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Mold Design and Analysis for Multi-Component Plastic Injection Parts with Contrasting Functional Features: Case Study

Akın Oğuz KAPTI*[1], Erdi ERTEKİN[1], Uğur ACUN[1]

Abstract

The classical plastic injection method is based on the principle of injecting a single color of a single polymeric material into the mold cavity under high pressure. In cases where the products are expected to have contrasted functional features and different colors, the classic injection process and the conventional injection molds are not sufficient. This paper proposes a new design approach for multi-component injection molds required by products containing different polymeric materials or different colors of the same polymeric material at the same time. It also presents a case study including the design of the hot runner, electromechanical rotary-cross, cooling, and ejection systems of a two-component, eight-cavity toothbrush mold. The polymeric materials are polypropylene for the first component, and styrene based thermoplastic elastomer for the second component, which exhibit good bonding properties with each other. In addition, an analysis study covering the filling parameters and production defect generations is also provided. The adopted design approach provides a production rate of 1600 parts per hour, corresponding to 18 s cycle time and 200 cycles per hour, and makes it sufficient to rotate only the 80 kg core plate instead of 1120 kg entire core side. Compared to existing methods, the results show that the proposed multi-component injection mold design method eliminates the need for particular injection machines and robotic systems, shortens the cycle time, and reduces energy consumption.

Keywords: Multi-component mold, plastic injection, mold design, rotary-cross method, toothbrush mold

1. INTRODUCTION

Plastic injection molding is one of the most used plastic part production approaches. It provides many advantages such as the suitability for mass production of identical parts, automation compatibility, the desired dimensional accuracy, flexibility in product geometry, unnecessity for additional processing, ease of metal attachments adding to the mold before injection, and ease of recycling [1, 2]. It offers a suitable option for giving the permanent shape of thermoplastic shape memory polyurethane [3]. Despite its superior features, this method is insufficient when

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the final product requires the contrasted functional properties [4, 5]. Plastic parts often require a combination of rigid and flexible structures together. For example, a screwdriver handle should be both rigid enough not to deform under applied tightening torque and flexible enough not to hurt or slip out of the user's hand simultaneously. Such situations, where different properties are expected from the same product, require multi-component molds (MCMs).

In MCMs, different types of plastic materials or different colors of the same plastic material are injected into the same mold. It is applied in many areas including car front/rear lights, pediatric products, mobile phone covers, stationery products, hand tools, buttons, etc. Such molds offer extra significant advantages such as better mechanical properties, esthetic appearance, low light, and sound insulation. MCMs reduce costs and are environmentally friendly since they allow recycling plastics material to be used inside of the product. On the other hand, they are difficult and costly to manufacture and require special and expensive injection molding machines [6, 7].

There are six current approaches applied in MCMs. These methods are the inter-machines transfer, core-back, sandwich molding, in-mold automated transfer, rotary-table, and vertical-turn methods [8-10]. In the inter-machines transfer method, a separate mold and a separate injection machine are required for each component. The part injected in a mold working on an injection machine is manually transferred to the other mold working on another injection machine. Although a multi-component product can be produced with this method, it cannot be considered a multi-component mold application since it requires as many molds and injection machines as the number of components.

In the core-back method, the jig drawn back on the core plate generates a space in the cavity for the second component to be injected in the second stage. The number of extruders of the injection machine should be two in this method.

In the sandwich molding method (or co-injection), at first, the plastic material to form the surface portion of the product is injected, and then, the plastic material to form the inner part of the product is injected. The material of the inner portion pushes the surface portion just injected, thereby allowing the mold's walls to be wrapped by the first injected material. The number of extruders of the injection machine should also be two in this method. However, both materials are injected from the same pathway.

In the in-mold automated transfer method, the parts injected in the first cavity group are transferred to the second cavity group of the same mold by a robotic manipulator. This method requires complicated robotic manipulators that increase the investment cost and the cycle time.

In the rotary-table method, the core side of the mold is rotated 180° for two-component molds (or 120° for three-component molds) as a feature of the injection machine. The core side designs are the same for both components, while the cavity side designs vary according to the geometric profile of the product. The number of extruders of the machine should also be two in this method. Each component is injected into the mold cavity from separate pathways.

In the vertical turn method, it is necessary to design a middle plate with the cavity groups looking in both directions. The blank portions that remained in the first injection are filled in the second injection after the central plate is rotated 180° around the vertical axis.

All these methods mentioned above have some disadvantages. In the inter-machines transfer method, the product cost is very high, and the processing time is quite long since it requires as many molds and machines as the number of components. The core-back method can only be applied to the parts with simple geometry due to the limitations it has in terms of part geometry and component number. In the sandwich molding method, it cannot be seen from the outside that it is a multi-component part since the components are in the form of a shell and a core. In the in-mold automated transfer method, the robotic manipulator required for the transfer process increases both mold cost and cycle time. In the rotary-table method, the half or one-third rotation of the core side in each cycle is considered a feature provided by the injection machine. Therefore, this method cannot be applied to a conventional injection machine. Similarly, the vertical turn method also requires a particular injection machine. The middle plate, which needs to rotate half turn around the vertical axis, extends the mold opening distance and thus the cycle time.

This study proposes a new method, called the rotary-cross method, eliminating the disadvantages of the other six methods mentioned above [11]. The rotary-cross method can be compared to the rotary-table method among the methods mentioned above. The new idea of the rotary-cross method is that only a part of the core plate is rotated by a mechanism placed in the mold instead of the entire core side of the mold being rotated by the injection machine. Thus, the need for a particular and expensive injection machine is eliminated. In addition, the mass that must be rotated by half or one-third turn in each cycle is significantly reduced. This study presents a case study investigating the design process of a MCM equipped with the rotary-cross system. The selected sample product is a two-component, eight-cavity toothbrush (180°–2C–2x8). The design study covers the cavity and core portions of the mold and the calculations of the hot runner, rotary-cross, cooling, and ejecting systems. In addition, an analysis study, including the filling time, filling easiness, post-filling temperature, post-cooling temperature, sink mark generation, trapped air, and weld line investigations is also provided.

