Comparative Study of Weldline Strength in Conventional Injection Molding and Rapid Heat Cycle Molding

JIQUAN LI[1,2], SHAOGUANG YANG[1], LIH-SHENG TURNG[2], ZUOJIAN XIE[1], SHAOFEI JIANG[1]*
[1]College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou 310014, China
[2]Department of Mechanical Engineering, University of Wisconsin–Madison, Madison, Wisconsin

Rapid heat cycle molding (RHCM) is a special molding process capable of producing molded plastic parts with high surface quality and improved weldline strength and appearance. This study investigated the influence of the weldline on the tensile strength of RHCM and conventional injection molded (CIM) components. The test specimens with and without a weldline were cut from RHCM and CIM parts for scanning electron microscopy (SEM) imaging to characterize the structure and dimensions of the weldline and tensile testing. The tensile testing results showed that the weldline reduced the tensile strength, but RHCM decreased the tensile strength reduction effect of the weldline. There was no distinguishable difference between the two molding processes for the tensile strength of specimens without a weldline. In addition, a thin surface layer of material containing the V-notch at the weldline was removed from the RHCM and CIM parts to examine its effect on the tensile properties. The thinned-out specimens with a weldline showed improved tensile strength, and specimens without a weldline showed decreased tensile strength, compared to specimens with the original full thickness.

Keywords: Weldline, RHCM (rapid heat cycle molding), tensile strength

Injection molding is widely used in the manufacturing of plastic parts [1]. In recent years, some special injection molding processes have been developed and emerged to improve part quality and extend the applications of plastic parts. These special injection molding processes include rapid heat cycle molding[2,3], gas-assisted injection molding [4], microcellular injection molding [5], co-injection molding [6], and micro-injection molding [7]. Among the aforementioned special injection molding processes, the rapid heat cycle molding (RHCM) method was specifically developed to improve the surface quality of molded parts [8]. Because of this, the surface appearance of the weldline was also improved by RHCM [9,10]. The surface appearance of the weldline usually corresponds to a smaller V-notch formed by two melt fronts meeting from opposite directions. Conceivably, the V-notch on the surface at the weldline location affects the weldline strength of the molded parts.

There have been studies on the weldline in relation to strength. Chen *et al.* [11,12] investigated the influence of processing conditions and part thickness on the weldline strength of thin-wall parts. The results showed that the weldline plays a very important role in the tensile strength, which is influenced by the melt temperature, mold temperature, injection speed, packing pressure, and part thickness. Wang *et al.* [13] discussed the effects of the cavity surface temperature just before filling in RHCM on the mechanical strength of the specimen with and without a weldline.

However, the majority of aforementioned studies have been conducted based on mechanical performance testing and without the consideration for the structure of the weldline under different molding methods and process conditions. Indeed, little is known about the different structures of weldlines and their effect on the tensile strength of RHCM parts from that of conventional injection molding (CIM) parts. To this end, this work was undertaken to study the effects of the weldline and its structure on the tensile strength and their process dependence. Dumbbell-shaped specimens with and without a weldline were cut out from a plate part molded by CIM and RHCM to conduct tensile strength testing with variable specimen thickness. The specimen surface and fracture surface of the weldline region were observed by SEM to investigate the structure of the V-notch. The relationship among molding process, weldline, and tensile strength were studied and are discussed here.

Experimental part

Material

The material used was an isotactic polypropylene (iPP), T30S, from the Zhenhai branch of Sinopec Corp., Ningbo, China. It is a semi-crystalline polymer with a melt flow index (MFR) of 2.5 g/10 min, a density of 0.91 g/mL, and an isotactic index greater than 94%.

