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The Study of Submarine Gate Shapes and Degating

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Keywords: Submarine gate, degating, ANSYS

ABSTRACT

In the injection modeling process, a good degating might be the key factor to minimize the possible failures. Therefore, this study discusses the design of a D-type submarine gate that provides optimum degating by changing the rotation angle (θ) of the gate axis, which is on the plane of rotation, around the origin of the coordinate. In the process of injection modeling, the degating occurs during the stage of ejection. A higher ejection force often comes with a temperature rise, which speeds up the in-mold ejection mechanisms wear-out and reduces life cycle. Therefore, this study is focused on how to reduce the force area and thus increase its stress. ANSYS Workbench, Computer Aided Engineering (CAE) software is used in this study to calculate the stress generated in the automatic degating of a submarine gate. The results could be inferred that the D-type submarine gate with θ=45 has superior degating performance than that of the gate with θ=0.

INTRODUCTION

With its advantages of high speed, mass-production and low cost, injection molding is the most widely used manufacturing process for the fabrication of plastic parts. Furthermore, a great variety of products that combine plastics with metals, ceramics and wood can also be manufactured using this method.

Plastic products are literally everywhere in our daily lives. The manufacturing of good plastic products using injection molding relies mainly on three factors, i.e. excellent plastic properties, proper mold design and stable injection machines. Of the three factors, proper design is playing a crucial role of completely combining with the other two. The runner system in the mold is responsible for guiding molten plastic and can be further divided into hot runner and cold runner systems. Hot runner systems offer the advantages of shorter molding cycle time, less materials waste and smooth cutting edge surfaces, which makes it perfect for production in large quantities. On the other hand, cold runner system, which has the drawbacks such as longer molding cycle time, higher materials waste and extra work for cutting, still enjoys its widespread popularity in the production of smaller batches thanks to low manufacturing costs and ease of processing (Herbert Rees, 2002; John P. Beaument, 2007).

For injection molding using a cold runner system, the gate that connects part and runner system needs to be removed in order to separate part from runner system. This separation process is called degating (John L. Bala, 1995). Four types of degating are commonly used, i.e. (1) submarine gate or tunnel gate, (2) tri-plate mold design, (3) in-mold cut, and (4) secondary degating. The relation between runner system, parts and gate is shown briefly in Fig 1. A gate and its associated coordinate system is shown in Fig 2. The image on the top left corner in the figure is the view along the Z-axis. The plane of rotation is formed by rotating the XZ plane around the Z-axis at an angle. The intersection of the plane of rotation and XY plane is called the gate axis.

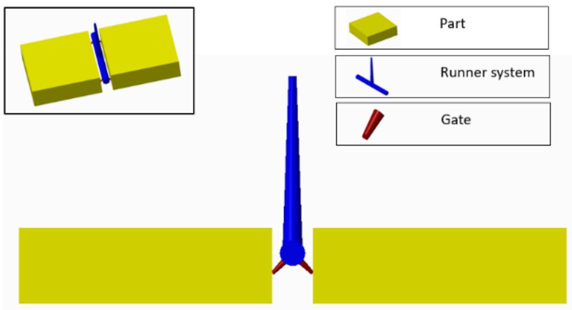

Fig 1 The relation between runners, parts and gates in a cold runner mold

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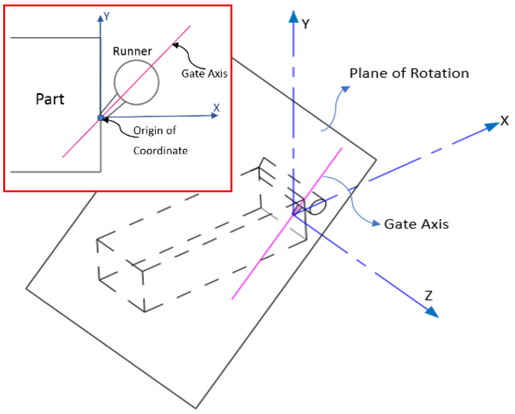


Fig 2 A submarine gate coordinate system (The image on the top left corner is the view along the Z-axis.)

