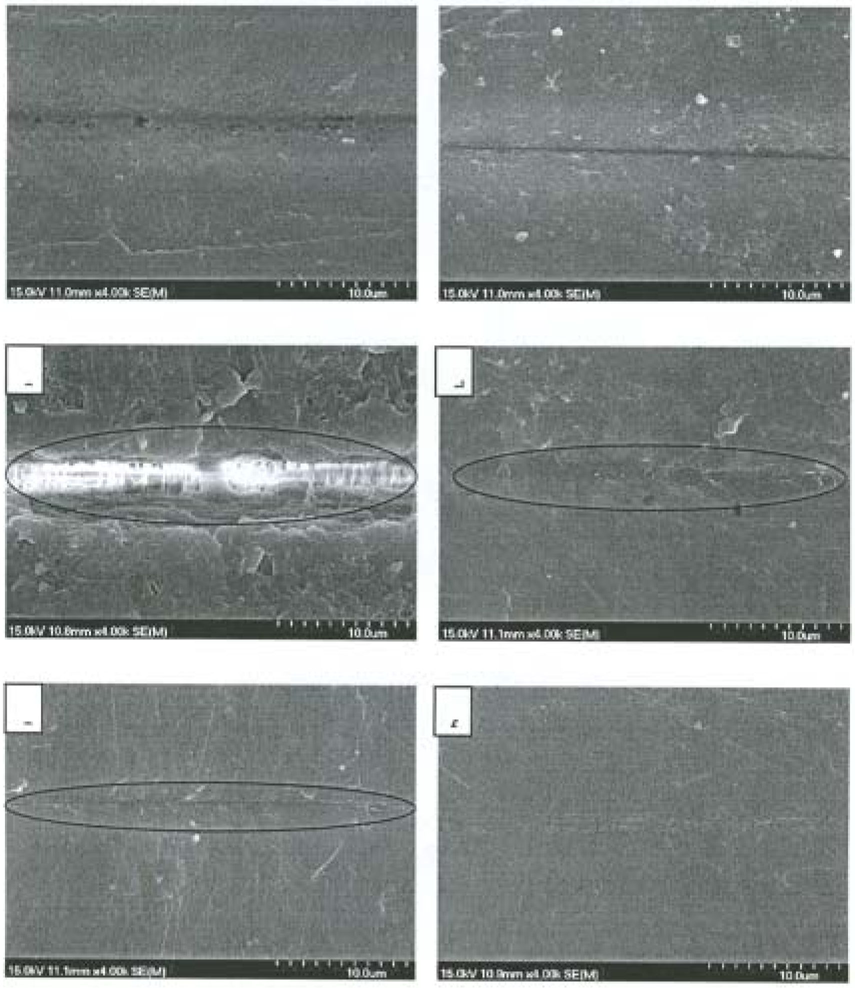

Fig.8. SEM photos of parts in different heating temperature˙4000 times (a)Room temperature, (b) Heating temperature 70°C, (c) Heating temperature 80°C, (d) Heating temperature 90°C, (e) Heating temperature 100°C, (f) Heating temperature 110°C

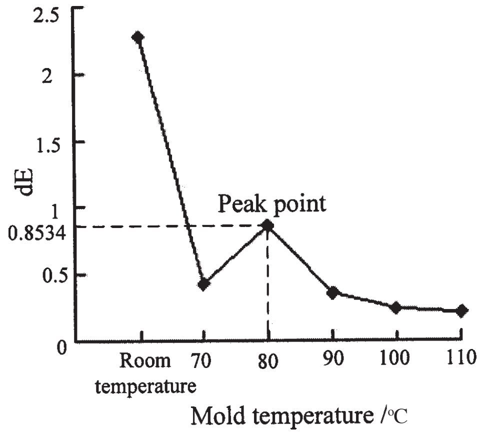

Fig.9 Effect of heating temperature on weld line

melt meets with the mold. The condensing layer not only makes the two shares of melt which are close to the mould cavity fused uneven, but also reduces the forming quality of the product after cooling stage. The environment of the filling stage can be improved and the condensing layer will disappear with the increase of the heating temperature.

Conclusions

Weld line of the product is greatly affected by forming process. Various processing parameters are listed in descending impact order: heating temperature, injection speed, holding pressure, injection pressure and melt temperature. Heating temperature has significant impact on weld line, while the impact of injection pressure and melt temperature can be almost ignored.

Orthogonal experiment method has been used to obtain the best combination of processing parameters, with the aim to reduce the visibility of weld line. Under the recommended parameter settings, weld line disappears because the value of *dE* is as small as 0.1756.

Weld line becomes more invisible with the increase of heating temperature. However, a peak point appears under 80°C. The trend of combination layer is similar to the trend of weld line. Therefore, we should adjust to a reasonable heating temperature according to the its trend obtained in this paper and try to avoid the peak point near 80°C in production.

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