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NUMERICAL SIMULATIONS AND EXPERIMENTS ON THE INJECTION MOLDING OF AIRCRAFT TRANSPARENCIES

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Abstract

The aircraft transparencies demand better dimensional accuracy and lower residual stresses. The properties of products are relevant to the molding methods and process conditions. Considering the special requirement, injection compression molding (ICM) is applied to mold the product with a similar shape to the aircraft windshield. Through comparing p-v-T programs and the properties of products produced by ICM and conventional injection molding (CIM), the results show that the ICM has great advantages in decreasing the residual stress and uneven shrinkage of the products. Compression related parameters, including compression stroke, compression speed and compression start-up, are analyzed via numerical simulation to obtain the influence of the molding process on the shrinkage and residual stresses. It is confirmed that increasing compression stroke and compression speed are beneficial to improving the qualities of products. Compression start-up is related to the final injected melt volume. The verification test is conducted to confirm the potential and usefulness of ICM.

1. Introduction

Aircraft transparencies are structural-functional integrated components that must endure variable load (for flight and ground load) and possess super-optical properties, including higher transmission, lower haze and deceased optical distortion. Meanwhile, the geometry accuracy of aircraft transparency is severely demanded for the assembly to metal airframe. Thus, the molding of such a part seems to be a great challenge and represents the most advanced technology in transparencies manufacturing. The traditional large aeronautical transparencies is shaped using hot bending technology, which includes cleaning, cutting, thermoforming and annealing, etc [1]. The above process is complex and high-cost. So, it is urgent to develop the new facile molding method with high efficiency, low-cost and high accuracy.

Injection molding has been widely used to manufacture a large variety of thermoplastic products with tight tolerances and complex shapes. However, the high packing pressure in conventional injection molding (CIM) causes high residual stresses and de-molding deformation, resulting in unsuited for precise molding [2-3]. Compared with CIM, injection-compression molding (ICM) is a special injection processing with adding compression, which shows great potential in producing transparent products with low stress and accurate geometry and has been successfully applied in manufacturing the light guides [4], optical lens [5] and DVD discs [6], etc. So, the ICM is hopeful to be applied in manufacturing aeronautical transparencies.

In this study, the ICM process has been comprehensively simulated in condition of different molding processes to evaluate the influences of compression-related parameters on the quality of the products, such as volumetric shrinkage and residual stresses. Based on the optimal simulation results, the verification test was conducted. The product with higher surface quality and lower optical distortion proved the superiority of ICM.

2. Methodology

The geometrical shape of the molded product is similar to the windshield of aircraft, as shown in Fig. 1-a, which is created in CATIA V5®. The part has curved surface structure with 870 mm maximum span. The maximum length and thickness of the part are 878 mm and 8 mm respectively. Autodesk MoldFlow Insight® is used to simulate and analyse the different injection molding processes. A meshing model is developed, as shown in Fig. 1-b. The hot runner with a needle-valve nozzle is used to guarantee the filling and control the sprue open or close. The fan gate is created to provide more uniform flow in the parallel direction. The material used in this study is an injection molding graded Polycarbonate (PC, Makrolon AG2677, from Bayer MaterialScience, German), which is an amorphous polymer with ultra-high transparency and has been used for various optical applications, including car lampshade and skylight. The properties of PC are listed in Table 1. The recommended melt temperature and mold temperature are 300°C and 100°C respectively, which will be used in subsequently simulating analysis. The fixed process parameters in CIM and ICM are showed in Table 2. The compression stroke, compression speed and compression start-up are studied with regard to shrinkage and residual stresses of the products. These compression-related parameters and their levels are listed in Table 3. The simulation is performed using Fill+Pack+Warp pattern, which does not consider the cooling effect. Considering the influence of the different process on the demension accuracy and optical distortion of the products, the volumetric shrinkage is analyzed based on the variation of shrinkage. The residual stress distribution in thickness are obtained by substracting average value of in-cavity residual stresses in the first principal direction. As shown in Fig. 1, the two probe points, named P1 and P2, are used for comparing the residual stresses of different areas on the products (corresponding to the filling area and the compressing area).