There are many design principles for runners and gates. In order to meet the needs of various applications, gates are designed with different types and shapes. Used together with the cold runner system, submarine gate is a design that offers an automatic degating feature. There are three designs for submarine gate cross section, i.e. round, oval and D shapes. The D-type submarine gate is capable of reducing the traces of degating. Although a submarine gate has better automatic degating results, burrs tend to occur on the parts due to imperfect degating after the submarine gate is used for a long period of time (John P.Beaument, 2007). In real manufacturing situation, the burrs created this way are normally removed manually, which leads to a longer production cycle and manufacturing costs.

The size in a gate design has a great impact on the part's residual stress, mold temperature, filling pressure, packing time and warpage (V. Leo et al., 1996; Pengcheng Xi et al., 2013; N. Zhang et al., 2015). In addition to research of gate size, the research about gate number and location is a great deal too. The problems include optimum molding of large plastic products, locations of weld lines, filling time, short shot, etc (Y. C. Lam et al., 2004; Y. K. Shen et al., 2008; H.S. Kim et al., 2003).

Compared with the studies of gate number, location and size, there is not much research conducted regarding the degating aspect of the gate. A good degating practice helps minimize the size of indentation marks or land length left on the parts after the runner system is separated from the part (Ampere A. Tseng et al., 1994).

Degating is crucial since the gate used primarily to connect part and runner system has to be removed completely afterwards. Take the components used in optical products and the semi-conductor industry for example. The precision industry will suffer great damage if optical or semi-conductor components are contaminated by the materials waste or burrs left on products. Since a cleaner degating of the edge gate can be achieved if the gate is smaller and thinner, a D-shaped submarine gate has better degating results (Randy Kerkstra, 2014). In addition to the three shapes suggested to be used by the submarine gate, CAD/CAM system is used by some research to calculate the optimal size of edge gate for automatic degating. The result is mainly applied to microinjection molding. With this method, an automatic degating mold that has 280 cavities and produces round plastic balls of 7.94mm in diameter has been successfully developed (Ampere A. Tseng et al., 1994).

Among the previous studies on gates, the research on the degating aspect of gates is found to be very limited. This paper is therefore focused on the degating issue of submarine gates. The study is based on the theory of failure. The goal is to design a D-type submarine gate that provides optimum degating by changing the rotation angle of the gate axis, which is on the plane of rotation, around the origin of the coordinate. Finite element analysis software is also used to compare the data collected from real experiments.

DEGATING CAPABILITIES

As previously described, degating refers to the process of separating the part and gate in a cold runner system. Theoretically, the optimum condition of degating a submarine gate is shearing. However, in reality, it contains shearing and fractures[12]. Both shearing and fractures are forms of failures. Failures generally refer to the failure behavior of the materials associated with the physical and mechanical properties such as crack, fatigue and corrosion, etc. Simply put, failure means the surface of an object changes in response to the external force applied to it (Marc Meyers et al., 2009; James C. Gerdeen et al., 2011; Dale Vanrberg et al., 1992). Fig 3 shows three different fracture modes.

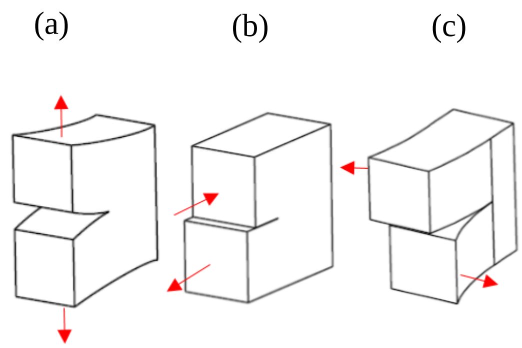


Fig 3 Different modes of fractures:(a) mode I opening mode, (b) mode II sliding mode, and (c) mode III tearing mode.

