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Development and Testing of a Metallic Mould for the Production of Thermoplastic Products

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ABSTRACT

A meaningful diversification of economy is only achieved through proper development of available technology. The plastic industry in Nigeria depends on importation for both machines and moulds. Design, fabrication and testing of a metallic mould, for production of thermoplastic products, was carried out in this work. Adequate development of metallic mould for the plastic industry will save the country foreign exchange spent on importation of moulds. Detailed principles that guide plastic mould design were followed and available technology and materials were used in fabrication of the metallic mould. The quality of products was characterized in term of dimensional accuracy. The results indicated a dimensional accuracy of 94.12% for the compressive test pieces, 89.3 % for tensile test pieces and 87.3% for flexural test pieces.

Key words: Thermoplastic, mould, design, shrinkage, machining.

Aims Research Journal Reference Format:
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1. INTRODUCTION

Nigeria has remained a mono economy. Successive governments in recent past have indicated the need to move away from overdependence on petroleum. The recent fall in the price of crude oil in international market makes the need for diversification more urgent. It is equally important that Nigeria needs to move away from being a consuming nation to a production based nation. There are sizeable numbers of small and medium scale plastic industries that use both imported/locally made petrochemical products. However the moulds for both simple and complex products are imported despite the fact that the technology for production of moulds is available. The main objective of this work is to design, fabricate and test a metallic mould for the production of thermoplastic test pieces.

The principles that guide the design and production of moulds for thermoplastic products have been studied by different researchers over the years. Rosato et al. (2000) submitted that a mould designer has to take decisions on (a) the number of cavities in the mould, (b) the parting line of the piece, (c) the type and location of gate, (d) the runner system, (e) sprue, (f) the ejection system, (g) the temperature control system and (h) the venting system. The quality of each of these decisions determines the performance of the mould (Rubin, 1979; Tecklehaimanot, 2011). The major factors that determine the number of cavities in the mould are, (a) the capacity of the injection moulding machine, (b) the size of the product and the clamp rating of the machine. The capacity of the machine refers to the volume of the plastic melt that can be injected per shot. The choice of number of cavities must ensure that the volume of plastic injected is enough to fill all the cavities, runners, gates and sprue. This volume depends on the size of the product. The size of the mould must be tailored to fit the clamp space of the machine (Goff, 2012).

Moreover the clamp pressure that keeps the mould closed during injection and cooling is opposed by the packing pressure which tends to open the mould. To keep the mould closed the clamping force of the machine must be greater than parking pressure (Goff, 2012; Greene, 2015; Anonymous, 2014). It is difficult to accurately maintain a dimension that crosses the parting line. Thus the critical dimensions that are to be kept within close tolerance must not be allowed to cross the parting line [Rubin, 1979]. The parting line that gives the smallest projected area is desirable since it yields the lowest clamping force.

The gate is the orifice through which the plastic melt from the runner flow into the cavity. It must allow enough material into the mould cavity before freezing (Greene, 2015). In multi cavity moulds, the gates must be balanced so that all the cavities fill at the same time. There are various systems of gate location in practice -sprue gate, edge gate, back gate, submarine gate, tab gate, fan gate [Teklehaimanot, 2011]. Edge gating is most common with multi cavity moulds. The dimensions of the gate can he obtained by applying the principles for flow through orifice. The flow rate is given by;

$$Q = K \frac{\Delta P}{\mu} \qquad (1)$$

where Q = the volume flow rate (m^3/s), ΔP = pressure drop (Pa), μ = viscosity of the fluid ($N.s.m^{-2}$) and K= a geometrical constant. For circular gates, the geometrical constant is

$$K = \pi \frac{R^4}{8L} \qquad (2)$$

where R = radius of gate (orifice) and L= length of gate.

For a slit gate, the geometrical constant is

$$K = \frac{wh^3}{12L} \qquad (3)$$

where h = thickness of gate and w = width of gate.

Equations (1) to (3) are obeyed by Newtonian fluids. They are used for initial design before corrections are made after testing.

The runner is the connection between the sprue and the gate. The full round runner is preferable because it has the smallest surface to volume ratio. Rosato et al., (2000) indicated that the runner should be located in the parting line. Cold slug wells or run-offs are often incorporated into the runner design. The run-off allows cooler material to be retained at the end of the runner while incoming hot material passes into the cavity. It is better to start with small runners as it is much easier to increase the size than to reduce it [Rubin, 1979].