Preparation of Specimens

CIM and RHCM parts were molded using an RHCM mold from Zhejiang JinDian Mold Co., Ltd., Taizhou, China. In the mold, there were electrical heating rods and cooling tunnels in the stationary mold half, and only cooling tunnels in the moving mold half. The electrical heating rods heated the mold rapidly before mold filling, and cooling tunnels cooled the mold with circulating water after filling. The heating of the electrical heating rods was controlled by an MTS-32II mold heating temperature controller from Beijing CHN-TOP Machinery Group Co., Ltd., Beijing, China. For CIM, the heating rods and heating temperature controller were all turned off.

The injection molding machine used was a Haitian MA3800 from Haitian Plastics Machinery Group Co., Ltd., Ningbo, China, with a maximum clamping force of 3800 KN, a largest melt volume of 1239 cm^3, and a maximum injection pressure of 182 MPa.

The molding conditions are shown in table 1. The same conditions, except for the heated mold temperature, were used in CIM and RHCM. The heated mold temperature was

* *emailo: jsf75@zjut.edu.cn, hutli@163.com*

	Conditions	Zone 1	Zone 2	Zone 3	Zone 4
Filling conditions	Barrel position (cm)	120	80	60	0
	Barrel temperature (°C)	210	240	240	220
	Pressure (MPa)	90			
	Speed (%)	60			
Heated mold temperature (°C) for RHCM		120			
Mold temperature (°C) for CIM		25			
Packing pressure (MPa)		50			
Cooling time (s)		30			

Table 1
MOLDING CONDITIONS

measured by K-type thermocouples that were embedded in the fixed half of the mold and were only used in RHCM.

One of the molded plate parts with holes is shown in figure 1. According to the GB/T 1040-2006 standard, dumbbell-shaped specimens with and without a weldline were cut out of the plate parts molded by CIM and RHCM processes, respectively. The dimensions of the dumbbell-shaped specimens are shown in figure 2; the thickness was 2.5 mm.

To investigate the influence of the weldline and the V-notch on the tensile strength, layer thicknesses of 0.1, 0.2, 0.3 and 0.4 mm were removed on the both sides of dumbbell-shaped specimens separately, using metallographic abrasive paper with a particle size of 300# on a polishing device.

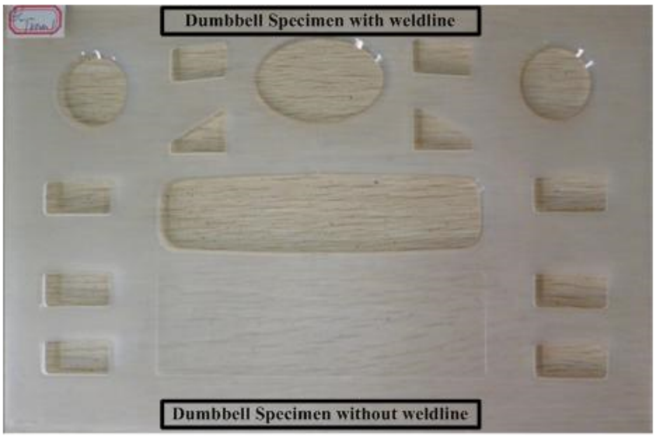

Fig. 1. A molded part and the sampling position

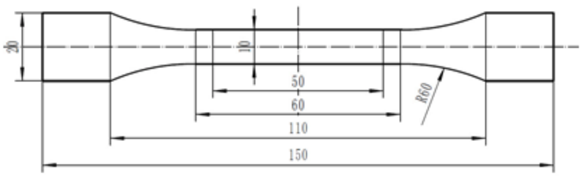

Fig. 2. The dimensions of the dumbbell-shaped specimens

Tensile Tests

Tensile tests were performed according to standard GB/T 1040-2006 and were carried out using a RG1100 tester—a universal testing machine from Shenzhen Reger Instrument Co., LTD, Shenzhen, China. The tester had a maximum load of 100 KN and a loading precision of ±0.5%. Test conditions were a crosshead speed of 5 mm/min and an ambient temperature of 25°C.