2. MATERIALS and METHOD

2.1. General Design Considerations

The number of cavities is 2x8. The total cycle time is 18 s, including 2 s injection time, 11 s holding and cooling time, and 5 s manipulating (opening, pushing forward, rotating, pulling backward, ejecting, closing) time. The design principles specified in the mold design handbooks [12-16], articles [17, 18], and thesis studies [19, 20] related to this research area are considered in the design of this two-component toothbrush mold.

Figure 1 The solid model and parting line of the molded two-component toothbrush

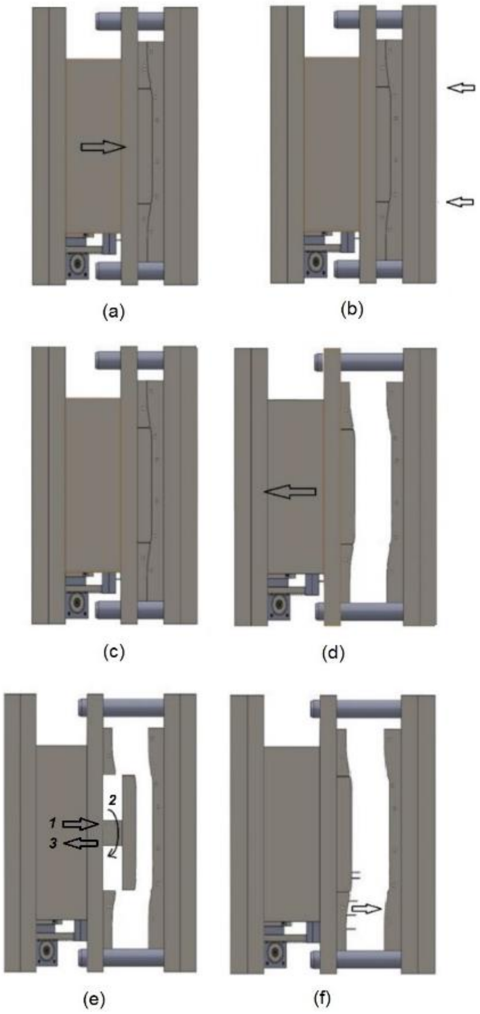


Figure 2 Stages of the cycle: a) The mold is closed and locked, b) PP and TPE polymers are injected, c) Waiting for holding and cooling, d) The mold is opened, e) The core plate is pushed forward, rotated, and pulled backward by the rotary-cross system, f) The entirely manufactured products are ejected

A mold design study starts with the part design. The solid model and parting line of the molded two-component toothbrush are shown in Figure 1. The molded toothbrush components' volumes, masses, and projection areas are obtained from the computer model as 8.1 cm^3, 7.3 g, and 10.4 cm^2 for the first component, 5.2 cm^3, 5.7 g, and 8.3 cm^2 for the second component, respectively.

In MCMs, the selection of polymeric materials is quite essential because the materials must bond with each other. We selected Polypropylene (PP) as the first component and styrene-based thermoplastic elastomer (TPE) as the second component. PP is the hard plastic material forming the toothbrush body, and TPE is the soft plastic material providing an aesthetic appearance and ease of holding to the toothbrush. Among the major categories, TPEs are the most widely used due to that they can combine well with many other materials, including fillers, extenders, modifiers, and other resins. The material properties of these polymers are given in Table 1.

Table 1 Material properties of the selected polymers [21, 22]

	First component Polypropylene (PP)	Second component Thermoplastic elastomer (TPE)
Density (g/cm^3)	0.9	1.1
Molding temperature (°C)	240	220
Specific heat (kJ/kg·K)	1.9	1.3
Thermal conductivity (W/m·K)	0.18	0.21
Thermal expansion coefficient (1/°C)	$1.46 \cdot 10^{-4}$	$2.35 \cdot 10^{-4}$
Young module (MPa)	1300	3
Yield strength (MPa)	33	-
Tensile strength (MPa)	41	15
Elongation at rupture (%)	100	500
Poisson ratio	0.4	-
Hardness (Shore)	66D	40A
Viscosity (Pa·s)	60	55
Shrinkage (%)	2	2

2.2. Structure of the Mold

A classical plastic injection mold consists of two main groups. One of them is the cavity group, which is the fixed side of the mold, and the other is the core group, which is the moving side of the mold. The process sequence in a classical mold is as follows: closing, clamping, injection, holding, cooling, opening, and ejecting. The MCM designed in this study has these classical sequential features, too. In addition to these, it also has some additional features. The stages of the cycle are shown in Figure 2. The process starts with the closing and clamping of the mold (Figure 2a). The polymers for the first and second components (PP and TPE) are injected into the mold (Figure 2b). After the holding and cooling process (Figure 2c), the mold is opened (Figure 2d). The core plate is pushed forward, is rotated 180°, and is pulled backward by the rotary-cross system, including two servomotors (Figure 2e). The eight entirely manufactured toothbrushes are ejected from the mold by the ejector system (Figure 2f). The mold is closed and locked again in the next cycle.

2.3. Hot Runner System

While the hot runner system is optional in conventional molds, it is strictly necessary for the MCM designed in this study. A hot runner system is a melt polymer feeding system that allows injection directly into the mold cavities without heat losses. It consists of manifolds, nozzles, heating resistances, thermocouples, and a control unit. There are many advantages provided by the hot runner system compared to conventional runner molds. It provides savings in energy, time, material, space, and labor. It makes it possible to produce better quality products [23- 26].

