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Prevention of Defects in Injection Molding Process in the Manufacturing of Ballpoint Pen

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Abstract: Injection molding is one of the major manufacturing processes for thermoplastic polymers. In injection molding machine, process variables play a very important role in generating defects in products. In the present paper manufacturing of ball point pen is taken up to investigate the prevention of defects through design and controlling various process parameters. Two molds are designed and fabricated specially for this experimental work. The analysis showed that the defect occurrence has close relation with pressure, speed and the temperature of the injection molding machine in addition to the basic design of the mold. The paper suggests preventive actions for the defects like flash, burn marks, short shot, shrinkage, weld line, warpage and sink mark. The preventive actions were successfully implemented in manufacturing the ball point pen.

Keywords: Injection molding, ball point pen, mold defect, preventive action

I. INTRODUCTION

Injection molding is the most significant process to produce plastic products. It produces most intricate complex geometry parts effortlessly. The parts which are manufactured by the injection molding contains some defects and these defects influences the quality of the component. Chao-chyun An, Ren-Haw Chen [1], in their paper have suggested that, defect of flow marks which can be easily controlled when mold temperature and injection speed are comparatively low. Lei Xie, Grehard Ziegmann [2], have studied comprehensively the mechanical properties of weld line defect for polypropylene (PP) composites. Mehdi Moayyedin et al.[3], presented an analysis of short shot possibility in injection molding process. They have adopted the Taguchi method to identify the significant process and geometric parameter to overcome short shot occurrence. Daniele Annicchiarico et al.[4] in their paper have developed a methodology to overcome shrinkage defects. Their analysis results showed that the methodology adopted was capable of detecting the factors which will have significant effect on shrinkage at a micro scale level.

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Shin-Chin Nian et al.[5] in their paper have described that the inconsistent thickness in component geometry, poor spruce, runner, gate sand improper molding condition settings may cause plastic parts to warp excessively. Xianjun Sun et al.[6] have opinioned that it is a challenge to produce parts that do not warp and have developed technology to measure part warpage quickly and accurately with digital image correlation method.
They have told that the mold temperature has a significant effect on warpage. Yu wang et al.[7] in their study, have examined the various cooling techniques in injection molding process. The spiral and conformal technique, cooling design of channels are able to achieve uniform mold cooling so that molded parts shape is maintained. Ming-Shyan Huang et al.[8] have examined the influence of clamping force on tie bar elongation and have opined that a small clamping force may produce defects such as flash and poor geometric accuracy. The large force results in insufficient air venting during mold filling, leading to the generation of the short shot. Ming-Shyan Huang and Cheng-You Lin [9], in his paper he has developed a novel searching algorithm based on information about tie-bar elongation with various clamping force settings to identify the proper clamping force value to set. Xundao Zhou et al.[10] have studied feature extraction and physical interpretation of melt pressure during the injection molding process and concluded that melt pressure is very crucial in injection molding. They installed variety of pressure sensors in injection molding machines and molds to collect melt pressure information and further inferred that challenges exist for these feature extraction. The experimental and analysis results show that the how geometric features of a part influence the melt flow. Abohashima H S et al.[11] have described minimization of defects percentage in injection molding process using design of experiment and Taguchi approach. The authors have concluded tha, in injection molding process, the processing parameter such as injection pressure, injection speed, cooling time and packing pressure plays a very important role in controlling the quality of the products. Marco Sorgato et al.[12] they examined tribological effects of mold surface coatings during ejection in micro injection molding. The effects of different mold coatings on the ejection force in microinjection molding were experimentally investigated. K Prashanth and Bharmara Panitapu [13], have experimentally studied how high thermal conductivity mold insert materials can be used to prevent defects like volumetric shrinkage and warpage. They replaced tool steel metal inserts by copper and beryllium inserts. N. Crisan et al.[14] in their paper, have opined that one of the current challenges in prevention of defects is linked to product design that enables a strong differentiation. Mohd.

Jamsheed et al.[15] in their paper have focused on design and analysis of an automatic plastic injection mold to give good surface finish. There are many factors which have significant effects on the quality of molded parts. Simulation software can help user in reducing time taken to conduct a preliminary test. However, user cannot fully dependent on the numerical simulation by software as it sometimes will give different result from the actual experiment [16]. Sink mark defects are extensively dealt by different authors and suggested different techniques for measurement, analysis, minimization and visual perceptibility to overcome this defect [17-20]. In summary, despite the undeniable literature studies available in the plastic injection mold product defects, the producers are faced with certain difficulties to prevent them appearing in the injection molded parts.