The effect of the weldline on the tensile strength can be quantitatively expressed in terms of weldline integrity factor F_{WI} defined as [14]:

$$F_{WI} = \frac{\sigma_w}{\sigma_n} \quad (1)$$

where σ_w is the tensile strength of the dumbbell-shaped specimen with a weldline, while σ_n is the tensile strength of the dumbbell-shaped specimen without a weldline.

Observations with SEM

The surface of the weldline with and without surface removal, and the frac-ture surface of the specimen at the weldline, were observed by a HITACHI S-4700 field emission scanning electron microscope (SEM) at an acceleration voltage of 15.0 kV. To examine the weldline quantitatively, the fracture surfaces at the weldline were investigated by SEM with a magnification of 90 or 350, and the depths of the V-notches were measured with the help of JMicroVision at five sites to get an average value. The measuring positions are shown in figure 3.

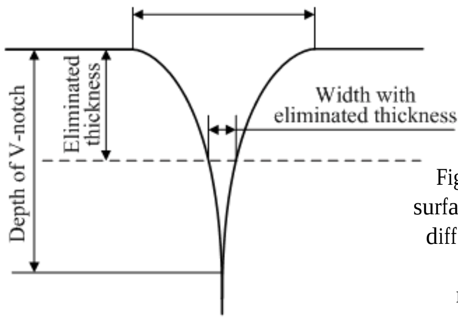

Fig. 3. Schematic of surface layer removal at different thicknesses and V-notch measurements

Results and discussions

The Fracture Surface of Specimens at the Weldline

A weldline develops when two portions of the polymer melt front meet. According to microscopic observation of the fracture surface at the weldline, as shown in figure 4 (a), there were three regions of melt flow that came together to form the weldline. The three regions were V-notch area 1, poor bonding area 2, and strong (rich) bonding area 3, as shown in figures 4 (b), (c), and (d), respectively.

Due to fountain-flow behavior at the advancing melt front during the filling stage, the flow front was cooled immediately by the cold mold at the area adjacent to the mold surface. Furthermore, there were different temperature distributions on the interface of the polymer melt flows when they met. The temperature was lower for the polymer adjacent to the mold surface, and higher for the polymer in the inner area.

In figure 4, the fracture surface of the V-notch area was smooth without any avulsion because the two polymer melt flows didn't bond with each other due to the low temperature during the filling stage. Meanwhile, in the strong (rich) bonding area, there was a strong bond