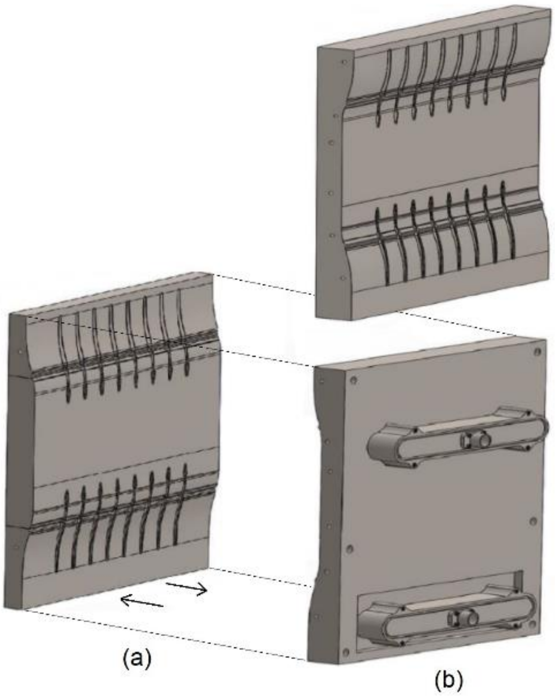


Figure 3 a) Front view of the core plate, b) Front and back views of the cavity plate and hot runner manifolds

The core and cavity plates and the hot runner manifolds at the backside of the cavity plate are shown in Figure 3. Two nozzle sets, each consisting of eight nozzles with diameters of 1.8 mm, and a gate length of 2 mm, are selected for both components. The pressure losses occurring in the gates are calculated by Equation (1) for the first and second components as follows:

$$\Delta p = \frac{8 \cdot \mu \cdot l_g \cdot V_p}{\pi \cdot r_g^4 \cdot t_{inj}} \quad (1)$$

Where Δp, μ, l_g, V_p, r_g, and t_{inj} are the pressure loss, melt viscosity, gate length, part volume, gate radius, and injection time, respectively.

By considering the average in-cavity cross-sections (A_c), which are 0.14 and 0.11 cm^2 for the components, the flow lengths are calculated by Equation (2) as follows:

$$L_f = \frac{t_p^2 \cdot p_{inj} \cdot t_{inj} \cdot A_c}{50 \cdot V_p \cdot \mu} \quad (2)$$

Where L_f, t_p, and p_{inj} are the in-cavity flow length, part thickness, and injection pressure, respectively. Calculated in-cavity flow lengths and pressure losses are within reasonable limits.

Two 16 kg mass-I type manifolds are selected for PP and TPE materials. The total heating power required to activate the manifolds of the hot runner system in 7 minutes with 65% efficiency in the first run are calculated by Equation (3) as follows:

$$P = \frac{m_m \cdot c_s \cdot \Delta T}{t \cdot \eta} \quad (3)$$

Where P, m_m, c_s, ΔT, t, and η are the heating power, the manifold mass, the specific heat of the manifold material, temperature difference, warm-up time, and heating efficiency, respectively. The appropriate flexible and cartridge resistances for manifold and spiral resistances for nozzles are selected to provide the calculated heating power.

2.4. Mold Set

The standard mold set is selected considering the part sizes and the cavity number. Accordingly, the main dimensions of the mold cross-section are 590x780 mm, the thickness of the cavity and core plates is 90 mm, and the distance between the parallel side blocks is 390 mm (see Figure 4). According to the projection areas of the components and 25 MPa injection pressure, the force to open the mold during injection is calculated by Equation (4), and the deflection occurring on the cavity plate during injection is calculated by Equation (5) as follows:

$$F_r = \sum_{i=1}^{2} \frac{A_{prj} \cdot n_c \cdot (p_{inj} - \Delta p)}{10^3} \quad (4)$$

$$l_{def} = \frac{5 \cdot L_{def}^4 \cdot Q_{dst}}{384 \cdot E_s \cdot I_b} \quad (5)$$

where F_r, A_{prj}, p_{inj}, n_c, l_{def}, L_{def}, Q_{dst}, E_s, and I_b are the force to open the mold during injection, projection area, injection pressure, cavity number, deflection occurring on the cavity plate during injection, deflection length (i.e., the distance between the parallel side blocks), distributed load on the cavity plate, elasticity module of the mold steel, and bending moment of inertia of the cavity plate, respectively. The calculated deflection value is safe because it is lower than the flash gap of the polymeric materials.

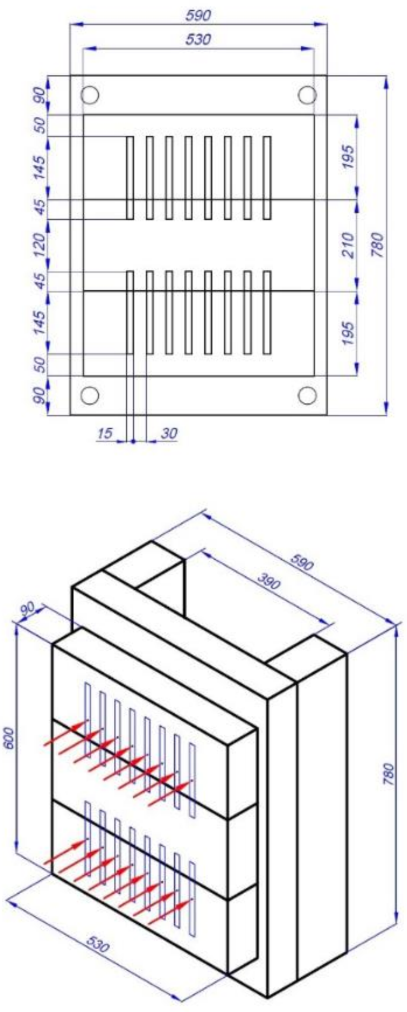


Figure 4 Dimensions of the selected mold set

2.5. Rotary-Cross System

The working principle of the rotary-cross system designed in this study is shown in Figure 5.