The objective of this paper is to study the prevention of defects in injection molding process experimentally by taking the actual complex product the ball point pen. The mold required for the manufacture of this ball point pen is having four distinct cavities with different shape and pattern and multiple type of clamps and ball catchers. This will facilitate to analyze many defects which may appear in the production process and how to prevent them effectively.

II. METHODOLOGY

Injection molding (IM) consists of high pressure injection of the raw material into a mold which shapes the polymer into the desired shape. In this process typically palletized thermoplastic raw material is fed through a hopper into a heated barrel with a reciprocating screw. On entrance to the barrel the thermal energy increases and the Vander Waals forces that resist relative flow of individual chains are weakened as a result of increased space between molecules at higher energy states. Due to this viscosity reduces and it enables the raw material to flow with the driving force of the injection unit. The reciprocating screw enables the mechanical shearing of the material and add significant amount of frictional heating to the raw material.

The injection molding process can be divided into three phases. Filling phase, the most important phase as plastics flow into cavity. Pressurization phase: it begins after the cavity has just filled. However the edge and corners of the cavity may not contain plastic. Compensating phase: plastics have a high volumetric shrinkage, around 25% from average melt temperature to solid. It requires more material must be injected into the cavity to compensate for the plastic shrinkage as it cools.

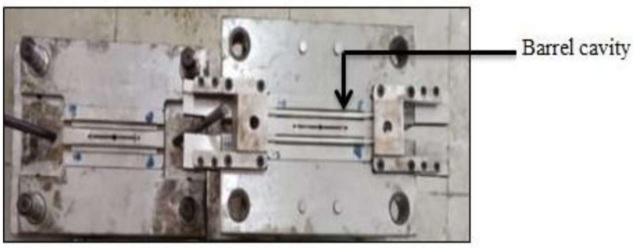


Fig. 1. Pen barrel mold

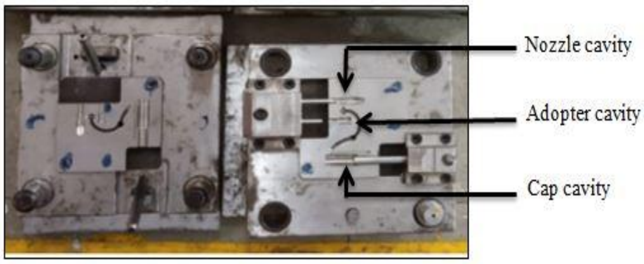
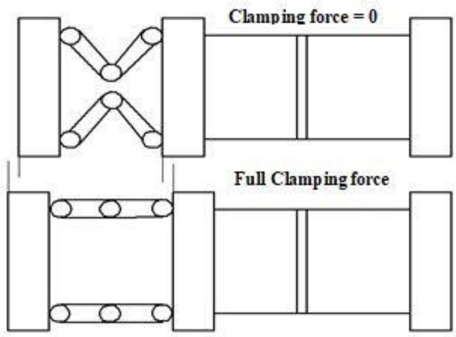


Fig. 2. Cap, adopter and nozzle mold

This study is fully focused on the prevention of defects in the manufacturing of a ballpoint pen parts. The mold designed and developed for manufacturing the parts of the ball point pen to study the prevention of defects is shown in Fig. 1 and Fig. 2. Essential characteristics like high tensile strength, high elasticity, good heat resistance, excellent wear resistance and good surface finish are taken care for the mold material and the cavities. Two molds one family mold for three cavities (cap, nozzle and adapter) and another mold with two cavities for the barrel is designed. This study shows that there are many factors which have significant effects on the quality of molded parts. Main process parameters which attributable to generate defects are listed as clamping tonnage, cooling time, pressure drop and heat transfer rate. These parameters have been specifically examined to find out their contribution to study the prevention of defects. The injection molding machine utilized for the manufacturing was Electronica Optima 75.

A. Clamping tonnage

The clamping force is estimated by the extent to which the toggle mechanism is expanded to the extent such that the mold halves to make the perfect contact. When the toggle mechanism is expanded completely as shown in Fig. 3, it is said to be a set mold clamping force is applied. The clamping tonnage is defined as the amount of force, generally estimated in Kilo Newton's, which is required to



hold the mold closed during operation. The clamping tonnage, F_{Clamp}, can be calculated using the formula $F= EA\varepsilon \times 4$, where E=Young's modulus(210 GPa), A=Projected area, ε=strain, 4=Number clamping bars).