The sprue takes the melt from the nozzle to the runner. The use of sprue is compulsory in multi cavity moulds. Round sprue is preferred [Rubin, 1979; Teklehaimanot, 2011]. The core of a round Sprue remains hot for a longer time compared to other sections. It is a common practice to make the orifice diameter of the sprue slightly bigger than that of the nozzle. Nkpubre (1988) indicated a sprue to nozzle orifice ratio of 9:5. Ejection of parts is done with knock out pins, knock out sleeves, stripper rings or stripper plates. The geometry of the part and the type of material are the major factors in selecting a knock-out mechanism. Most parts eject easily with a one degree (1^o) per side taper (GE Plastics, 2015; Eastman Polymer, 2015). Polishing should be in the direction of ejection. When knock out pins are used, the cross-sectional area of the pin or ring must be large enough, so it does not pierce into the piece.

The pressure built up by trapped air could prevent proper moulding (Anonymous, 2014). A typical vent may be 0.025 mm deep and 25.4 mm wide. Rubin, (1979) suggested that brass shim washers should be put over each lead pin so that the mould remains open approximately 0.13 mm in order to confirm if inadequate venting is cause of improper filling. The cause of the mould filling problem is not venting if this measure does not cure it.

The design of cavity dimensions must take the fact of shrinkage into consideration. Levy and Duboise, (1984) suggested Equation (4) for the dimensions of cavities at the initial design stage,

$$D_c = D_p + D_pS + D_pS^2 \qquad (4)$$

where D_c = dimension of cavity, D_p = dimension of moulded part and S = shrinkage (mm/mm).
The mould must be constructed so that changing dimension to correct for shrinkage can be done by removing metal from the cavity.

2. MATERIALS AND METHODS

2.1 Materials

High density Polyethylene of grade DOW.HDPE25055N was used for testing the mould. The cavity plate and the cover plate were machined from mild steel plates. The bushings and plug pins were made with mild steel rods.
The equipment used included, floor mounted milling machine, pillar drilling machine and power saw.

2.2 Design Analysis and Calculations

There are standard geometrical forms and sizes for the test pieces needed. The American Society for Testing and Materials (ASTM) standard D638-02a of 2003 was used.

2.2.1 Tensile Test Piece

The ASTM D638-02a specifies that the thickness of flat specimens should be from 1 mm to 14 mm and a minimum length of 36.75 mm. The specimen is a bar 2 mm thick, 20 mm wide and 136 mm long. It is reduced to 12 mm width for 50 mm of its length (Figure 1).

2.2.2 Compression Test Piece

ASTM D695-63T is applied in the design. This standard recommends that the principal width of the specimen must not be less than half the length of it in order to prevent buckling failure. The specimen is a bar 10 mm thick, 12 mm wide and 20 mm long.

2.2.3 Flexural Test piece.

ASTM D79O-67T is applied in the design. The specimen is a bar 12 mm wide, 3 mm thick and 120 mm long.

2.2.4 Design of cavities

The dimensions of the cavities must account for shrinkage. The shrinkage range for po1yethlene (both low and high density polyethylene) is given as 0.02 to 0.05 mm/mm (Levy and Duboise, 1984). A shrinkage value of 0.02 mm/mm is used for first design.

Substituting $D_p = 0.02$ into Equation 4, the 2mm thickness dimension of the tensile test piece becomes,

$$D_{c1} = 2 + 2(0.02) + 2\,(0.02)^2 \quad = 2.041 \text{ mm}$$

The variation in dimension can be obtained by finding the difference between the maximum and minimum dimensions. Substituting S = 0.05 yield,

$$D_{C2} = 2 + 2\,(0.05) + 2\,(0.05)^2$$
$$= 2.105 = 2.11 \text{ mm.}$$

Thus size variation = 0.064 mm.

The tolerance is less than or equal to 0.064 mm. The expected thickness of the piece is 2 ± 0.064 mm. All the dimensions on tensile test piece cavities were obtained in the same way and presented in Table 1.