The Griffith theory dictates that the failure of a brittle material is caused by fractures and defects. The stress is calculated as shown in Equation (1). Based on this Equation, Equations (2) is derived, which can be used to find the approximate solutions to the stress field in the areas at the crack tips of the three fracture propagation modes shown in Fig 3. K_I is related to the external force and fracture length. It grows as the stress increases. When $K_I \geq K_{Ic}$, fracture propagates and develops further into a break, the values of K_I for a range of commonly used materials at 20℃ are shown in Table 1(Marc Meyers et al., 2009; James C. Gerdeen et al., 2011).

$$\sigma = \frac{F}{A} \tag{1}$$

$$\sigma_{ij} = \frac{K_I}{\sqrt{2\pi r}} f_{ij}(\theta_p) \tag{2}$$

Table 1 Fracture Toughness Values for a Range of Materials at 20℃

Materials	**G_{Ic} (kj/m^2)**	**K_{Ic} (MN/m$^{3/2}$)**
ABS	5	2-4
Epoxy	0.1-0.3	0.3-0.5
Nylon66	0.25-4	3
PC	0.4-5	1-2.6
PP	8	3-4.5
PS	0.3-0.8	0.7-1.1
Glass	0.01-0.02	0.75
Mild steel	100	140

It is known from the Griffith theory that the failure of a material occurs only when a fracture propagates, i.e. $K_I \geq K_{Ic}$, where K_I is directly proportional to σ. According to the stress calculation Equation (1), σ can be increased by raising F and/or lowering A. In the process of injection molding, the degating of a submarine gate occurs during the stage of ejection. Raising F in this stage is apparently easy but a higher ejection force often comes with a temperature rise, which speeds up the in-mold ejection mechanism wear-out and reduces life cycle. Therefore, this study is focused on how to reduce the force area and thus increase its stress. According to stress calculation Equation (1), the force area must be perpendicular to the external force exerted. As shown in Fig 2, when the gate and part on the ZY plane are to be separated, the force area can be obtained by multiplying the profile of the gate's cross section by a thickness. This thickness must be kept as small as possible in order to minimize the resistance of degating. The force area then approaches infinitely to the profile of the gate's cross section, i.e. A≃L.

Equation (3) (Dale Vanrberg et al., 1992) is used to calculate the length/distance of equation f in the interval [a,b]. The profile of the D-type submarine gate is defined by Equation (4) (the circle centered at origin (h,k) and Equation (5) (a line with slope γ). At first, it is assumed that degating is to be performed on a D-type submarine gate with radius R and angle θ, where 90≤θ≤0. The object represented by the dotted line in Figure 5 is the part to be ejected. The other one in black solid line is the fixed mold. Y-axis is the direction of the ejection. Ejection refers to the process of the part being separated from the mold. Once the part starts to be ejected, a blade along the ZY plane will cut the gate on the fixed mold. Substitute ejection distance k into Equations (4) and (5) and the interval [a,b] on Z-axis is obtained, which is bounded as -R ≤ [a,b] ≤ R cosθ. The cutting stroke is -R sinθ ≤ y ≤ R.

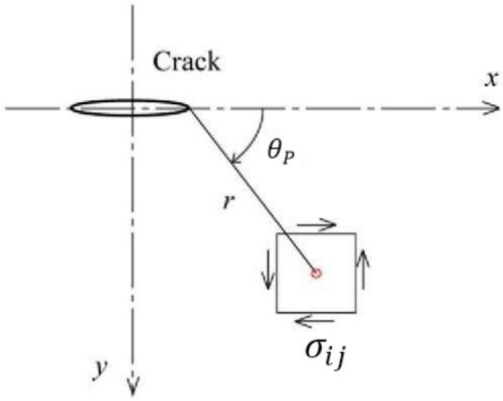


Fig 4 The stress field around any point of an object and crack tip (Equation 2) is calculated based in cylindrical coordinate system. Therefore, the stress field σ_{ij} must be calculated using the crack tip distance r and crack tip angle θ_p.