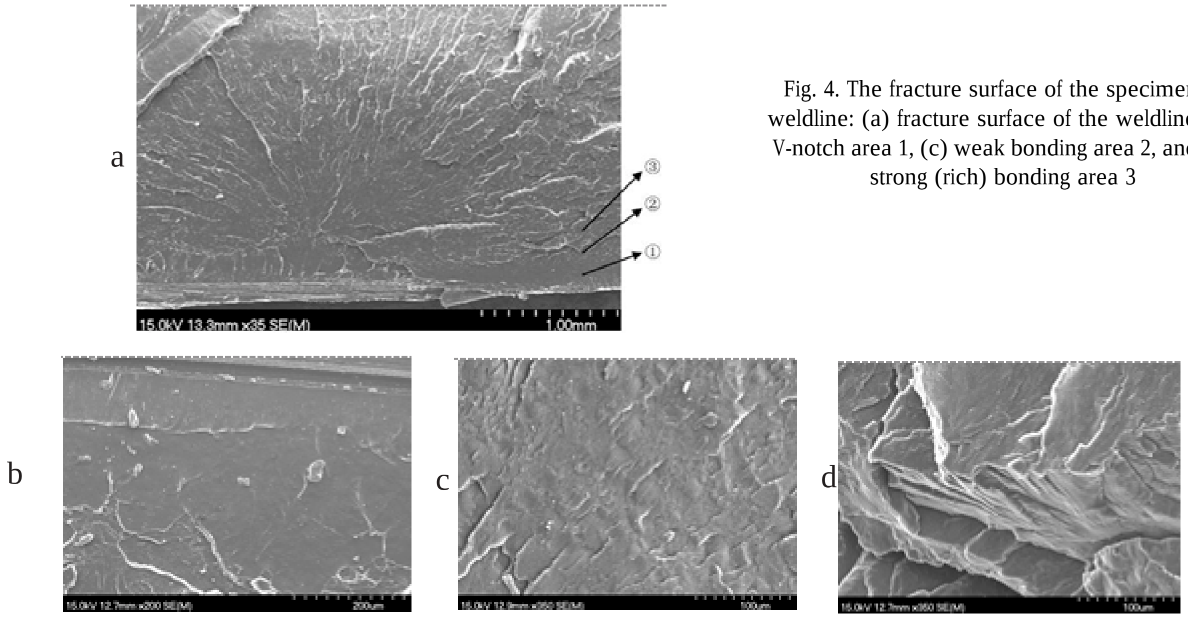

Fig. 4. The fracture surface of the specimen at weldline: (a) fracture surface of the weldline, (b) V-notch area 1, (c) weak bonding area 2, and (d) strong (rich) bonding area 3

between the two polymer melt flows due to the higher temperature during the filling stage, which introduced many deep avulsions on the fracture surface. Between the V-notch and the strong bonding area was the poor bonding area, which was an approximately smooth fracture face with some superficial avulsions. The bonding of the melt interface at the weldline was influenced greatly by the process conditions and principally influenced the strength.

Surface Appearance of Weldlines

The three regions of the weldline (V-notch area, poor bonding area, and strong bonding area) on the cross-section of the part at the weldline location spanned at different depths of the weldline. The surfaces containing the weldline for the CIM specimens with decreasing thicknesses are shown in figure 5. There was an obvious line with a definite width on the surface of the weldline. When a 0.1 mm layer was removed from the surface of the part, a narrow line was still visible on the surface. However, there was no visible line except scratches on the surface when 0.2 mm was removed from the part surface.

The surface of the weldline on the RHCM parts was different from that on the CIM parts. Furthermore, the surfaces on the opposite sides of the mold were also different, as shown in figures 6 and 7. On the specimen surface adjacent to the moving half (i.e., the non-heated surface), a weldline was easy to find, while on the specimen surface with a removed thickness of 0.1 mm, a line was very difficult to find. When the surface thickness was reduced by 0.2 mm, there was no visible line.

On the specimen surface adjacent to the stationary (heated) half, a weldline could only be observed at a large magnification of 5000. A weldline was not observable on the surface with after a thickness of 0.1 mm was removed from the part surface.

The different surface characteristics of the weldline were caused by different molding processes under different thermomechanical histories. To get more information on the weldline, a quantitative investigation was conducted based on the SEM images, as detailed in the following section.

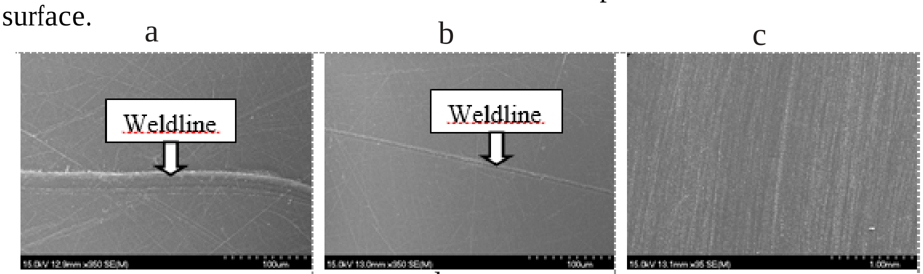

Fig. 5. The surface of the weldline on the CIM part, with layer removal thickness of (a) 0 mm (as-molded), (b) 0.1 mm, and (c) 0.2 mm