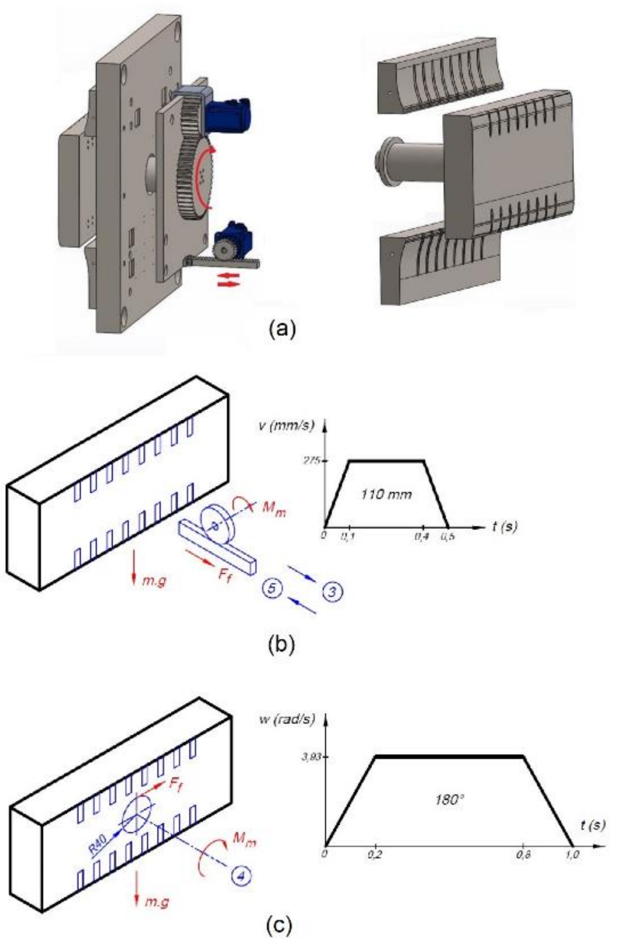


Figure 5 a) Schematic of the rotary-cross system, b) Pushing forward and pulling back, c) Rotating

The main feature of this system is that a portion of the core plate is pushed forward when the mold is opened, then it is rotated 180°, consecutively in reverse each time, and then it is pulled back to the neutral position. Total manipulating time is considered 5 s (including 1 s for opening, 0.5 s for pushing forward, 1 s for rotating, 0.5 s for pulling backward, 1 s for ejecting, and 1 s for closing). There are two stepper motors in the system for translational and rotational movements. The first stepper motor torque output required to activate the translational motion is calculated by Equation (6) as follows:

$$M_{m1} = \frac{m\cdot R_p\cdot(g\cdot\mu+a)\cdot s}{\eta} \tag{6}$$

where M_m, m, R_p, g, μ, a, s, and η are the stepper motor torque output, totally shifted mass, the radius of the pinion gear, gravitational acceleration, sliding frictional coefficient, translational acceleration, safety coefficient, and mechanical efficiency, respectively.

The second stepper motor torque output required to activate the rotational movement of the rotary-cross system is calculated by Equation (7) as follows:

$$M_{m2} = \frac{(m \cdot f \cdot g \cdot R_f + J \cdot \alpha) \cdot s}{i_r \cdot \eta} \tag{7}$$

Where f, R_f, w, h, α, and i_r are the rolling frictional coefficient, frictional radius, width and height dimensions of the rotating core plate, angular acceleration, and gear reduction ratio, respectively.

2.6. Cooling System

An effective cooling system is essential to keep the cycle time within an appropriate range. It is also strictly necessary to maintain the process correctly, to prevent the occurrence of product defects, and to keep the mold temperature constant at a specific value by transferring the heat load of the injected polymeric material [27, 28]. Water circulation in circular cross-section channels processed in the cavity and core plates is adopted in cooling system design. Considering the melt temperatures of the first and second components (240 and 220 °C) and the exit temperature of the molded part (50 °C), the total heat load to be transferred from the mold is calculated by Equation (8) as follows:

$$Q_h = \left[(m \cdot c \cdot \Delta T)_{pp} + (m \cdot c \cdot \Delta T)_{tpe}\right] \cdot n_c \cdot n_{cc} \tag{8}$$

Where Q_h is the heat load that needs to be transferred from the mold; m, c, and ΔT are the mass, specific heat, and temperature difference of each component; n_c and n_{cc} are the number of the cavity and the number of the cycle per hour, respectively.

Based on the heat load to be transferred from the mold, the diameter of the circular cross section-cooling channels, needed cooling water flow rate, the length of the cooling channel network, and cooling time are calculated by Equations (9 – 12) [19], and the turbulent flow regime in the cooling network is checked by Equations (13) as follows:

$$\frac{Q_h}{3600} = \frac{\pi \cdot {d_c}^2}{4} \cdot \vartheta_w \cdot c_w \cdot d_w \cdot (T_{out} - T_{in}) \tag{9}$$

$$Q_w = \frac{\pi}{4} \cdot {d_c}^2 \cdot \vartheta_w \tag{10}$$

$$L_c = \frac{Q_h \cdot d_c}{3.53 \cdot Q_w \cdot (1 + 0.015.T_w) \cdot (T_m - T_w)} \tag{11}$$

$$t_c = \frac{{t_p}^2 \cdot d \cdot c}{\pi^2 \cdot k} \cdot ln\left(\frac{4}{\pi} \cdot \frac{T_{mlt} - T_m}{T_{pe} - T_m}\right) \tag{12}$$