$$L = \int_a^b \sqrt{1 + [f'(z)]^2}\, dz \tag{3}$$

$$(z-h)^2 + (y-k)^2 = R^2 \tag{4}$$

$$y = \gamma z \tag{5}$$

It was learned from Equation (3) and Fig 5 that under the same degree of ejection, the increase of angle θ will lead to smaller interval [a,b] projected on Z-axis. Therefore, higher stress can be achieved under the same Fig 6 shows the relationship between ejection displacements and profile lengths for four different θ angles. In this figure, a greater slope of the line implies a longer profile length to be cut at that point. For the line with θ=0, the slope increases abruptly between displacements 90 and 100 mm, which indicates that the sudden drop of stress before the gate is cut. That is, shearing becomes bearing in the last stage and tears the gate. This extrusion failure also leads to mold wear. However, the interval of slope rise decreases as the θ angle grows. Therefore, a higher θ is preferred. On the other hand, increasing θ will result in a longer ejection stroke. The ejection stroke is only required to be long enough to push the part away from the mold, normally 1.5 to 2 times the thickness of the part (Gunter Menning et al., 2013). The ejection stroke should be controlled and kept as small as possible since longer ejection stroke will lead to a longer production cycle. It can be seen from Fig 6 that the ejection stroke at θ=60 is nearly 80% longer than that at θ=0. θ=45 is chosen for the experiment due to the considerations of force area and ejection stroke.

Fig 6 indicates that, compared to θ=0, the profile length is 16.68% lower and ejection displacement and stress are 15% and 20% higher, respectively, for θ=30. Similarly, when θ=45, the profile length is 25% lower and ejection displacement and stress are 41% and 33% higher, respectively. Lastly, when θ=60, the profile length is 33.34% lower and ejection displacement and stress are 73% and 50% higher, respectively.

It can be seen that the decrease in profile length (16%) for θ=30 is insignificant. For θ=60, the ejection displacement increases rapidly (73%), compared to the relatively low decrease in profile length (33.34%). Therefore, based on the considerations of force area and ejection stroke, θ=45 is chosen for the experiment since the profile length is 1/4 lower and it causes more obvious change in the stress than θ=30 while still maintaining proper ejection displacement.

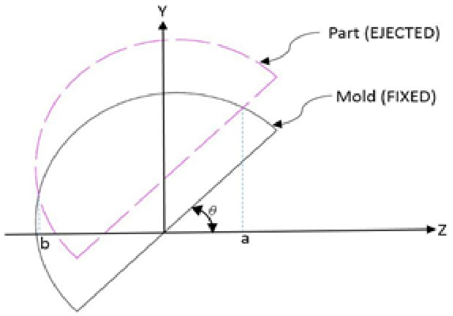


Fig 5 The red dotted line represents the part ejected. Black solid line is the fixed mold and Y-axis is the direction of ejection.

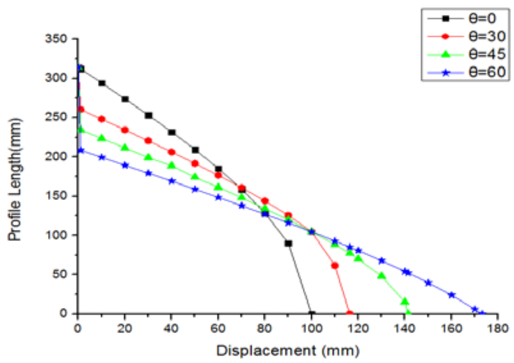


Fig 6 D-type submarine gate displacement and profile length compared by different rotate angles

FINITE ELEMENT ANALYSIS OF SUBMARINE GATE

In the previous chapter, the Griffith theory is used to explain the shearing behavior and characteristics of a D-type submarine gate. The largest stress for the D-type submarine gate with θ=45 is 1.33 times the stress of the gate with θ=0, based on the calculation using Equations (1) and (3). In this chapter, ANSYS Workbench, Computer Aided Engineering (CAE) software is used to calculate the stress generated in the automatic degating of a submarine gate and verify whether the result matches what the theory describes in the previous chapter. If so, the assumption of this paper can also be proved to be correct.

The plastic model used for finite element analysis is shown in Fig 7 The radius of D-type submarine gate is 0.6 mm. The models with angle changes for analysis are shown in Fig 8 and 9. As shown in Fig 2, the gate axis on the plane of rotation rotates around the origin of the coordinate (center point). Fig 10 shows the mold for analysis model. In CAE software ANSYS WORKBENCH, the materials can either be a rigid body or a flexible body. It is assumed in this paper that the mold is a rigid body with no deformation and the plastic part is a flexible body made with ABS.