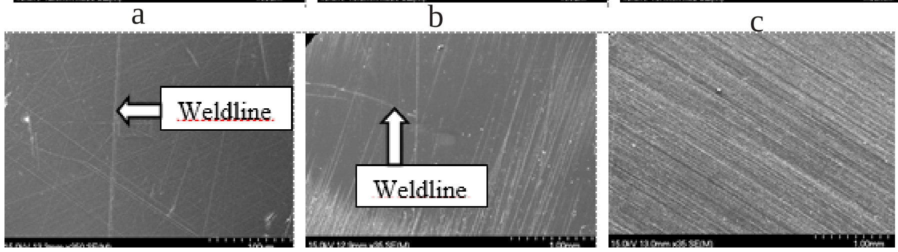

Fig. 6. The surface of the weldline on the RHCM part adjacent to the moving half with a layer removal thickness of (a) 0 mm (as-molded), (b) 0.1 mm, and (c) 0.2 mm

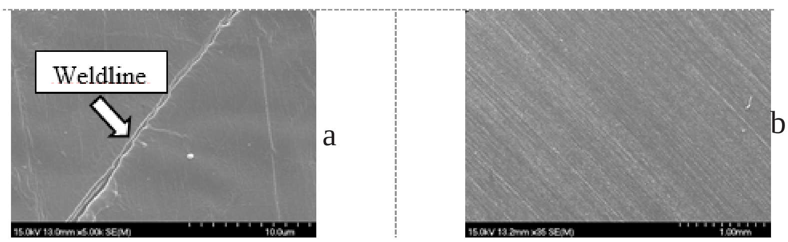

Fig. 7. The surface of the weldline on an RHCM part adjacent to the stationary half, with a layer removal thickness of (a) 0 mm (as-molded), and (b) 0.1 mm.

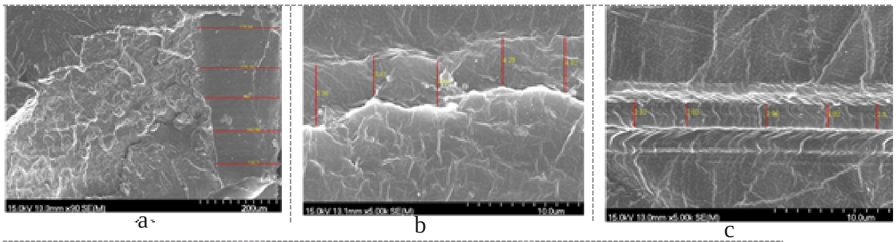

Fig. 8. The dimension of the V-notch in a CIM part (a) depth of V-notch: 156.19 μm, (b) width on the part surface: 4.32 μm, and (c) width of 2.12 μm on the surface with a layer removal thickness of 0.1 mm

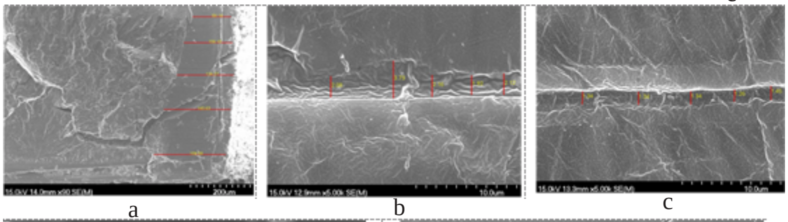

Fig. 9. The dimension of the V-notch in an RHCM part adjacent to the (non-heated) moving mold half: (a) depth of V-notch: 123.75 μm, (b) width of V-notch on the part surface: 2.39 μm, and (c) width of 1.35 μm on the surface at a layer removal thickness of 0.1 mm

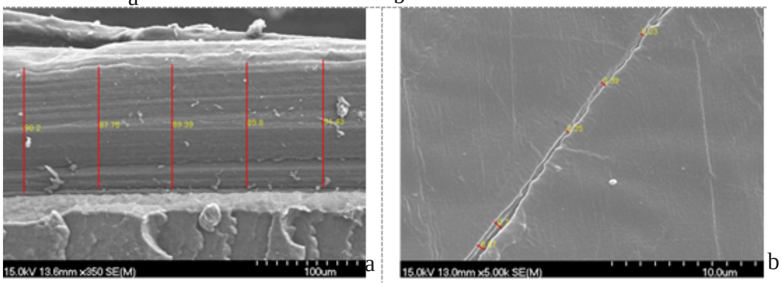

Fig. 10. The dimension of the V-notch in an RHCM part adjacent to the heated stationary mold half (a) depth of V-notch: 89.71 μm, and (b) width on the part surface: 0.49 μm