Fig. 3: Clamping mechanism under zero clamping force and full clamping

B. Cooling time

Thermal management in IM is well connected to the shape accuracy of the molded part. The molds in IM are subjected to cyclic thermal variations. Therefore, cooling channels are embedded in the mold for faster cooling times.

The uneven thermal changes lead to uneven expansion which will cause inherent stress and the defects like cracks. The conformal cooling structure for plastic injection moldings could be a technique to improve the plastic product quality. This approach can generate conformal cooling channels with higher flow rate so that heat transfer efficiency is improved in plastic IM. To decide the cooling time, it is important to give some basis that demonstrates when the molding is rigid enough to be ejected from the mold. One sensible methodology is to think about the modulus of the material, which is a measure of the material to resist deflection. The cooling phase of the molding process commands the cycle time since the rate of heat flow from the melt to the colder mold steel is limited by the low thermal diffusivity of the plastic melt. However, the plasticization time may surpass the cooling time for substantial shot volumes with low plasticization rates. The cooling time is defined as the measure of time required after the mold is filled for the plastic to turn out to be rigid to discharge. There is an almost no progression of the melt after the shape is full, the exchange of heat between plastic and the transient heat conduction equation is given by $\partial T/\partial t = \alpha\ (\partial^2 T/\partial z^2)$. Where **α** is the thermal diffusivity, which is equal to $(k/\rho)C_p$, where T is the temperature, t is the time, z is the dimension in the thickness direction, k is the thermal conductivity (0.1 w/m. K), Cp is the specific heat (0.46 cal/gm ^{o}C) and ρ is the density of polypropylene (0.905 gm/cm^3) material. By substituting these values in heat conduction equation we get the thermal conductivity (α) = 2.4289X10^3 m^2/s. Then the cooling time calculated as

Cooling time (t_c)

$$t_c = \frac{h^2}{\pi^2 \cdot \alpha} \ln\left(\frac{4}{\pi}\frac{T_{melt} - T_{coolant}}{T_{eject} - T_{coolant}}\right)$$

Can be solved to provide required cooling time as a function of the melt temperature (T_{melt} = 220^{o}C), coolant temperature ($T_{coolant}$ = 30^{o}C), ejection temperature (T_{eject} = 190^{o}C). Finally the required cooling time comes out to be t_c = 18.013sec.

C. Pressure drop

Pressure drop dP/dL is the pressure drop per unit length. The simplified equation for the pressure drop is 2τ/h, where τ is shear stress, h is mold cavity thickness and L is the total cavity length. The *pressure drop* occurs due to frictional forces caused by the resistance to melt flow in the cavity. In the present experimentation τ = 13000 Pa, h = 0.001m and the length of the cavity plate (0.063x2) m. The pressure drop for total length in injection molding process is calculated as 3.276 Mpa. Pressure drop is also the function of volumetric flow rate. IM process with low pressure drop increases the reason for having highest possibility of short shot.

D. Heat transfer

The fundamental mechanisms of injection molding are heat transfer and pressure flow. There are three methods for transferring heat in the IM process, radiation, convection, and conduction. The hot melt from the nozzle is moved into the mold spruce bushing. The heat from the melt moves by convection through the polymer until it achieves the depression surface of the mold. The heat is then led through the mold cavities to the mold cooling system and the cooling channels. A substantial amount of heat reaches outside the mold surface, where the heat is lost by radiation. In the IM process, around 60% of heat is expelled by the mold. However, some heat is left in the molded parts after they are expelled from the mold cavities after ejection. Approximately 35% of the heat is expelled by radiation from the mold and 25% is expelled by the cooling fluid that controls the mold cavity surface temperature [5]. For efficient heat transfer system the cooling channels should be placed at a proper distance from the mold cavity. Another significant consideration in cooling channel design is to ensure that coolant circulates in turbulent rather than laminar flow. The coefficient of heat transfer of the cooling system is drastically reduced in laminar flow. The regime of the flow, turbulent or laminar is estimated by the Reynolds number (Re). For a circular cross section channel, turbulent flow occurs when the Re > 2300. From heat transfer co-efficient equation U = (Nu.k.12/D) heat flow rate $Q=UAL(T_c-T_f)$ can be calculated**.** Here, Q is the heat flow rate, N_u is the Nusselt flow number, k is the thermal conductivity of the cooling fluid, D is the diameter of cooling channel, A is the exposed surface cooling area, L is the length of the cooling channel, T_c is surface cavity temperature and T_f is the Cooling fluid temperature. For the experimental ballpoint pen mold, Q is calculated as Q = 983.92 W/m^2. From the heat transfer rate, for better cooling effect to prevent defects it is required to increase the difference in temperature between the mold cavity surface and the mean cooling fluid and increase the exposed surface cooling area.