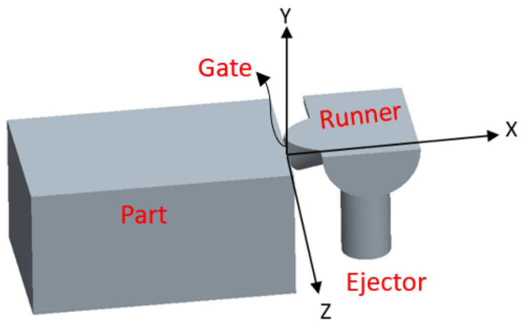
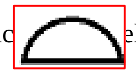


Fig 7 The benchmark model of plastic  element analysis

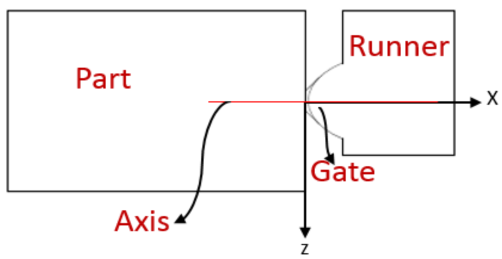


Fig 8 The plastic model for analysis for θ=0, with the cross section on the YZ plane shown at the bottom right

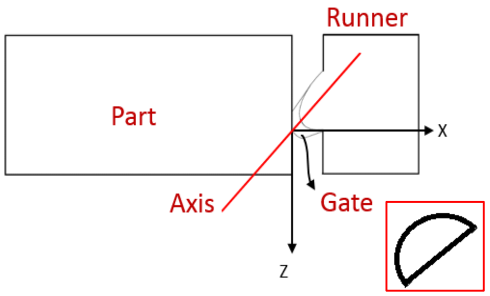


Fig 9 The plastic model for analysis for θ=45, with the cross section on the YZ plane shown at bottom right

Table 2 Boundary Condition

	Dimensions	Position
Fixed Support	--	Bottom of Mold
Force	10N	Bottom of Plastic
Displacement	2.5mm	Bottom of Plastic

This paper is focused on the degating of submarine gates so that the part's geometric shape is neglected. The boundary conditions are shown in Table 2 and Fig 11. Boundary conditions are applied based on the following assumptions. A 10 N force is even applied to the bottom of plastic when the plastic is ejected. The ejection displacement is 2.5 mm, as shown in red in Fig 11. The mold (blue area) is fixed and no force is applied.

The purpose of the analysis in this section is to prove that a D-type submarine gate with θ=45 receives greater stress than the one with θ=0. Since the deformation issue is ignored when evaluating analysis results, only a simple observation of whether a greater stress is received is performed. ANSYS WORKBENCH analysis results indicate that the θ=45 D-type submarine gate receives a stress of 359.9 Mpa, which is greater than the 289.48Mpa received by the regular D-type submarine gate. The analysis results are shown in Fig 12. The ratio of the stress between the two is 1.25. The ratio calculated with Equation (3) is 1.33. The degree of match between them is 94%. The difference is caused by the fact that the calculation is based on the equation of a circle but the shape of the gate is oval in reality, i.e. the error results from the difference between theoretical calculation and analysis.