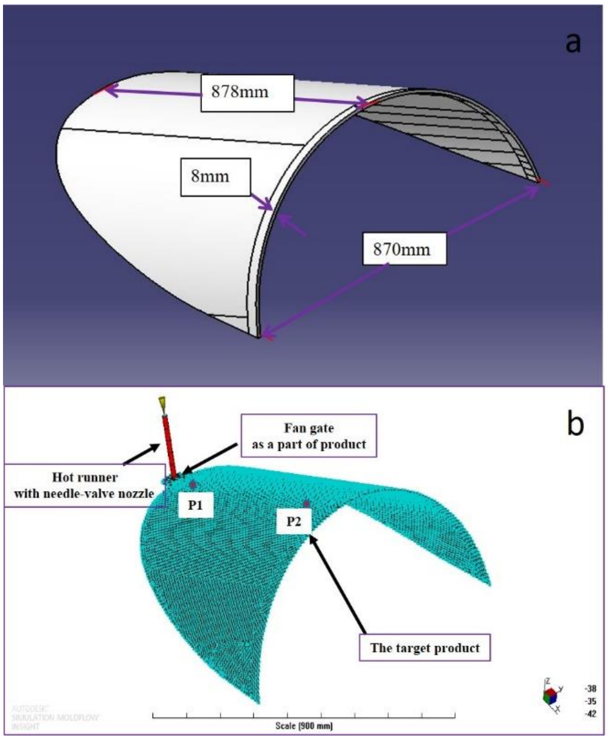

Fig. 1. Demensions and meshing model of the molded product (similar to aircraft windshield)

Table 1. General properties of PC used in this study

Properties	Values	Unit
Material structure	Amorphous	
Density (Solid)	1.20	g/cm^3
Density (Melt)	1.03	g/cm^3
MFI (Melt flow rate)	8.90	g/10min
Transition temperature	150	°C
Elastic modulus	2400	MPa
Poissons ratio	0.38	
Shear modulus	869.6	MPa
Recommended melt temperature	300	°C
Recommended mold temperature	100	°C

Table 2. The fixed process parameters used for analysis of CIM and ICM

Process parameters	Values CIM	Values ICM	Unit
Injection time	3.25	3.25	s
Ejection temperature	130	130	°C
Packing pressure	40	0	MPa
Packing time	200	200 (Comp time)	s
Cooling time	240	240	s
V/P switch-over	99	compression start-up	%

Table 3. The compression related parameters and their levels

Parameters	Level 1	Level 2	Level 3	Unit
Compression stroke	2	4	8	mm
Compression speed	10	30	50	mm/s
compression start-up	108	112	116	%

3. Results and discussion

3.1 p-v-T programs in CIM and ICM

Adding compression to the injection molding changes the thermodynamic history of materials, which is relevant to the final properties of product. It is neccesary to analyse and compare the pressure-volume-Temperature (p-v-T) diagrams of CIM and ICM processes, as illustrated in Fig. 2. The CIM process follows the path of 1-2-3-4-5. The path 1-2 represents the filling and packing to the peak pressure, which is equal to point 2. Path 2-3 indicates packing after peak pressure. The gate is frozen at point 3. Path 3-4 indicated cooling at constant volume. When the presssure droped to atmospheric, the cooling continues to follow path 4-5 but without constraint from mold. The point 4 can also be named as the “ detachment point, which distinguishes the free shrinkage and restrained shrinkage. Acoording to Greener [7], the location of detachment point determines the control capability of shrinkage. If the tempearture at detachment is below glass-transition temperature (T_g), it is considered the dimension of the molded product is conformed to be equal to the dimensions of cavity. In contrary, if the detachment temperature is above T_g, the following shrinkage will not be controlled. It has been proved incearesing the peak pressre leads to the precise injection molding [8].