III. Identification of Defects, Causes and Prevention

The difficulty of injection moldings and the interconnection of many variables included, it means every defects in injection molding have some causes. Accordingly, a preparation that cures one defect may produce another. Quality of the injection-molding parts will arise from a small minor surface defects to gradually challenging problems they can affect function, performance, safety and aesthetic importance of the part. In the manufacturing of ballpoint pen we have come across with many troubleshooting while manufacturing. These trouble shooting defects are flow mark, burn marks, short shot, shrinkage, weld lines and warpage. In the present study all these defects are analyzed technically and prevention measures are accorded.

A. Flash

Flash, is also known burrs, it is an excess polymer melt that seems as a thin rim or lip at the edges of product. It appears because the molten material has over flowed at outside of the specified flow channels and in between cavity plate and core plate. Flash is normally delicate but it is considered as a major defect in obvious of a product. Poorly clamped molds are having major contribution on flash. Extremely high injection pressure and mold temperature will also cause flash. While manufacturing we faced large flash defect at the barrel segment, the escaped part as shown in Fig. 4.

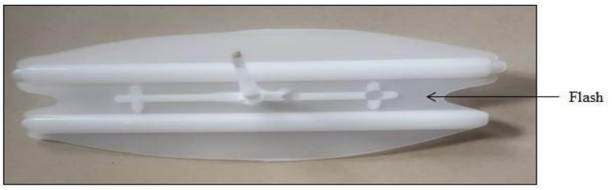


Fig. 4. Large Flash

Possible causes of flash can be listed as insufficient clamp force, extreme melt temperature, and failure of mold parting surface, flow restriction for more cavities in a multi-cavity mold. Flash can be prevented mainly by increasing the clamp force. In the present case the clamping force which was around 620 KN by analytical solution was increased to 750 KN for a perfect clamping of molds.

B. Burn Marks

Burn marks are generally appearing as dark colored staining on a face or edge of a molded plastic part, which seems to be burned. Burn marks generally do not affect part integrity, except that the plastic is burned to the extent of degradation. In injection molding the entrapped air may cause a small explosion due to the compression of air and polymer vapour, so this is called as diesel effect. Because of this the tool will erode and plastic parts are ejecting with burn marks. Well-designed proper venting system can give the good filling of mold and required injection pressure will maintained by lowering of counter pressure.

While manufacturing of pen cap we observed burn marks at the edges of cap. The trapped air is fundamental reason for these defects, overheated mold cavity at injection stage. High injection speeds or overheating of raw material regularly lead to causes burns. The Fig. 5 shows the presence of burn mark.

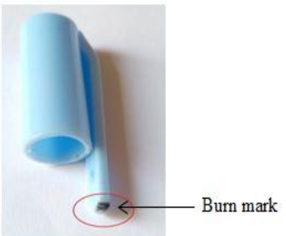


Fig. 5. Burn marks

To keep away from this defect, the melt temperature which was set at 230°C to 215°C by analytical method was reduced by 85°C to 75°C which prevented overheating as well burn marks. Also the injection speed is reduced to restrict air trapping in mold.

C. Short shot

When sufficient polymer melt is not injected into the mold cavity, a short shot happens. It is caused by various factors such as insufficient charge flow, incorrect processing parameters, and injection speed. Sometimes complexity in the gating system and viscous flow of melt also matters for short shot. While manufacturing of ballpoint pen except for adopter we discovered short shot possibility in remaining parts of ballpoint pen. The Fig. 6 shows the appearance of a defect in ballpoint pen.