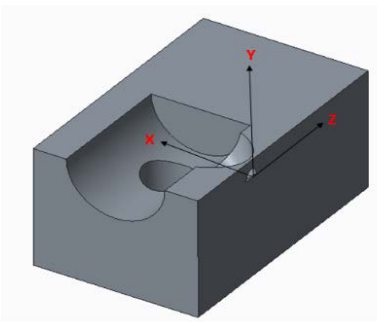


Fig 10 The benchmark model of mold for finite element analysis

If looking at the Equivalent Stress results only, the D-type submarine gate with θ=45 does receive greater normal stress to be used to separate the part and runner. It has been proved that the assumptions used in the previous chapter are correct. The difference in safety factors of the two designs under the same boundary conditions can also be seen in ANSYS WORKBENCH. Safety factor, defined in WORKBENCH as the ratio of the largest stress an object can withstand to the structural stress, is used to determine if an object is carrying a load that is beyond its capacity. An object with a smaller safety factor implies that it is easier to experience failure than the one with a higher safety factor under the same conditions. A safety factor under 1 means that the object cannot even withstand the current load (H.H. Lee, 2011). Fig 13 shows the analysis results of the safety factors. Safety factor is below 1 in the red area. The box-counting dimension method as shown in Fig 14, is used to calculate an area with complex patterns. With this method, the whole image is divided into much smaller boxes of the same size. The total area of an object in the image is then obtained by counting the boxes covering the patterns. The smaller the boxes are, the higher accuracy this method achieves (P-K. Wang, 2013). Using this method, it is known that the red areas in the images of D-type submarine gates with θ=45 and θ=0 are about 70~80% and 30-40%, respectively.

RESULTS AND DISCUSSION

Based on the results from previous discussions, it can be inferred that degating of D-type submarine gate with θ=45 is easier than that of the gate with θ=0. The processed gas inserts are shown in Fig 15. Since the direction of ejection is along the Y-axis, as shown in Fig 10, more attention is paid to the measurements of the lengths of processed gate inserts along the Y-axis with a 2.5D image measuring instrument (See Fig 16.). The lengths of the gate inserts with θ=0 and θ=45 are 0.69 mm and 1.18 mm, respectively. Injection molding data for the experiment is shown in Table 3. The experiment results are shown in Fig 17, in which the tear length is obtained by subtracting the gate's theoretical length (0.69 mm for a gate with θ=0 and 1.18 mm for a gate with θ=45) from the actual gate length on the process product.

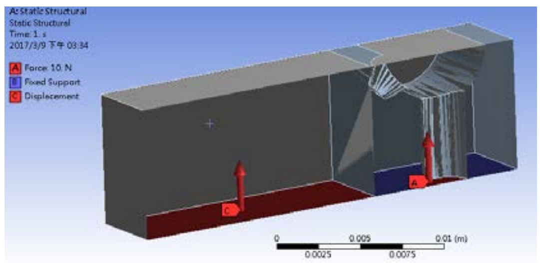
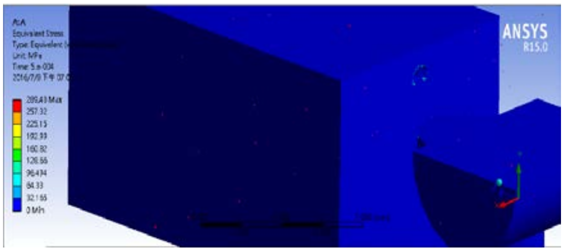
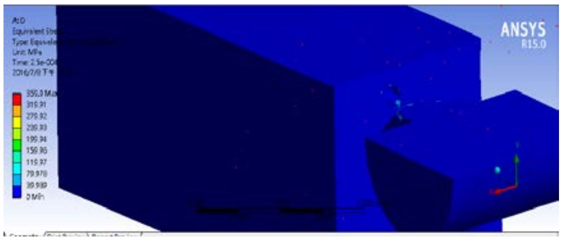


Fig 11 The positions where boundary conditions are applied

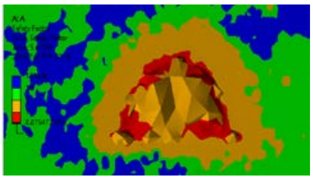


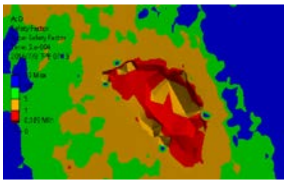
(a)



(b)

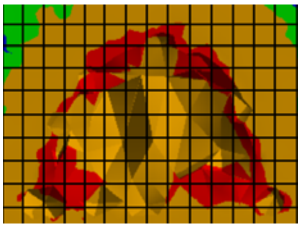
Fig 12 Maximum stress of D-type submarine gates from Equivalent Stress results: (a) 289.48 Mpa, and (b) 359.9 Mpa, transposed gate

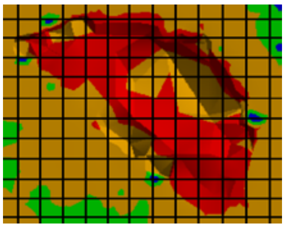




(a) (b)

Fig 13 Safety factor of D-type submarine gates: (a) 30~40% for θ=0 (b) 70~80% for θ=45





(a) (b)

Fig 14 By using box-counting dimension method, the cross sections of the gates are divided into boxes of the same size. The percentage rate of the area that has a safety factor below 1 is estimated by dividing the number of boxes with safety factor lower than 1 by the total number of boxes. Result & Discuss.

