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Design and Finite Element Analysis of Medium Carbon Steel Toilet Brush Cup Injection Mold

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Abstract **Review Article**

The usage of plastics is mainly due to their lower weight, melting temperature and cost compared to other materials like metal, composites etc, accompanied with decent flow characteristics. Thus, the demand for smaller, precise and compact designs with intricate geometries, on using plastics, has to be met. Injection molding is an ideal plastic manufacturing process due to its ability to manufacture complex plastic parts with high precision and production rates at low operating costs with only a relatively high initial investment for mold design and fabrication. This study, structural analysis of a 0.3% carbon of medium carbon steel toilet brush cup injection mold, centers on the structural analysis of the assessment and reassessment of the heat treated medium carbon steel injection mold material to ascertain the structural integrity of the assessed and reassessed mold material. The maximum equivalent von –mises stress and directional deformation of the structural analysis of the mold material before heat treatment were $3.441*10^9$Pa and $9.0095*10^{-4}$m respectively. While the maximum equivalent von –mises stress and directional deformation of the structural analysis of the mold material after heat treatment were $3.432*10^9$Pa and $8.4722*10^{-4}$m respectively. The results were favorable for injection molding application and wear reduction.

Keywords: Medium Carbon Steel (MCS), Injection Mold.

1. INTRODUCTION

Injection molding (IM) is a common manufacturing technique used for plastic products. The manufacturing technique could be used to produce both small as well as large products in a weight range of 0.000001 kg to 100 kg [2]. The raw material, called resin, is usually shaped as granules, these granules are stored in a feed hopper, a bottom opened bottle which feed the press with resin. The granules need to be molten to enable an injection into the tool cavity chamber; the IM machine is therefore equipped with a plasticizing unit in order to melt the resin. Initially in the plasticizing unit a screw, which rotates with the help of a motor, melts the granules. Most of the heat is created by friction in the screws rotation but heating bands are often added to supplement the heat generation, when the granules are melted the screw inject the polymer into the cavity chamber with an axial movement.

2. REVIEW OF RELATED STUDY

Iftekhar, H *et al.*, (2002) [4] reported in his work, the development and manufacture of injection molds for high quality technical parts is a complex task implying an integrated knowledge of the injection molding process and the material changes undergone during processing. In the case of the design of moulds with deep cores (e.g. for piping accessories), the prediction of the mold dimensions in order to obtain parts with the correct size and shape after molding, and the prediction of the forces required for the ejection of the moldings, are two important task. In this work the shrinkage and the ejection force were studied in injection molding samples. Two types of moldings were produced: a edge gated rectangular plate and a spider gated cylindrical tube. The mold has the means to measure the pressure and temperature histories, and the force evolution during the ejection process. The monitoring of the variables was done in real processing conditions and time. For the tube moldings only, the force evolution during the ejection was measured. Two materials were used for the moldings: a polycarbonate and a polypropylene, as paradigms of amorphous and semi-crystalline materials. The strain gauge technique was used to monitor the shrinkage variation during molding cycle and proved to be very useful to address the effect of constraint in the shrinkage and to measure the onset of shrinkage. The recorded pressure and temperature during the processing were analyzed and compared with simulations performed using a commercial software C-Mold v. 99.7, and an open code UNISA developed at the Università di Salerno. The experimental data were qualitatively in agreement with those predicted by the software. However some discrepancies can be observed when the effect of pressure on viscosity and mold deformation are not considered. The as-molded shrinkage was analyzed and compared with simulations performed using the C-Mold v. 99.7 and a thermo-mechanical model originally developed at the Università di Salerno and modified within this research to suit specific aspects of the geometries being studied. This thermo-mechanical model gives a satisfactory description of the shrinkage and shows the relevance of using the degree of crystallinity as criterion of solidification. The ejection force was well described by a thermo-mechanical model accounting for crystallinity effects and the shrinkage evolution developed in this work.