$$R_e = \frac{d_c \cdot \vartheta_w}{\nu_w} \tag{13}$$

Where υ_w, c_w, d_w, Q_w and ν_w are the velocity, specific heat, density, flow rate, and kinematic viscosity of the cooling water; T_{in}, T_{out}, and T_w are the inlet, exit, and medium temperatures (15, 25 and 20 °C) of the cooling water; d_c and L_c are the diameter of the circular cross-sectional cooling channel, and the total length of the channel network; T_m, T_{mlt} and T_{pe} are the mold, melt, and product exit temperatures; t_c, t_p and k are the cooling time, product thickness, and thermal conductivity, respectively. The results show that the cooling channel network with 10.5 mm diameter and 2.19 m length is required. The cooling water flow rate is 2.6 lt/min at 15 °C inlet temperature. The cooling times are calculated as 30.6 and 10.7 s for the first and second components. The design of the cooling system is completed by circulating the channel network in the appropriate zones.

2.7. Ejecting system

To eject the fully manufactured toothbrushes from the mold when the mold is opened, it is necessary to equip the mold with an ejector system. The usage of pin type ejector system is adopted. The lengths of the ejector pins are varied due to the geometry of the cavity. The ejector pins are subjected to compression stress and buckling under the influence of 25 MPa injection pressure. Five ejector pins with a diameter of 3 mm were used for each cavity. The general structure of the ejector system is shown in Figure 6.

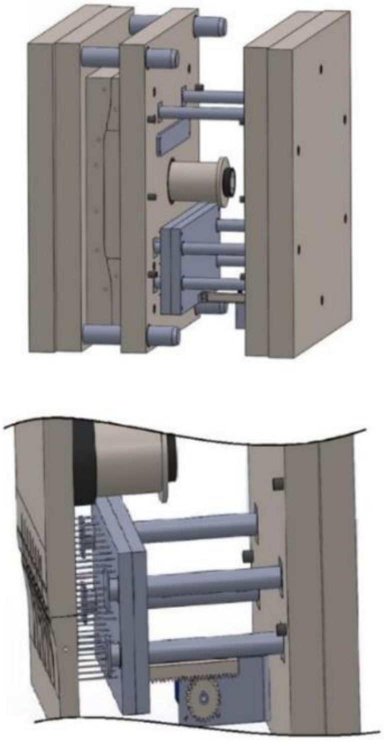
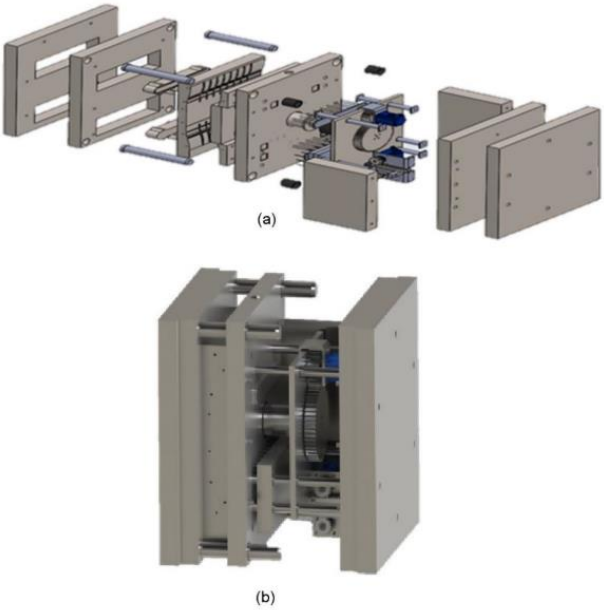


Figure 6 Plates and the rock-pinyon mechanism of the ejector system

2.8. Mold Assembly

There are many standard elements such as centering columns, bushings, lifting lugs, cooling water connection fittings, pins, and bolts that should be used in formwork assembly. The assembly of the mold has been completed after selecting these standard complementary elements. The exploded view of the mold components and the assembled mold are shown in Figure 7.



(a)

(b)

Figure 7 Exploded (a) and assembled (b) views of the mold

3. RESULTS and DISCUSSION

3.1. Design

The MCM design parameters obtained in the design study are listed in Table 2. When these results are examined, it is seen that a production rate of 1600 parts per hour, corresponding to 18 s cycle time and 200 cycles per hour, is achieved. The total mass of the mold is 1840 kg, of which the core side is 1120 kg, and the cavity side is 720 kg. The rotary-cross method proposed in this study provides improvements in product cost and cycle time when compared to the other five methods, except for the rotary-table method. The rotary-cross method also provides some advantages when compared to the rotary-table method, which is the closest alternative. First, it eliminates the need for a special injection machine. In addition, it makes that rotating only the 80 kg core plate is sufficient, instead of 1120 kg core side entirely. These improvements provide the side benefits of the more straightforward design, smaller stepper motors, and reduction in energy consumption.