After being used for a long time, the center of the gate with θ=0 starts to show signs of tear instead of shearing and the signs of tear becomes obvious after 1,500 degating times. The original gate shape is indistinguishable due to the long tear length. It is known from Fig 5 that the center of the gate shows signs of tear instead of shearing or bearing due to a fast drop of stress. The gate shows more wear after each use and thus the thickness of the gate increases. In this situation, the same stress is not large enough to cut the surface, which makes the cutting length shorter. The surface removal that used to take only one cutting now requires many more, leading to longer cutting stroke and gate shape changes. The results of repeated experiments indicate that material scrap shown in Fig 18 are generated if the torn surface is not completely separated from the part, which may contaminate the products manufactured in the clean rooms used by the semi-conductor or electronics industry.

The degating test results for D-type submarine gate with θ=45 are shown at the right side of Fig 17. It can be easily observed from the images that the gate shape remains unchanged until a slight tear with 0.04 mm in length appears after 5,000 degating times. The tear grows to 0.12 mm after 50,000 degating times. In comparison, the D-type submarine gate with θ=0 has tears longer than 0.12 mm after 1,500 degating times and reaches even 0.45 mm after 50,000 degating times.

The above results prove that the D-type submarine gate with θ=45 has superior degating performance. However, in electrical discharge machining (EDM), it takes only one angle change for the D-type submarine gate with θ=0 to complete the processing. In comparison, two angle changes for the D-type submarine gate with θ=45 are needed so that a special mode-to-order jig is required to successfully finish the processing. Furthermore, the drop depth of EDM electrode after two angles has much greater influence over gate size. Positioning is more difficult as well (see Fig 19).

Table 3 Injection molding parameters for the experiment, with a total molding cycle of 25.17 seconds.

Materials	ABS
Cycle(s)	
25. 17s	Filling =0.62s
	Packing =4.05s
	Cooling =16s
	Close =2s
	Open =2.5s

INJ.V	P3'S	P2'S	P1'S	V/P	1'S	SEG.
	7	1	1		85	V %
	23			26	60	PT.mm
	3	0. 55	1. 5			T s
	65	25	35		20	P bar

INJ.END	1'S	SUCKB	SEG.
	65	23	V %
	75	3. 5	PT. mm
	55	23	P bar
	13		BP. Bar

Clamping Force (TON	
Pre	75
Real	75

RET. END	2'S	1'S	SEG.	1'S	2'S	FWD.END
	40	50	V %	18	28	
	3	10	PT mm	27	46	
	25	25	P bar	20	20	
			Count	2	3	

Temp	SEG.	H1	H2	H3	H4	
	Temp ℃	204	220	214	200	
				Cooler	CO. ℃	CAV.℃
					18	18

(a) (b)

Fig 15 External appearance of D-type submarine gate inserts (a) θ=0, with 0.69 mm of length along Y-axis, (b) θ=45, with 1.18 mm of length along the Y-axis

Fig 16 The processed gate inserts are measured with 2.5D image measuring instrument. The gates with θ=0 and θ=45 have lengths of 0.69 mm and 1.18 mm along Y-axis, respectively.