Table 1: Dimensions of Tensile Test Piece Cavity

Piece Dim (D_p)	Cavity (D_{c1})	Cavity (D_{c2})	Tolerance
2mm	2.041mm	2.105mm	± 0.064
50mm	51.02mm	52.625mm	± 1.6
12mm	12.2448mm	12.63mm	± 0.39
20mm	20.41mm	21.05mm	± 0.64

A similar application of Equation 4 to the dimensions of the compression and flexural test pieces produced the dimensions of the cavities presented in Table 2 and Table 3 respectively.

Table 2: Dimensions of Compression Test Piece Cavity

Dimension Test piece D_P	**Cavity Dim D_{c1}**	**D_{c2}**	**Tolerance**
20 mm	20.41 mm	21.05 mm	± 0.64
10 mm	10.2 mm	10.525 mm	±0.32
12 mm	12.25 mm	12.63 mm	±0.38

Table 3: Dimensions of Flexural Test Piece Cavity

Dimension Test piece D_P	**Cavity Dimension D_{c1}(mm)**	**D_{c2}(mm)**	**Tolerance**
120mm	122.45	126.3	± 3.85
12mm	12.25	12.63	± 0.38
3mm	3.061	3.1575	± 0.096

2.2.5 Parting Line Design

This work deals with production of a small quantity of test pieces, hence a knock-out system is not necessary. A parting line that keeps the products in one side of the mould was used.

2.2.6 The Runner Design

A slit runner was chosen due to ease of manufacture when compared to round runner. Another good alternative is removable round runner. It has to be in two halves, which may be difficult to make for small test pieces.

Employing equation (1) and (3)

$$Q = K\frac{\Delta P}{\mu} = \frac{wh^3 \Delta P}{12\mu L} \tag{7}$$

The flow rate Q is in volume per time. Let an injection time of 10seconds be used.

The volume of melt delivered to the tensile cavity, V_1 is essentially equal to the volume of the test piece.

Thus;

V_1 = 2x50x12 + 2(2x20x43) = 4.64x10^{-6} m^3

Thus the flow rate into the tensile cavity is;

Q_1 = $\frac{4.64x10^{-6}}{10} = 0.464x10^{-6}$ m^3/s

Let one gate deliver material to both the compression test piece cavity and flexural test piece cavity in order to enhance simplicity (Figure 2). Thus the combined volume of melt for the two test pieces is 6.792x10^{-6} m^3. The cavities must fill at the same time. Thus the flow rate into the second cavity is;

Q_2 = $\frac{6.792x10^{-6}}{10} = 0.6792x10^{-6}$ m^3/s

The design of the runner could be approached in two ways. The dimensions could be selected and the pressure drop calculated.

On the other hand the allowed pressure could be decided on and the dimensions calculated. The quality of the result depends on the experience of the designer rather than the approach. The pressure drop must be kept at possible minimum. Minimum pressure drop implies maximum runner size which may increase waste.

The second approach is used for preliminary design and the first approach used to correct the design. It is important to keep the length at a practicable minimum. Let the lengths of the runners be in the reverse ratio of their flow rate. Let the length L_2 of runner to the flexural/compression cavity be 8 mm.
Therefore, L_1 = 8 x 1.5 = 12mm.

Tadmor, (1979) gave the viscosity of high density polyethylene at zero shear rate as,

1.17x10^3 N.s/m^2

Let the pressure drop be limited to 4MPa and h = 0.5w. Thus for Q_1;

Q_1= 0.464x10^{-6} m^3/s = $\frac{w_1(0.5w_1)^3 x4x10^6}{10^{-3}x12x1.17x10^3 x12}$

Solving yields, w_1 = 3.54 mm and h_1= 1.77 mm.

Similar considerations yields, w_2= 3.515 mm and h_2 = 1.757 mm.

The difference is small and considered negligible. Therefore w = 3.5 mm and h = 1.8 mm for ease of manufacture.