Granter CES Edu pack (2011) [7], developed three-dimensional finite-element thermal-stress models to predict temperature, distortion and residual stress in the mold of thin slab continuous casters. Geometrically, there were two kinds of molds to achieve high-speed casting funnel-shaped and parallel mold. The mold shape and high casting speed led to higher mold temperatures and shorter mold life than in conventional slab casters. Heat flux and the effects of mold shape on distortion of the mold in a thin slab caster were also investigated. Mold wall temperature measured in the plant was analyzed to determine corresponding heat-flux profiles in thin slab molds using an Inverse Heat Conduction model, and this data was then used in an elastic-visco-plastic analysis to investigate the deformation of the molds in service for different mold shapes. The model predictions of temperature and distortion during operation match plant observations. During operation, the hot face temperature reaches 430ºCand the copper plates bend toward the steel, with a maximum outward distortion of about 0.3mm. This occurs just above the center of the wide faces, and is smaller than the distortion of a conventional slab mold.

Avery, J (1998) [8] gave the method to solve the clamping force optimization where the locators were assumed as deformable and the work piece as rigid body. The optimum clamping force is found to reduce the location error due to the application of the machining forces. Shakhashiri, B. Z (2008) [10] modeled the work piece fixture system by considering work piece as elastic body and fixture as a rigid body. The locators were modeled as displacement constraints that prevented work piece translation in the normal direction. The clamping force was modeled as point force. The work piece is considered as 2D by assuming the work piece is subjected to plane stress. Static analysis is used to find out the elastic deformation of the work piece under machining.

2.1 AIM AND OBJECTIVES OF THIS STUDY

The aim and objectives of this work are as follows;

1. To design injection mold using computer aided design software (solid works).
2. To alter mechanical properties of carbon steel through heat treatment.
3. To assess the structural integrity of the carbon steel before and after heat treatment
4. To investigate the effect of the clamping force on the designed mold

2.2 SCOPE OF THE STUDY

The scope of this research covers component study of the injection molding, the conceptual design and calculation of injection mold, analysis for the component, the use of Cambridge engineering software for medium carbon steel material selection, using Solid works for the modeling of the mold, assessment of the material and reassessment of the heat treated medium carbon steel for injection mold applications using finite element software such as ANSYS14.0 workbench.

3. MATERIAL AND METHODOLOGY

Calculation of the 3D model

Part details

Name of component: toilet brush cup mold

Material: polypropylene

Shrinkage: 0.012-0.022

Numbers of cavities: single cavity

Density of polypropylene= $890 kg/m^3$

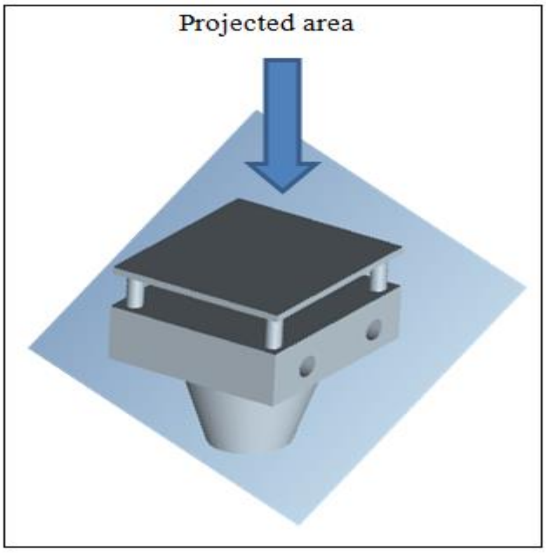

Figure 1: Details of the component of the core

Projected area of component: 552.25cm^2 (from CAD model)
Volume of component:

Weight of molding
Kiran *et al*., (2014), reported that,

Actual mass of component (M) $= \rho * V$ …….. (1)

Where,
$\rho =$ Density of polypropylene $= 890\text{kg/m}^3$
$V =$ Volume of component from CAD model $= 869.9\text{cm}^3$
Therefore, actual mass of component (M) $= 0.79\text{kg} = 7.75\text{N}$

$$Total\ weight\ = M * Number\ of\ cavities \ldots\ldots\ldots\ldots\ldots (2)$$
$$Total\ weight\ = 7.75 * 1 = 7.75N = 0.79g$$

The weight of the sprue and the runner related to the molding must not generally be neglected. This should be considered in the formula while determining the molding weight. The molding weight should be substituted in the formula and multiplied with the multiplication factor (M.F).