Table 2 Summary of the design parameters

Design parameter	First Component Polypropylene (PP)	Second Component Thermoplastic elastomer (TPE)
Cavity number	8	8
Volume (cm^3)	8.1	5.2
Mass (g)	7.3	5.7
Projection area (cm^2)	10.4	8.3
Average cross section (cm^2)	0.14	0.11
Average thickness (mm)	3.5	2.5
Nozzle diameter (mm)	1.8	1.8
Gate length (mm)	2	2
Flow length (cm)	32.6	23
Injection time (s)	2	2
Injection pressure (MPa)	25	25
Pressure loss (MPa)	1.9	1.1
Manifold mass (kg)	16	16
Manifold heating power (kW)	6.2	5.6
Cooling time (s)	30.6	10.7
Mold cross-section (mm)	590x780	
The thickness of the plates (mm)	90	
Distance between parallels (mm)	390	
Force to open the mold (kN)	351	
Distributed load (N/mm)	595	
Deflection of the core plate (μm)	18	
Mass of the core plate (kg)	80.14	
Inertia of the core plate ($kg \cdot m^2$)	2.17	
Linear acceleration (m/s^2)	2.75	
Angular acceleration (rad/s^2)	19.6	
Mass of the mold (kg)	1840	
Cycle time (s)	18	
Stepper motor torques ($N \cdot m$)	11.5; 32	
Heat load (kCal/h)	1490	
Cooling water velocity (m/s)	0.5	
Reynolds number	6105	
Inlet/exit temperatures (°C)	15/25	
Flow rate (m^3/h)	0.156	
Cooling channel diameter (mm)	10.5	
Length of the cooling channel (m)	2.19	

Both values of in-cavity flow lengths are longer than the product length. This result shows that there is no difficulty in filling the cavities, and a single gate is sufficient for each cavity. The 10.7 s cooling time of the second component is appropriate since it is already shorter than the applied cooling time (11 s). On the other hand, the 30.6 s cooling time of the first component does not seem appropriate because it is far longer than the selected cooling time. At this point, it is necessary to remember an essential feature of MCMs. While the second component is ejected from the mold at the end of the cycle in which it is injected, the first component remains in the mold for two consecutive cycles. As a result, it can be said that both calculated cooling times are provided within the appropriate limit. A turbulent flow regime desired in injection molds is also provided. In this case, study focusing on the MCM design, the ratio of the entire core side mass to the rotating portion of the core plate mass is 14. This ratio indicates a significant gain in energy requirement.

3.2. Analysis

Computer-aided analysis studies assist designers in all areas of engineering by showing problems before they arise. Therefore, it has a wide range of applications in mold making as well as in all other areas. It provides foresight about the parameters such as filling time, filling temperature, injection and holding pressures, temperature after cooling, and production defect generations such as the air bubbles, sink marks, and weld lines. This foresight makes it possible to optimize the mold design before starting mold manufacturing [29- 32].

A number of production defects occur due to material properties, mold design, and machine process parameters. The most important of these defects are short shot, burrs, warpage caused by uneven shrinkage, jetting, hot ejected part caused by insufficient cooling, sink marks, sear caused by trapped air, and weld line. Accordingly, the analyses of the filling time, filling easiness, temperatures at the end of the filling and cooling, generations of the sink mark, trapped air, and weld line are performed. The results obtained in this analysis study run in SolidWorks software are given in Figures 8-14.

The filling time analysis given in Figure 8 shows that no difficulties are encountered in filing the mold cavities. The color distribution is from blue to red in this analysis. The red zone represents the region where the polymer flow has last arrived. It is seen from the analysis study that the filling time of both components is realized as 2 s in the framework of the selected hot runner system elements and working parameters.

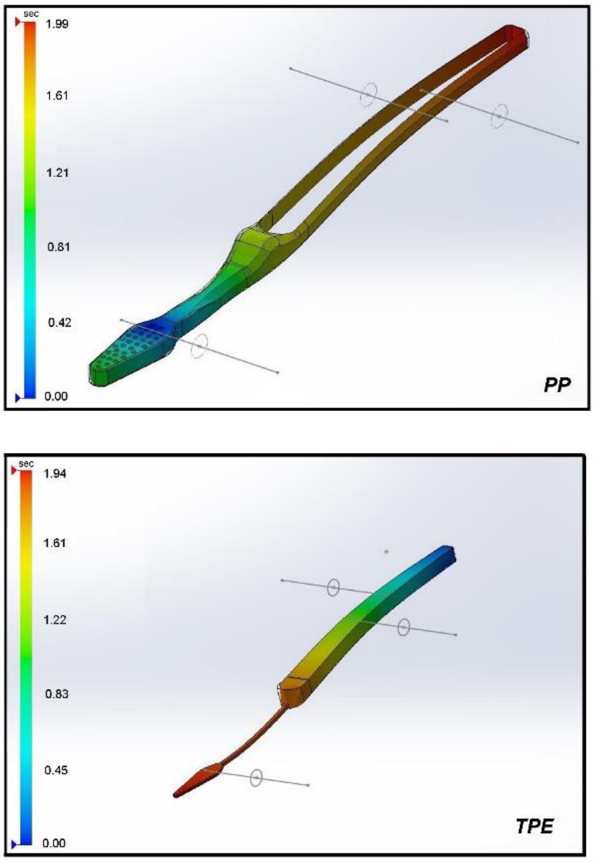


Figure 8 Filling time analysis

The short shot is the inability to fill the mold cavity completely; the burr is the polymeric material overflowing from the parting line due to the excessive injected material quantity or high injection pressure, and the jetting is the trace resulting from the entry of the material into the mold cavity by snaking with high injection speed. The green color in the filling easiness analysis given in Figure 9 indicates that no difficulties are encountered in filling the cavities in terms of the number and position of the gate, injection velocity, and the part geometry. No short shot, burr, or jetting were observed in this analysis.