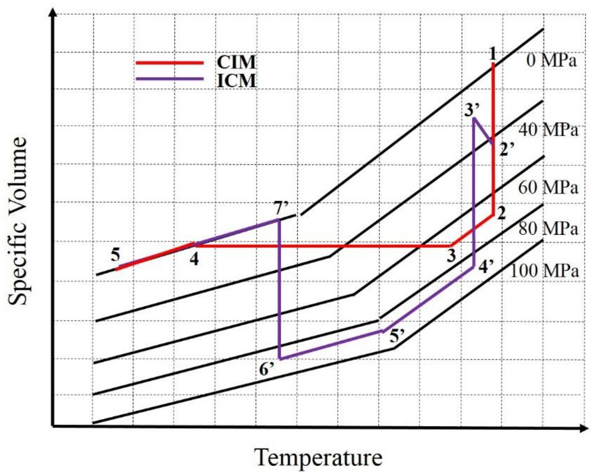

Fig. 2. Schematic representation of P-V-T programs in CIM and ICM process

The ICM process followes the path of 1-2‘-3‘-4‘-5‘-6‘-7‘-5 on the p-v-T program. Path 1-2‘ represents the filling and packing stage. The peak pressure in this stage is lower than CIM for enlarged cavity. Path 2‘-3‘ indicates the delay between the start of compressing and the end of packing, following shut off gate at point 2‘. Path 3‘-4‘ indicates the compressing at constant speed reached maximum clamping force. Then, compressing continues to follow path 4‘-5‘-6‘ until the maximum clamping force. Path 6‘-7‘ indicates the end of compressing. Point 7‘ is the detachment point. The continued cooling at atmospheric pressure followes path 7‘-5. Compared with CIM (path 1-2-3, 4-5), ICM process has more pressure controllable stages (path 1-2‘, 3‘-4‘-5‘-6‘-7‘-5) [9], resulting in improvement in dimension accuracy and decreasing residual stresses, which will be simulated in the next section.

3.2 Shrinkage and residual stresses of CIM vs ICM

The process conditions are essentially different between ICM and ICM. The packing pressure is considered as the most important influence factor on the properties, including shrinkage and residual stresses [10], in CIM. However, the clamping force and the compression-related parameters have been more obvious in ICM. This section focus on the differences of shrinkage and residual stresses of CIM and ICM, with same fill-related conditions. The process parameters are listed in Table 2 and the medium levels in Table 3 are selected for ICM.

Fig. 3 shows the distribution of volumetric shrinkage of the product and its variation under different process. It is found that the minimum shrinkage of CIM is close to the ICM. The maximum shrinkage 3.667% of CIM is higher than the 2.762% of ICM, resulting in the higher variation of shrinkage in CIM as large as 2.428%. The gate packing is used for compensating volumetric shrinkage in CIM. Because the pressure decreased along the flow direction, the shrinkage of the position far from the gate become more serious. In ICM process, the compressing from moveable platen can even the shrinkage in the cavity and decrease shrinkage effectively.

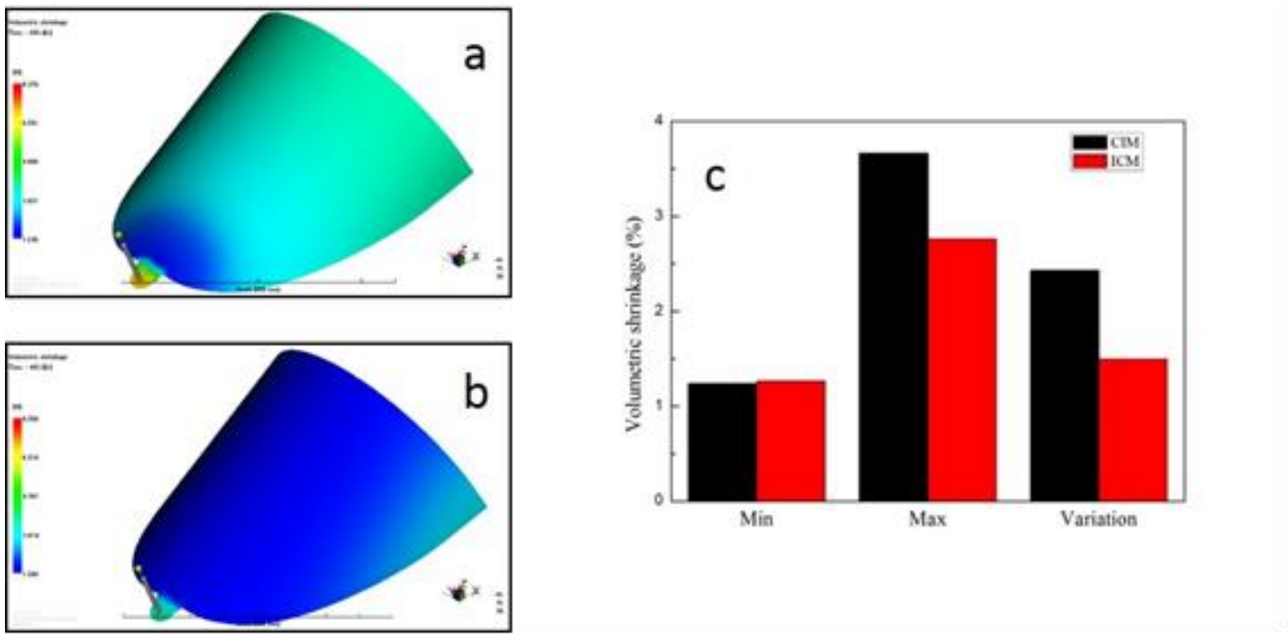

Fig. 3. Distribution of the volumetric shrinkage of the molded part and the variation by CIM and ICM