Measurement of the V-Notch

The widths of the weldlines were measured based on the SEM investigation of the weldline surface with different layer removal thickness. Figure 8 shows the depth and width of the V-notch of a CIM part, in which the red lines transverse the area of V-notch and the location and orientation of the V-notch were shown in figure 3.

Figures 9 and 10 show the depth and width of the V-notch on both sides of the RHCM part. The depth adjacent to the stationary (heated) mold half was 89.71 μm, which is smaller than 0.1 mm, and this invisible on the surface when the surface thickness was removed by 0.1 mm.

The depth and width of the V-notch for the RHCM parts were smaller than those of the CIM parts. In the RHCM process, the mold was pre-heated before the polymer melt filled the mold cavity. The heated mold surface reduced the heat loss and improved the fluidity of the polymer melt during the filling stage. The two melt fronts that formed the weldline merged under a higher temperature and pressure, which welded them better together than in the CIM process. The improved weld interface reduced the V-notch dimensions of the weldline and improved the bonding strength at the weldline.

Evidently, the dimensions of the V-notch adjacent to the heated stationary mold half were much smaller than those of the opposite V-notch, especially the width. On the mold surface of the stationary half, the heated mold surface improved the fluidity of the polymer melt during filling. The two polymer melts merged earlier near the stationary side (cf. fig. 11) and with a higher temperature than that of the moving half, which introduced the smaller dimension of the V-notch.

The structure and dimensions of weldline formed under different bonding conditions not only affect the surface appearance of the weldline but also the part strengths, which will be discussed below.

The Tensile Strength of CIM Specimens

Figure 12 shows the tensile strength of the dumbbell-shaped specimens cut from a CIM part with and without a weldline. The tensile strength with weldline was lower than that without weldline. The lower strength was because there was a stress concen-tration point on the transition area between the V-notch and the weak bonding area, and the strength of the bonding interface at the weldline was not as strong as that of the matrix.

In the specimen without a weldline, the tensile strength decreased slightly when the part thickness was reduced by 0.1 mm, and was almost constant as the surface layer removal thickness increased. For the specimen with a surface layer removal thickness of 0.1 mm, the skin layer was eliminated from the surface. The skin layers of the CIM and RHCM parts were discussed in an earlier study [15]. Since there was a stronger molecular orientation in the skin layer than in the shear and core layers, removing

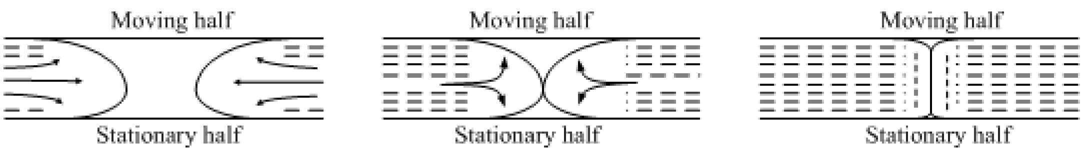

Fig. 11. The forming process of the weldline in the RHCM process: (a) filling stage, (b) packing stage, and (c) after cooling