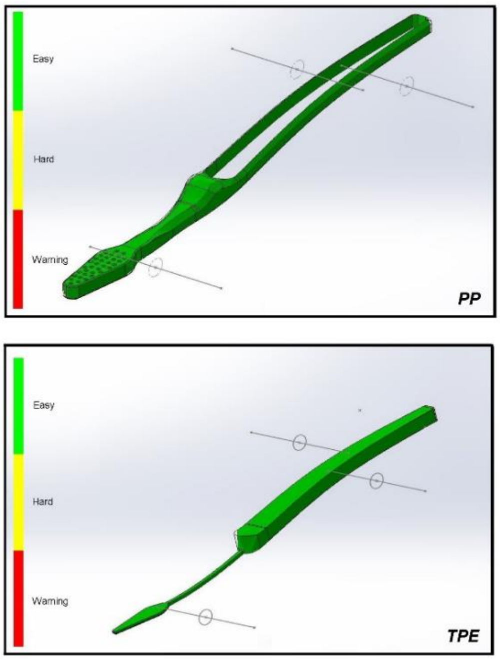


Figure 9 Filling easiness analysis

In the end-of-filling temperature analysis, as expected, the temperature appeared as 240 °C for PP, and 220 °C for TPE, in proximity to the gate and in fleshy regions (Figure 10). In the end-of-cooling temperature analysis, it is seen that the temperature values are reduced to 50 °C, which is the expected temperature for the ejected part, but the cooling is not enough near the gate location. This result suggests that the cooling system should be revised or the cooling period should be extended (Figure 11)

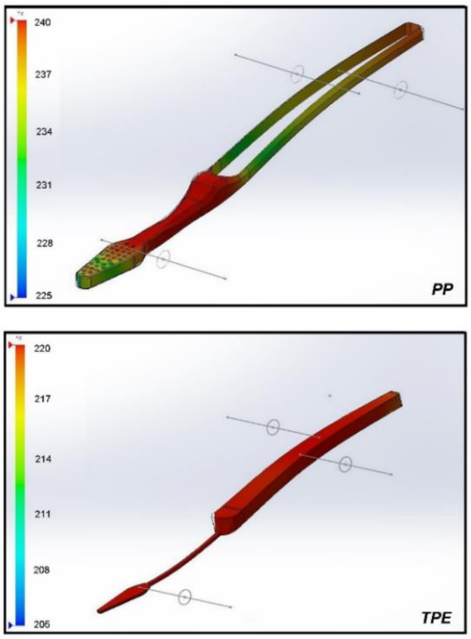


Figure 10 End-of-filling temperature analysis

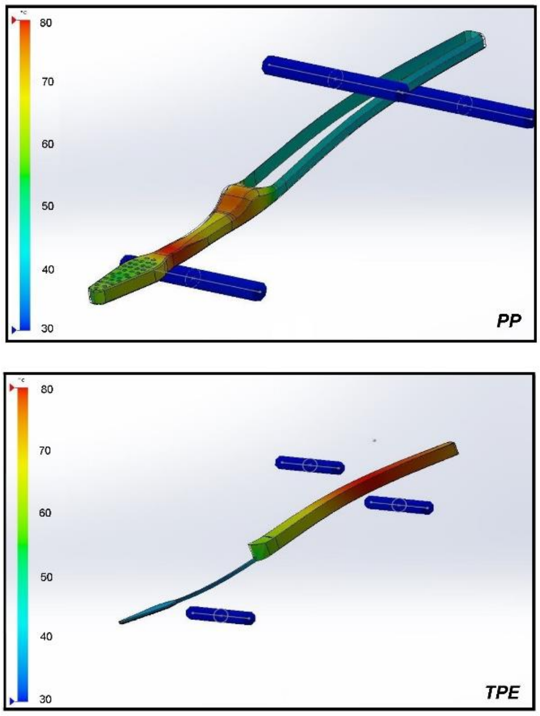


Figure 11 End-of-cooling temperature analysis

A sink mark is a defect caused by excessive shrinkage in the areas of material condensation due to part design. Other reasons are inadequacy of holding pressure and time, injected material quantity, and gate cross-section. The sink mark values encountered in the analysis given in Figure 12 are 0.031 mm for PP and 0.044 mm for TPE. These values are within reasonable limits.

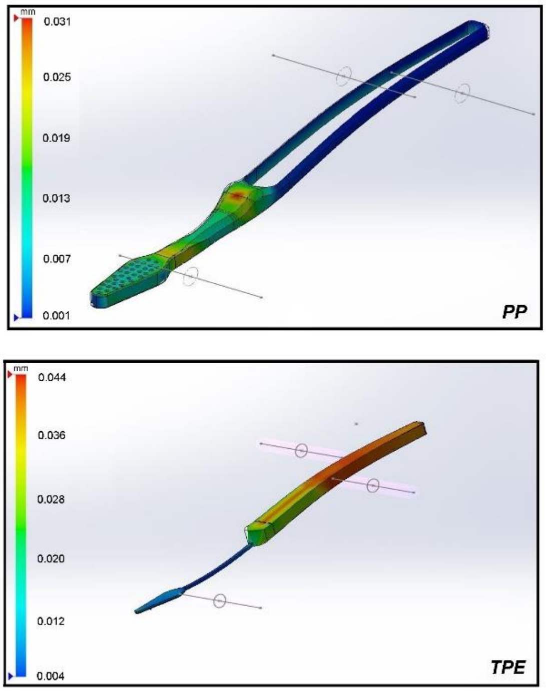


Figure 12 Sink marks analysis

Burn mark or sear is described as a blackening or yellowing of a part of the part. The most important reason for this is that the air cannot evacuate the mold cavity during the injection and is trapped in a region. When the air in the mold cavity is not fully evacuated from the mold to the outside during injection, due to the high injection speed and the inadequacy of the air channels, it causes a burn mark at the regions where the air is trapped. From the analysis, it is seen that air is trapped at the points specified on the Figure 13. It is necessary to open the air duct from these points for air release. The dimension of these air ducts should be smaller than the flash gap limit of the polymeric materials.