Fig. 4 shows the residual stresses distribution at the different zones of the molded part by CIM and ICM. For CIM, the residual stresses of the locations near to or far from the gate exhibited a typical " tensile-compressive-tensile" pattern [11], which is constituted of flow-induced stresses and thermo-induced stresses. The differences in values are due to the different molecular orientation controlled by shearing. For ICM, the adding compression decreases the shear-induced stresses and counteracts the initial filling effects. As shown in Fig. 4, the residual stresses are mostly varied from -2 MPa to 1 MPa.

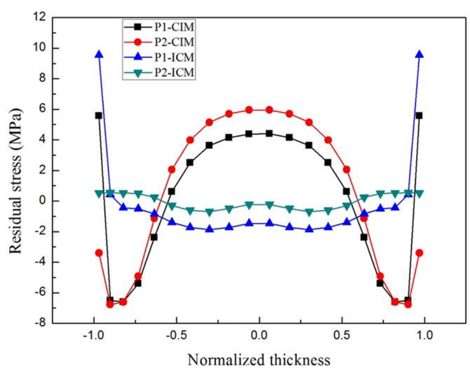

Fig. 4. The residual stress distribution at the different zones of the molded part by CIM and ICM

3.3 Effects of compression-related parameters in ICM

The influence of the compression-related parameters, including compression stroke, compression speed and compression start-up, are analysed in this section. Their levels is listed in Table 3. The medium level of process conditions, compression stroke 4 mm, compression speed 30 mm/s, compression start-up 112 %, is kept any two constant to analyse the effect of the other parameter.

Fig. 5 shows the effects of different compression parameters on the variation of volumetric shrinkage. It is observed that increasing compression stroke and compression speed cause decreasing in the variation of shrinkage. It is evident from y-axis range that the effect of compression speed on variation of shrinkage is less than compression stroke. The compression, under larger initial stroke and speed, will give a more uniform compensate for shrinkage, which is also smaller than CIM. As shown in Fig. 5-c, the variation of shrinkage increases as increasing the compression start-up. However, the maximum volumetric shrinkage at compression start-up 116% is 2.703%, which is much smaller than the minimum volumetric shrinkage 5.959% at compression start-up 108%. So, the variation of shrinkage at higher compression start-up will not lead to serious sink marks and optical distortion.