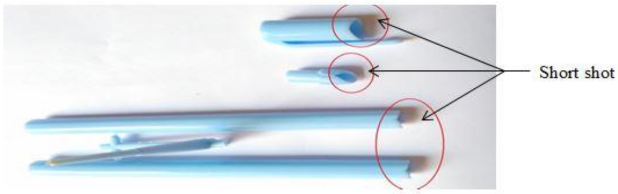


Fig. 6. Short shot

The preventive action for this defect is, increasing the charge flow rate for barrel part from 12.5 cm^3/sec to 13.5cm^3/sec and for the cap, adopter and nozzle charge flow is changed from 5cm^3/sec to 6.5cm^3/sec simultaneously along with flow rate, the injection speed also varied as per the requirement.

D. Shrinkage

Shrinkages are the defect caused by the variations in the processing parameters like mold temperature, melt temperature, holding pressure, injection pressure and holding time. The Fig. 7 shows the shrinkage defect appeared in the component.

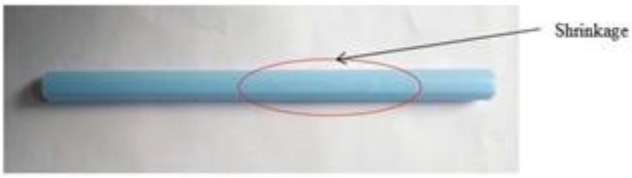


Fig. 7. Shrinkage

To prevent shrinkage defect, the variations are made for mentioned processing parameters. Injection pressure was reduced from 850 KN to 750 KN. Holding pressure was reduced correspondingly. Melt temperature for this product was 220°C, which was reduced to 215°C, but its mold temperature was increased from 60°C to 75°C and holding time was decreased from 10sec to 7sec. A preliminary experimental trial and error method is conducted to arrive at low and high values. A set of value for each parameter were chosen, such that the higher value was obtained by expanding from underlying setting until the presence of flash was notable. The lower value was achieved by diminishing the parameter value until notable defects started to appear.

E. Weld line

Weld lines are most common defect in IM process. Indexing of Weld line is the evaluation parameter which is known as weld line index $F_{WL} = P_Y / P_N$, where P_Y is with weld line mechanical properties and P_N is without weld line mechanical properties. If the F_{WL} is big, the weld line properties are better and the molded part weakness is lower. With high holding pressure, moderate melt temperature and low mold cavity temperature is possible of better indexing [16]. Weld lines are appears on the surface of the product where the melt flow meets. In the manufacturing of ballpoint pen, the weld line appeared in barrel section at the parting line. In cap, nozzle and adopter sections the weld lines are very negligible. Weld line eliminations without modifying the part geometry is found to be difficult in ball point mold. However by experimental trial and error method the defect on part performance and appearance can be reduced. The Fig. 8 shows the weld line defect appeared in the barrel section.

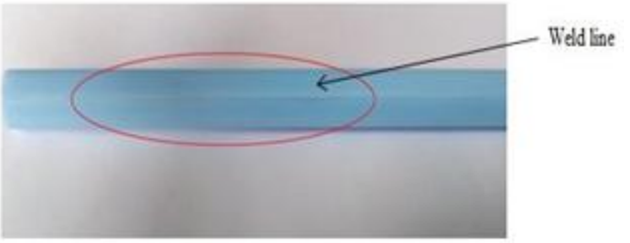


Fig. 8. Weld line

F. Warpage

Warpage is because of residual stresses arising while shrinkage is differential and anisotropic across the part and part thickness. The temperature variance between lower and upper mold surface causes shrinkage between the core and cavity which produces the bending moment. To control warpage, neutral axis of bending moment is considered as to alternative possible warping direction. Neutral axis as in beam theory is the axis which has no longitudinal stresses or strains. High temperature molten polymer shrinks substantially when it comes to room temperature. The cross sectional temperature distribution and the location of its neutral axis can indicate the warping trend. Thus the warpage behavior is explained by considering neutral axis theory. If the temperature is balanced, at neutral axis the maximum temperature will appears. Thus uneven shrinkage will cause the warpage. This is possible to adopt after simulation study. In the present work, the maximum warpage was at the barrel section at the parting line, as shown in the Fig. 9.

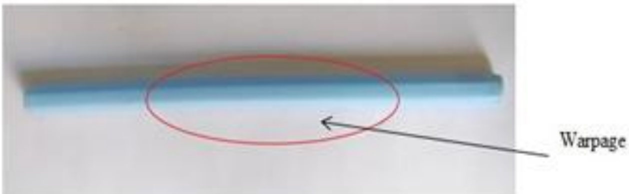


Fig. 9. Warpage

To prevent this effect, the melt flow temperature was reduced from 220°C to 210°C and cooling time was expanded for a little expansion. The results show that uneven cooling effect at the different regions of the mold contributes to warpage.