2.2.7 The Sprue Design

The injection nozzle of the moulding machine is 3.5 mm. According to Levy and Duboise, (1984) the runner should be 1.8x nozzle diameter. That is 6.3 mm. A standard orifice of 6 mm diameter was chosen as initial design. The length of the sprue was chosen on the basis of geometrical considerations since it must extend to the centre of the runner. The length of the longer cavity is 144.9 mm. Let the cavity be located 20 mm from the edge of mould plate (Figure 1). Adding 20 mm to half the length of the longer cavity and accounting for the size of constricted gate the length of the sprue was found to be 94.2 mm.
A runoff of 3mm was added to accept and retain the first surge material. Applying the law of continuity the flow into the two cavities was found to be 1.1432×10^{-6} m^3/s.

Substitution into equation (1) resulted in a pressure drop of 3.96MPa in the sprue.

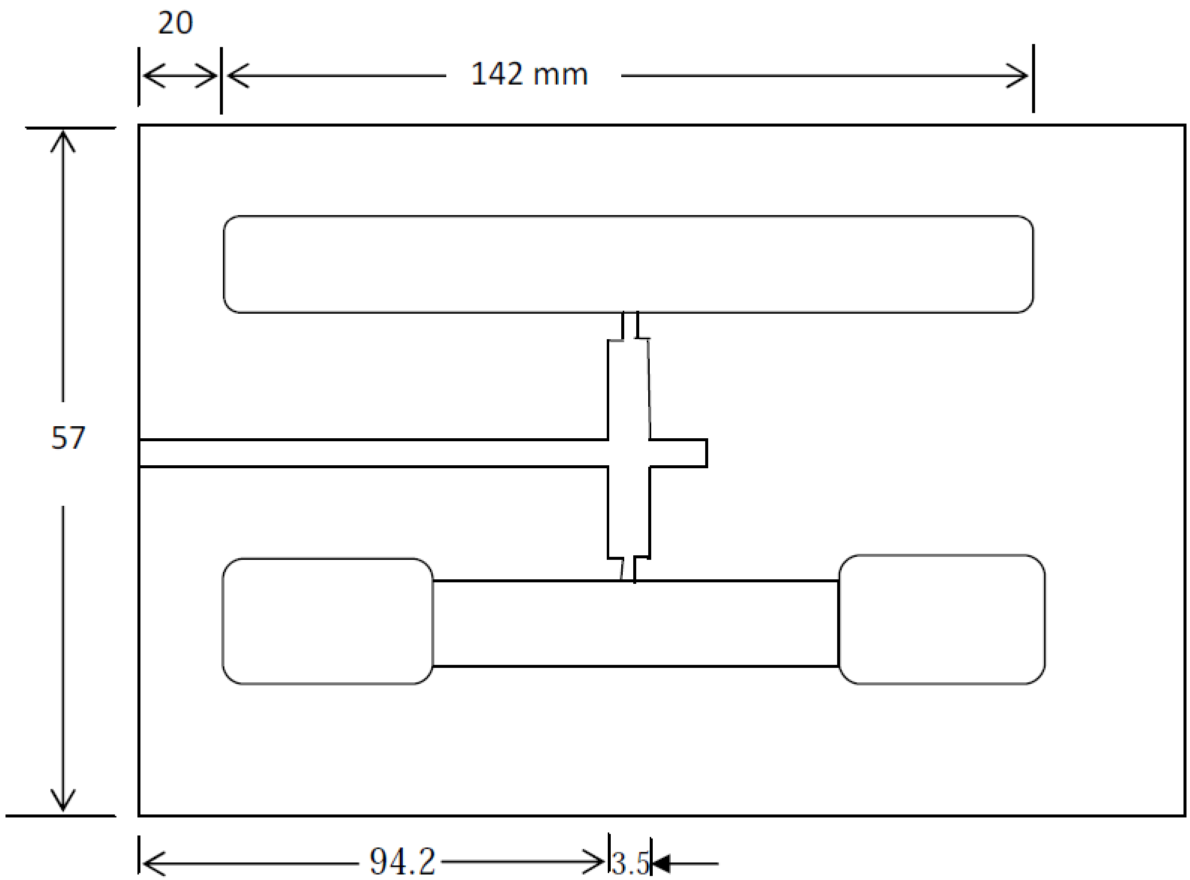

Figure 1: The Pattern of the Plastic Mould

2.2.8 Design of Gates

Each of the gates is designed to meet the flow rate requirements. The flow rates to the two cavities are 0.464 x 10^{-6} m^3/s and 0.6792 x 10^{-6} m^3/S. The numbers of pieces to be produced are few; hence automatic fracture at the gate is not a high priority, though desired**.** A simple slit gate is chosen for this work (Figure 1). By combining equations (1) and (3) the flow rate Q_1 through the first gate is;

$$Q_1 = \frac{wh^3\Delta P}{12\mu L} \qquad (8)$$

Short length is desirable, therefore let L be 1mm (Jones, 2014). Let the height, h be half the width w.