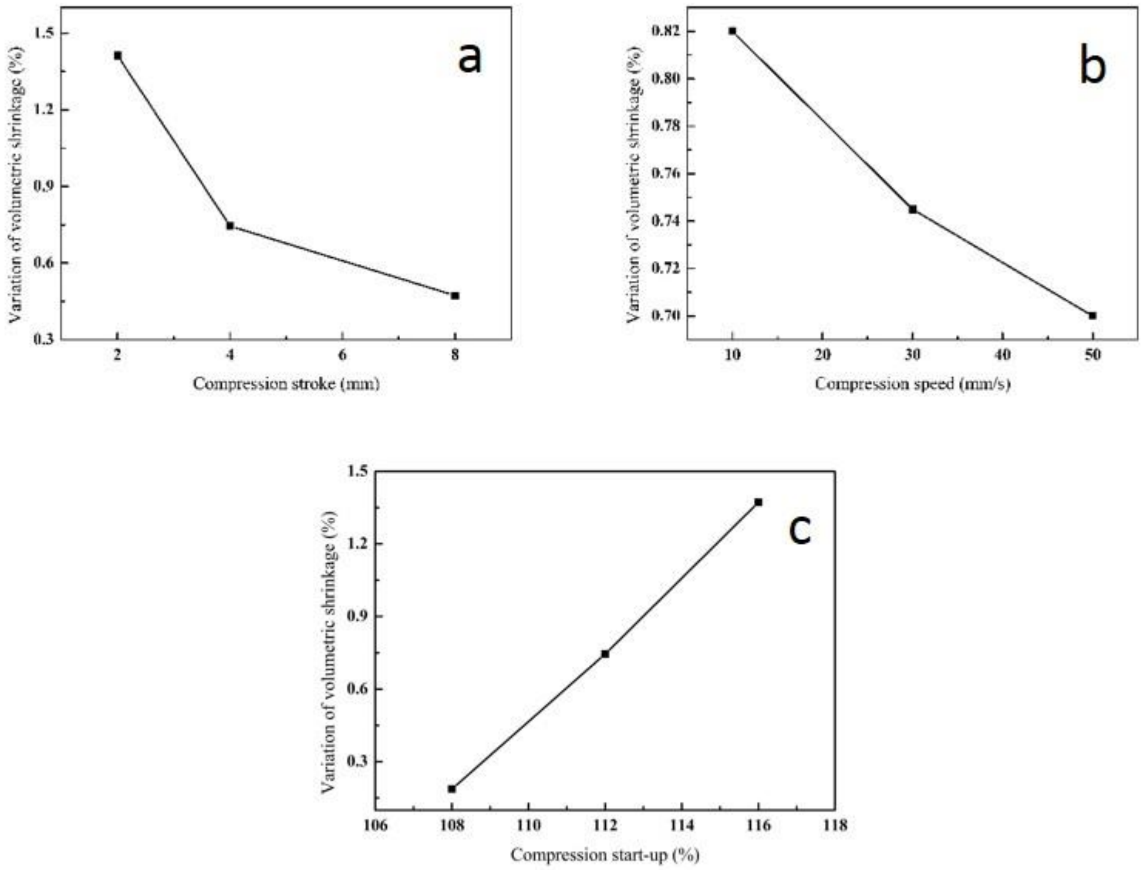

Fig. 5. Variation of volumetric shrinkage of the molded part by ICM under different compression stroke, compression speed and compression start-up

Fig. 6 shows the effects of different compression parameters on the residual stress distribution on thicknesss at different areas. As can be seen in Fig. 6-a, an increasing compression stroke causes increase in the tensile stress at the core region and in compressive stress at the sub-surface region (corresponding to shear layers). Fig. 6-b shows increasing compression speed also raises the stresses values. The effect of compression speed is less than compression stroke. The second sqeezing flow of the melt is caused by the adding compression. The larger initial stroke and speed, the more obviously squeezing flow, will result in the higher flow-induced stresses, but much lower than CIM. Meanwhile, the stresses at the compression area (P2) is a little higher than the filling area (P1). The main reason is that back-flow trend in ICM process can change the velocity distribution in thickness and decrease the pressure gradient. As shown in Fig. 6-c, it is evident that compression start-up has a strong effect on the residual stresses, which is relevant to the mass injected from feed system. The higher compression start-up means the more materials is injected into the cavity and more obvious compression.