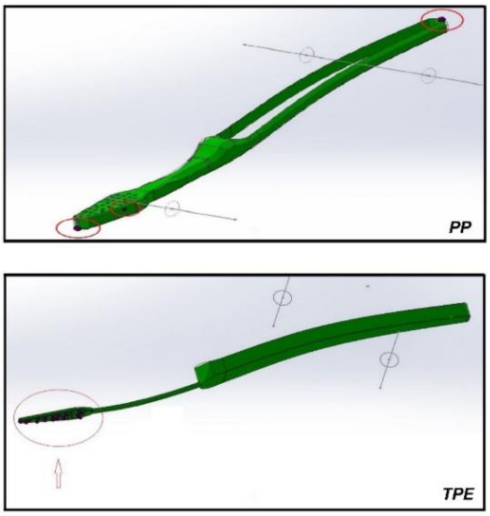


Figure 13 Trapped air analysis

Weld line is a flow trace formed where the polymeric material from the multi-gate or multi-flow line joins and fuses. In addition to being a visually disturbing trace, it also causes the weak cross-section of the part that can easily break even at low loads. In the weld line analysis given in Figure 14, it is seen that there is a weld line in the region specified for the first component, and there is no weld line for the second component.

The analysis results show that the approaches adopted in the multi-component mold design are appropriate and compatible with the literature. For the composite products produced by the multi-component injection method, it is necessary to provide the interface compatibility between the components regarding shrinkage and stiffness. In this respect, the selection of the component materials crucially influences the properties of the composites. In addition, the adjustment of the ratio between the component volumes must also be carefully adjusted. Moreover, the position of the sprue and the design of the molded parts are more important than the processing parameters. The uniformity of the layer thicknesses is primarily determined by the viscosity of the components. To prevent flow instabilities, the ratio of the viscosities of the core to the skin material should be around one. Otherwise, poor filling behavior, varying wall thickness distribution, and ruptures can be encountered.

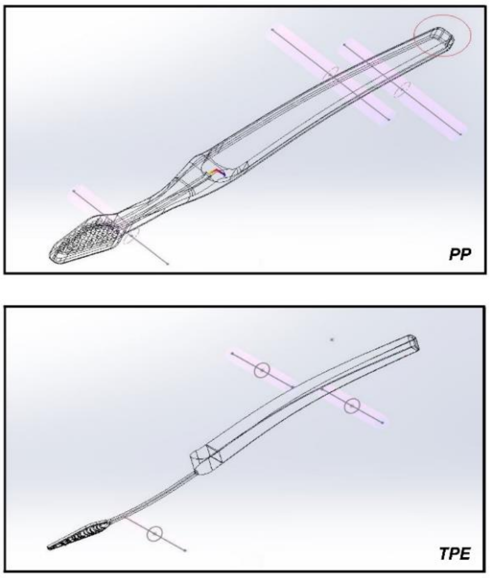


Figure 14 Weld line analysis

4. CONCLUSION

Although MCMs have many superior features compared to conventional injection molds, their applications are limited due to their more expensive and challenging design and production procedures. This study aims to contribute to facilitating the design of such molds. To achieve this goal, the rotary-cross method eliminating the disadvantages of the current methods is proposed. The idea of the proposed method is that only a part of the core plate is rotated by a mechanism placed in the mold instead of the entire core side of the mold being rotated by the injection machine. This idea eliminates the need for a particular and expensive plastic injection machine. A mold using this method can also be worked on a conventional injection molding machine. These improvements provide the side benefits of the more straightforward design, smaller stepper motors, and reduction in energy consumption.

It is also aimed to contribute to the awareness and widespread of such molds. For this aim to be fulfilled, this study presents a case study investigating the design process of a MCM equipped with the rotary-cross system. The selected sample product is a two-component, 8-cavity toothbrush (180°–2C–2x8). The case study covers the design of the cavity and core portions of the mold and the calculations of the hot runner, rotary-cross, cooling, and ejecting systems. In addition, the analysis study including the filling time, filling easiness, post-filling temperature, post-cooling temperature, sink mark generation, trapped air, and weld line investigations is also provided.

According to obtained results, the filling time was 2 s for both components. No difficulties are encountered in filling the cavities in terms of the number and position of the gates. No short shot, burr, or jetting were observed. The end-of-filling and end-of-cooling temperatures were appeared as expected. The inadequacy of cooling near the gate location shows that more meticulous work should be done on the cooling system in MCMs. The sink marks were within reasonable limits. No weld lines and air traps were found at a level that could be considered a problem. These results show that the MCM design approach adopted in the study is appropriate.

APPENDIX

Symbols		Subscripts	
A, a	Area (m^2), Linear acceleration (m/s^2)	b	Bending
c	Specific heat (kJ/kg·K)	c	Cycle, Cooling, Cavity, Core plate
d	Diameter (mm), Density (g/cm^3)	def	Deflection
E	Modulus of elasticity (MPa)	dst	Distributed
f	Rolling frictional coefficient	f	Frictional, Flow
g	Gravitational acceleration (m/s^2)	g	Gate
h, w	Dimensions of the rotating core plate (mm)	h	Heat
I	Moment of inertia (m^4)	inj	injection
i	Gear reduction ratio	m	Mold, Manifold, Motor
J	Mass moment of inertia ($kg \cdot m^2$)	mlt	Melt
k	Thermal conductivity (W/m·°C)	p	Product, pinion gear
L, l	Length (m)	pe	Product exit
M, m	Torque (N·m), Mass (kg)	prj	Projection
n	Number	pp	Polypropylene (1st component)
P, p	Power (kW), Pressure (Pa)	tpe	Thermoplastic elastomer (2nd component)
Q	Heat load (kCal/h), Flow rate (m^3/s)	s	Steel
R, r	Radius	w	Water
t	Time (s), Thickness (m)		
T	Temperature (°C)		
V	Volume (m^3), Velocity (m/s)		
η	Efficiency		
α	Angular acceleration ($1/s^2$)		
μ	Frictional coefficient, Viscosity (Pa·s)		

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Authors' Contribution

The first author contributed 50%, the second author 25%, and the second author 25%.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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