That is; h = 0.5w. It is better to start with a small gate which may be opened up if there is need than to start with a big gate. However, pressure losses across small gates are usually high. Therefore consider a pressure drop of 6MPa across the gate. Thus; L=1 mm, $\Delta P = 6x10^6$ Pa, h = 0.5w, and μ= $1.17x10^3$ $N.s.m^2$. Back substitution into Equation 1 yields; w_1 = 1.7 mm and h_1 = 0.85 mm. The dimensions of the gate to the compression and flexural test piece cavity is obtained by similar calculations as; L_2 = 1 mm, w_2 = 1.9 mm and h_2 = 0.95 mm.

2.2.9 The Number of Cavities

The decision to mould the three test pieces in one shot is subject to the capacity of the moulding machine. The machine has a shot capacity of 0.04297 kg. If the two cavities are to be filled at the same time, the mass required to fill them must be less or equal to the rated capacity.

- Volume injected into cavity 1= 4.64 $x10^{-6}$ m^3
- Volume injected into Cavity 2 = 6.792 $x10^{-6}$ m^3
- Volume of material retained in gate 1 and 2 = 1.81 $x10^{-9}$ m^3
- Volume of material retained in the runner = 126 $x10^{-9}$ m^3
- Volume of material retained in the sprue = $\pi r^2 L$ = 2.663 $x10^{-6}$ m^3

Therefore, total Volume = 14.2243 $x10^{-6}$ m^3.
The relative density of high density polyethylene is given as 0.93 to 0.95. Using a relative density of 0.95; the mass of material injected per shot is 14.2243 x 10^{-6} $x0.95x10^3$

= 13.513 x 10^{-3} kg
= 13.513 g

The machine is very capable of coping with the two cavities per shot (Figure 3).

2.2.10 Cooling Channels

The thickness of the test pieces and other dimensions are small. It is therefore considered that two channels in each plate of the mould should be adequate for controlling the cooling rate. The cooling channel design is as shown in Figure 3. Each of the channels is 8mm in diameter.

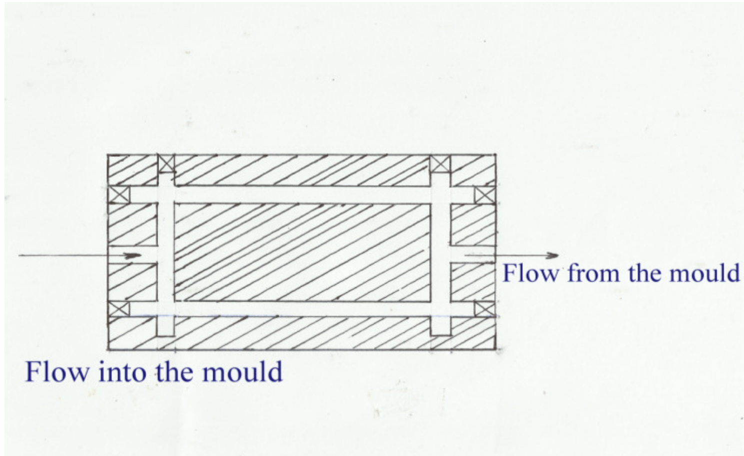

Figure 2: Schematic of cooling water channels

2.2.11 Mou1d Plates

The mould plates were installed in the clamp by sliding them into slots in each of the platen. The platen can only accommodate a fixed width of mould. The slot in the platen is also fixed. Thus the size and shape of the plates are based on the clamp of the experimental injection moulding machine. Figure 3 shows the cavity plate. The top plate is similar in shape but has no core. It carries the locating pin and seals the cavities when the mould is closed (Figure 4).