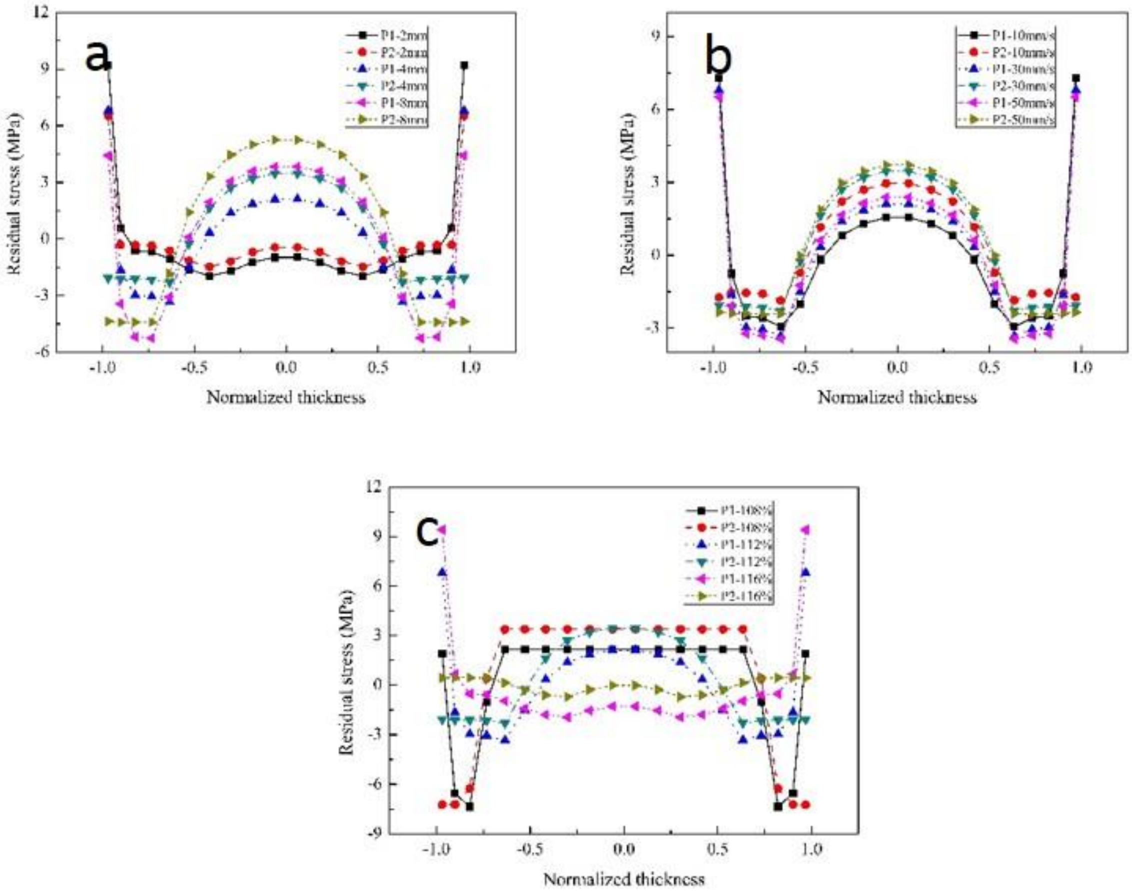

Fig. 6. Distribution of residual stress of the molded part by ICM under different compression stroke, compression speed and compression start-up

Generally, ICM can control the volumetric shrinkage and residual stresses flexiblely. Through simulation analysis, the relationship between process parameters and the final properties can be founded, which is beneficial for adjusting the process conditions and mold modifications.

3.4 Verification test

After studying the influences of process conditions, the final phase is to verify the usefulness and potential of ICM in molding the aicraft transparency. The optimal experiment conditions are selected: a melting temperature of 300 ^{o}C, a mold temperature of 100 ^{o}C, an injection time of 3.25 s, a compression start-up 112 %, a compression stroke 4mm, a compression speed 30 mm/s, a compression time 200 s and a cooling time 240 s. As shown in Fig. 7, The appearance and light transmittance of the product is perfect. The optical distortion is related to the variation of shrinkage and residual stresses. Owing to advantages of ICM, The mesh distortion of molded product is also small, which is consistent with the simulation.

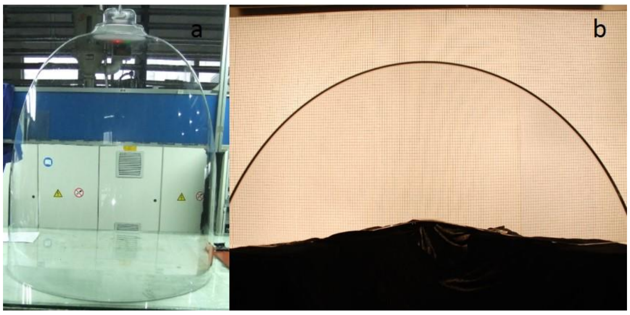

Fig. 7. The final part molded by ICM

4. Conclusions

In this study, the ICM has been conducted and analyzed through both simulations and experiments. p-v-T programs and the properties of the products have been compared for both CIM and ICM. It can be concluded that:

1. p-v-T program of ICM exhibits that ICM process has more stages controlled by pressure, which is a crucial factor for controlling the shrinkage and residual stresses.
2. Compared with CIM, ICM can prepare the product with more uniform volumetric shrinkage and decreased residual stresses in the simulation. In other words, ICM would be more suitable to manufacture aircraft transparencies.
3. The rise of compression stroke, compression speed could cause decreases in variation of shrinkage and change the distribution of residual stresses in thickness for more compressing effects. The compression start-up is relevant to the injected melt volume.
4. The qualified product, with higher dimension accuracy and lower optical distortion, is molded using ICM process.

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