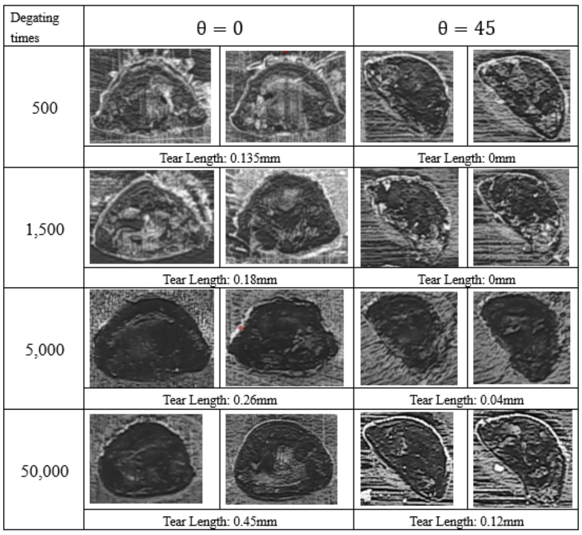


Fig 17 The tear lengths between the D-type submarine gates with θ=0 and θ=45 are compared after different degating times. The tear length is obtained by subtracting the gate's theoretical length (0.69mm for gate with θ=0 and 1.18 mm for gate with θ=45) from the actual gate length on the processed product.

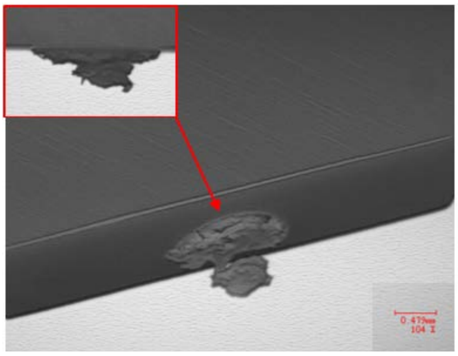


Fig 18 The scrap caused by incomplete tear of D-type submarine gate with θ=0

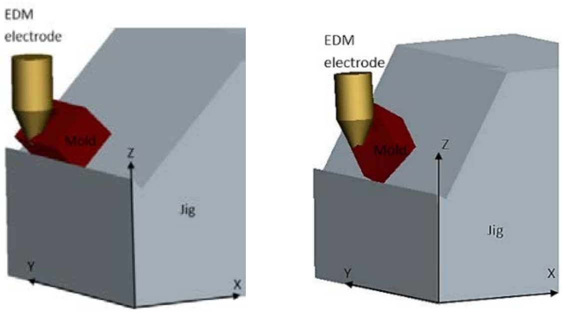


Fig 19 Number of angle changes needed to complete the processing of EDM: (a) one for a gate with θ=0 (b) two for gate with θ=45

CONCLUSION

Based on the results, the D-type submarine gate with θ=45 has superior degating performance than that of the gate with θ=0 in many ways. The capability of gate to receive stress for separating the part and the runner, the gate shape, and the signs of tear are all determinants. Therefore, a designed D-type submarine gate is suggested to be used in the injection modeling in order to produce the low-cost and the high quality plastic products.

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NOMENCLATURE

A	=	The area against a vertical force (Equation 2-1)
F	=	The external force exerted (Equation 2-1)
G_{Ic}	=	Griffith factor (Table 2.1)
K_I	=	Stress intensity factor (Equation 2-1)
K_{Ic}	=	Fracture toughness (Table 2.1)
L	=	Gate profile length (Equation 2-3)
R	=	Gate Radius (Equation 2-4)
r	=	The distance from any point on the object to crack tip (Equation 2-2)
θ_p	=	The angle from any point on the object to crack tip (Equation 2-2)
σ	=	Pressure stress (Equation 2-1)

潛伏式澆口形狀與去澆能力關係之研究

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摘要

在射出成型製程中，良好的去澆能力或許是減少不良品的關鍵因素。因此，本研究透過改變 D 型潛伏式澆口軸心旋轉角度已獲得最佳的去澆效果。射出成型製程中，去澆是發生在頂出階段，較大的頂出力量通常伴隨著溫度和速度的上升，也加速了頂出機構的磨耗使得其生命週期的減少。固本研究著重在於如何在同樣的頂出力量下減少受力面積，從而增加應力。利用 ANSYS Workbench，電腦輔助工程（CAE）軟體

計算潛伏式澆口在自動去澆時所產生的應力。由結果可以推斷，$\theta = 45$ 的 D 型潛伏式澆口具有比 $\theta = 0$ 的澆口有更好的去澆性能。