G. Sink mark

During the solidification phase local internal volumetric sink starts and it continues until part temperature reaches to the room temperature, and the process may go beyond the injection molding cycle. It occurs at areas where there is increment in local mass and thermal mass. Polymer pressure v/s temperature behavior and the cooling rate are the dependent variable of shrinkage. Due to low thermal conductivity of the polymer, mass accumulations are insulated from the neighboring polymer material, thus those areas shrink more than their surroundings. Sink mark creates despondency in thicker material zones. Fig. 10 shows the sink marks appeared in our work.

Fig. 10. Sink marks

The outside material inward before the chance to adequately cool because of resulting sink mark, leading to a depression. These defects are influenced mainly due to the inadequate holding pressure in mold. It occurs after the injection during cooling phase. Sink marks can be reduced by applying proper holding pressure and increasing the packing time. After repetitive trials the cooling time is increased from 18 sec to 22 sec to avoid sink marks. To avoid the sink marks after the ejection the product was even dipped in cold water tray to get high quality product.

IV. Results and Discussion

The aim of this experimental study is to prevent the occurrence of defects in the manufacturing of ballpoint pen through IM process in Electronica Optima75 injection molding machine. Prevention of defects plays major role in injection moldings. In this present study the various defects produced in the manufacturing of ballpoint pen is analyzed. Selection of suitable design parameters and process parameters are very much important in this respect. Large flash is the major defect in our work and with the perfect clamping force we could eliminate this defect. Overheating of mold and air trapping will cause the burn marks. It was overcome by setting the temperature as per the mechanism of heat transfer and flow process analysis. The possibility of short shot is caused by melt with high temperature increment in the injection pressure prompts an increase in the, and melt with moderated temperature decrease the injection pressure prompting a reduction in the possibility of short shot. The mold temperature is the factor with higher extent, however inverse to the flow direction case lower mold temperature prompted prevention in shrinkage. The prevention of weld lines in IM depends on different parameters such as melt temperature, injection pressure and mold design. The cooling time has the largest effect on the warpage. The warpage will create the bending structure in the injection molding parts. Keeping the melt flow temperature in moderate level and increasing the cooling rate prevent the warpage imperfection. Sink marks occur more easily when the injection speed and mold temperature is low, so we have to keep both the processing parameters in a moderate level.

V. Conclusion

Injection molding is a complex process with many complex problems. In addition to the aesthetic properties of the product various physical conditions of the molding process should be looked into to prevent defects that can impact the quality of the product. In the present paper the study is focused on prevention of defects arising due to the process parameters which are often encountered in the manufacturing of ball point pen.

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The major process parameters which are analyzed are clamping tonnage, cooling time, pressure drop and heat transfer rate. Different factors cause various defects in the products like flash, burn marks, short shot, shrinkage, weld line, warpage and sink mark during the manufacturing process. Based on analytical analysis and experimental trials the following conclusion can be drawn with respect to the prevention of defects.

- The flash defect appearance is highly correlated with clamping force. About 10% to 20% increment of clamping force from the analytical value is found to be preventing any flash in the manufacturing process.
- The burn mark is the defect due to the indirect effect of inadequate heat transfer rate and venting. Thermal management in injection molding is of high importance to overcome the burn mark effect.
- The defect short shot is caused by sharp decrease in the flowing channel. Thus, a high injection speed is required for complete filling and packing during the injection molding process.
- The results show that shrinkage is likely to occur in the region near the cooling channel as compare to other regions.
- The weld line defect is controlled by, increasing the melt temperature and injection speed. The effect of these two in injection molding process parameters are experimentally investigated in terms of their influences.
- The neutral axis theory can be considered to explain the warpage behavior. If the rate of cooling of female and male mold plate is adjusted to enable the maximum temperature to be located exactly on the neutral axis, the warpage can be eliminated. This neutral axis theory design can be adopted after simulation study.
- Sink marks appear as unwanted shallow depressions or dimples which are caused by the difference in the amount of shrinkage during cooling phase of the injection molding. The amount of shrinkage is directly proportional to thickness of the part.

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