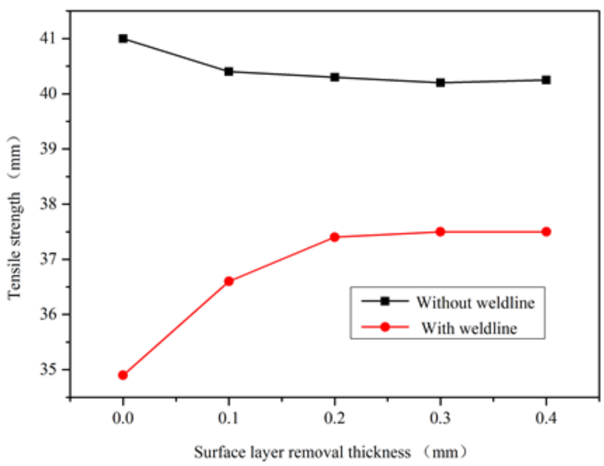

Fig. 12. The tensile strength of specimens cut from a CIM part.

that skin layer did negatively affect the tensile strength of specimens without a weldline.

In the specimens with a weldline, the tensile strength (which takes into account the cross-sectional area of the specimens) increased noticeably with increasing surface layer removal thickness. The largest in-crease of strength was at a layer removal thickness of 0.1 mm. As the surface layer removal thickness increased further, the tensile strength increase was smaller, and there was no change in tensile strength after 0.3 mm of surface was removed.

According to the aforementioned structure and dimensions of the weldline, the depth of the V-notch is deeper than the removal thickness of 0.1 mm. Nonetheless, the layer removal still reduced 64% of the non-bonding area on the weldline, thereby reducing the stress concentration and increasing the tensile strength. When the thickness was reduced by 0.2 mm, the V-notch was eliminated completely and a portion of the weak bonding area was also eliminated, which also led to a large strength increase, even though it is not a big as that with a thickness removal of 0.1 mm. Although the tensile strength increased as the weak bonding area decreased or eliminated, the subsequent increases became smaller as more material was removed because the bonding strength increased from the surface to the core area of the weldline. After the weak bonding area was eliminated completely at an approximate thickness of 0.3 mm, the tensile strength didn't show any more variation with increasing surface layer removal thickness. The strength of the different positions in the strong bonding area were almost identical.

The Influence of RHCM on the Tensile Strength

Figure 13 shows the tensile strength of the dumbbell-shaped specimens cut from RHCM parts with and without a weldline. The varied trends of the RHCM speci-mens were similar to that of the CIM specimens because there were skin layers or a weldline on both kinds of specimen. However, some values were different from each other. The tensile strength of the RHCM specimen with the weldline was higher than that of the CIM specimen, but the strength without the weldline was almost the same as that of the CIM specimen.

For specimens without a weldline, the strength of the RHCM specimen was slight-ly higher than that of CIM. In the RHCM process, the heated mold kept the polymer melt from cooling too quickly, and as such, there was more time for polymer molecules to diffuse and bond better. In addition, for iPP material used in this study, a slower cooling rate also facilitated crystallization, thus improving the tensile strength. Since the surface temperature of the stationary half was higher than that of the moving half, the strength of the layer-removed specimens adjacent to the stationary half was also slightly higher than that adjacent to the moving half.

For specimens with a weldline, the strength of the RHCM specimen was signi-fi-cantly higher than that of CIM due to the smaller dimensions and higher bonding strength of the weldline. As discussion above, the dimension of the weldline on the RHCM specimen was smaller than that of the CIM specimen. Furthermore, the two melt fronts that formed the weldline welded together better due to the higher tempera-ture and pressure in the RHCM process as compared to the CIM process, thus enabl-ing the higher bonding strength of the weldline.

Weldline Integrity Factor

The weldline integrity factors of different specimens with increasing layer removal thicknesses (cf. fig. 14) were