In this design, a multiplication factor (M.F) of 0.022 is chosen for a polypropylene.

Total weight of single component with feed system $=$ total weight $*$ M.F …………. (3)

Total weight of single component with feed system:
$$= 7.75 * 0.022 = 0.17N$$
$$= 0.017g$$

Clamping Tonnage (Force)
Technical directory on design and tooling for plastics, CIPET, (2016), stated that:

Clamping tonnage required $=$ Total projected area of the mould $*$ cavity pressure $*$ no. of cavities ……….. (4)

Table 1: Cavity pressure

Cavity pressure	(kgf/cm^2
Lower injection pressure	200-400
Higher injection pressure	400-600

Source: Misumi, (2019)

Herbert Rees, (2020) reports that;

Cavity pressure $= (1/_2 *$ injection pressure) for easy flow materials and ………. (5)

Cavity pressure $= (1/_3 *$ injection pressure) for viscous materials ………………. (6)

In this design, Polypropylene material of easy flow characteristics is chosen, hence, from table 3.7, a cavity pressure of 600kgf/cm^2 is chosen for a worst case scenario.

$$Cavity\ pressure\ = \frac{1}{2} * 600 = 300kgf/cm2\ = 29{,}420.04Pa$$
$$\therefore, clamping\ tonnage\ required = 0.0552 * 29420.04 * 1 = 1623.99N$$
$$clamping\ tonnage\ required = 1623.99N = 15.93tons \sim 16tons$$

Taking a factor of safety of 1.3 (30% of actual tonnage) in this design, we have a
tonnage $= 4.8$ tons$\sim$5tons

Therefore, an injection machine of a clamping tonnage of 21 tons is selected
It is suggested that Mathmann 30T injection machine is selected.

Table 2: Mechanical properties of untreated medium carbon steel

Density (kg/m^3)	**7800kg/m^3**
Young's modulus (GPa)	205
Yield strength (elastic limit) (MPa)	508
Tensile strength (MPa)	706
Poisson Ratio	0.28
Elongation (% strain)	10
Hardness (Vickers)	200

Source: Granta CES edu pack (2021)

Table 3: Mechanical properties of treated medium carbon steel under different quenching medium for a period of 40 minutes

Quenching medium	Temperature ^{O}C	Young's Modulus (Gpa)	Tensile strength (Mpa)	Poisson's ratio	Hardness No (Vickers hardness)	% Elongation	Yield strength (Mpa)
As received	1380	205	706.5	0.28	280	7	504
Water	850	207	836.25	0.282	350	33.2	575
Water	900	209	890.35	0.285	412	34.4	605
Water	950	210	999.56	0.289	425	36.1	625
Condemn Oil	850	218	860.45	0.291	440	29.5	710
Condemn Oil	900	215	930.90	0.293	490	31.7	790
Condemn Oil	950	217	1050.75	0.295	510	32.6	810