2.2.12 Locating Pin

Moulding the pieces in one plate reduces the degree of accuracy which locating devices usually demand. The sprue and runner are however on both plates. It is therefore important to ensure proper location of the plates with a locating pin. The locating pin is tight fitted to the top plate and enters the cavity plate with a clearance of 0.3 mm. Diameter of locating pin = 8 mm

2.2.13 Ejection System

The pieces to be produced are small and the numbers are few. Moreover the production is not on a continuous basis. It is therefore not wise to design an elaborate ejection system. An ejection system which is based on the shrinkage of plastic as it cools was used. The pieces came out easily from the mould since the cavities are very shallow.

2.2.14 Air Vents

Lines drawn on the surface of the cavity plate, starting from the cavities to the outside, served as the air vents. This should be adequate because the cavities are very shallow.

2.2.15 Manufacture of Experimental Mould

The processes employed in the manufacture of the mould include marking out of the cavity plate, milling operation with end mill cutters to produce the cavities and the runner (Figure 3 & 4). Other machining operations such as turning, drilling and tapping were adopted in making the sprue, the slit gates, locating pins/holes (Figure 4), cooling channels (Figure 2), bushings and plug pins. The mould was fabricated at a total cost of eighteen thousand, four hundred and ten (N18410.00) naira.

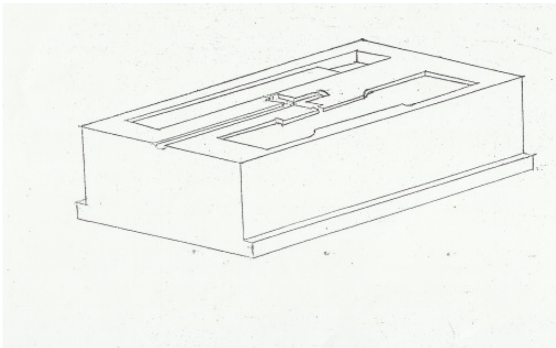

Figure 3: Mould Cavity Plate

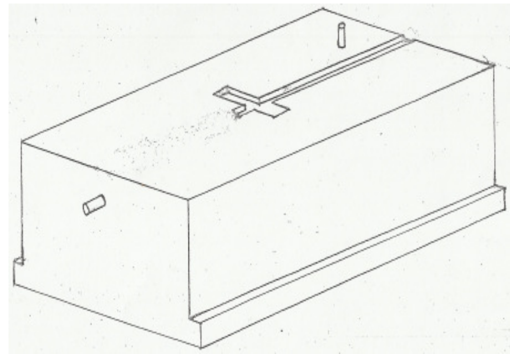

Figure 4: Mould Cover Plate

3. TESTING, RESULTS AND DISCUSSION

Short filling occurred when the mould was tested. Increasing the melt temperature and pressure could not cure it. The gates were therefore opened up gradually until the cavities were completely filled.

The cross-sectional dimension of the tensile test piece was found to be 12.5 mm x 2.15 mm as against a target dimension of 12 mm x 2 mm. Thus the dimensional accuracy of the product was 89.3%. Similarly the cross-sectional dimension of the compression test piece was 12.5 mm x 10.2 mm while the target dimension was 12 mm x 10mm. This gave a dimensional accuracy of 94.12%. The flexural test piece gave a dimensional accuracy of 87.3%.

Two reasons might have accounted for the deviation from the expected dimensions. Available values of the shrinkage of high density polyethylene are a range from 0.02 m/m to 0.05 m/m. Inaccuracy in shrinkage value will translate into reduction in dimensional accuracy. The second possible reason is the precision of machining. The milling machine used for this work was manually controlled. This reduced the precision with which the depths of the cavities were produced. Moreover the available end mill cutter could not give a finished cavity width of high precision. However a dimensional accuracy of 94.12% is commendable for a locally fabricated mould.

4. CONCLUSION

The design analysis, fabrication and testing of a metallic mould for injection moulding of thermoplastic products was successfully carried out in this work. The products of the test mould achieved a dimensional accuracy of 94.12%. This work indicated a good prospect for the design and fabrication of plastic moulds for Nigeria industry.

5. RECOMMENDATIONS

The deviation between the desired dimensions and finished dimensions could be reduced by using modern machining equipment. Further research is required to characterize the various thermoplastic materials being used in the country in term of shrinkage value, viscosity and density in order to improve dimensional accuracy.

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