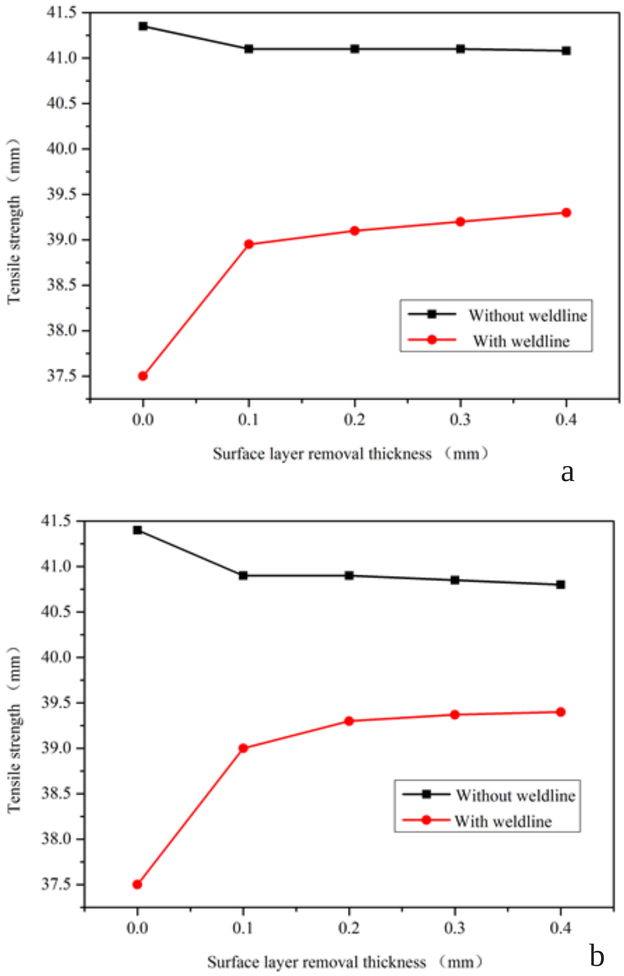

Fig. 13. The tensile strength of specimens cut from the RHCM parts: (a) the surface layer was removed from the surface adjacent to the heated stationary half, and (b) the surface layer was removed from the surface adjacent to the moving half

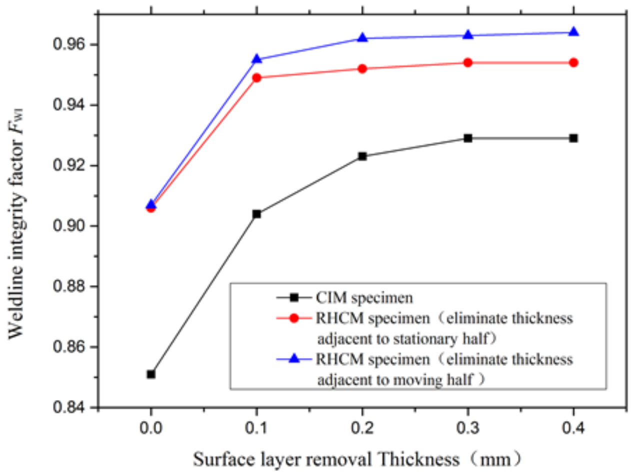

Fig. 14. Weldline integrity factor of different specimens

calculated to further quantify the improvement of the RHCM process on the tensile strength. Several observations can be made. First, the RHCM process improved the weldline strength significantly. Second, a layer removal thick-ness of 0.1 mm improved the weldline strength greatly, and as the layer removal increased, the improvement of weldline strength tapered off. Third, there were differ-ences in the weldline integrity factor among the RHCM specimens with only one side of the part surface thinned out, while the differences were much smaller among the CIM specimens.

Conclusions

In this study, dumbbell-shaped specimens with and without a weldline were cut from molded parts to comparatively investigate the influence of the weldline and its dimensions on the tensile strength in the CIM and RHCM process. The structure and strength were investigated at different later surface removal thicknesses. The following results were obtained. (1) The dimensions of the weldline decreased in the RHCM process, especially the width of the weldline on the side adjacent to the heated stationary half. (2) The weldline decreased the overall tensile strength, with RHCM decreasing that reduction in tensile strength. Meanwhile, there was no distinguishable influence on the tensile strength of the specimens without a weldline in the RHCM process. (3) Removing the surface layer of specimens with a weldline improved the tensile strength, but reduced the tensile strength in specimens without a weldline.

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