4. RESULTS

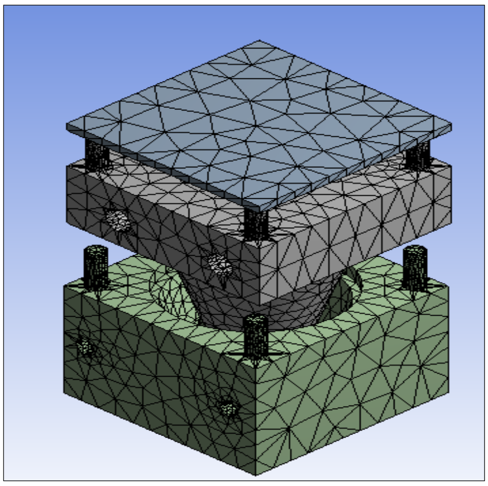

Figure 2: Fine size meshing of the isometric view of the cavity and core mold

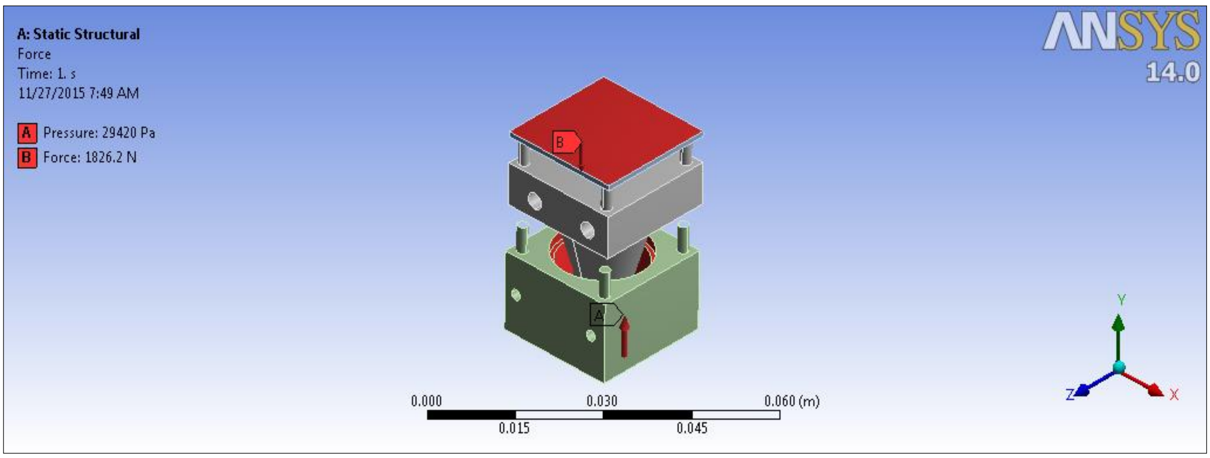

Figure 3: 3D model of the core and cavity showing how the clamping force and the injection pressure were applied on the mold

Table 4: Boundary conditions of structural analysis of the untreated injection mold

Density	7800kg/m^3
Young's modulus	205(GPa)
Yield strength (elastic limit)	508(MPa)
Poisson Ratio	0.28
Clamping force	1826.2N
Injection pressure	29420Pa

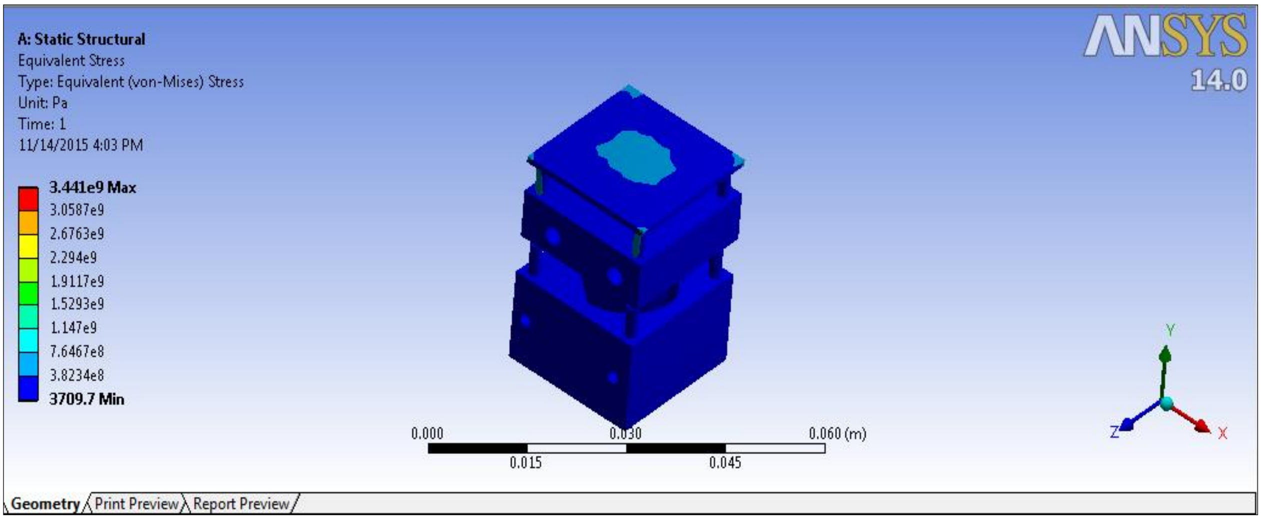

Figure 4: Equivalent Von-Mises of the static analysis of the un-treated injection mold

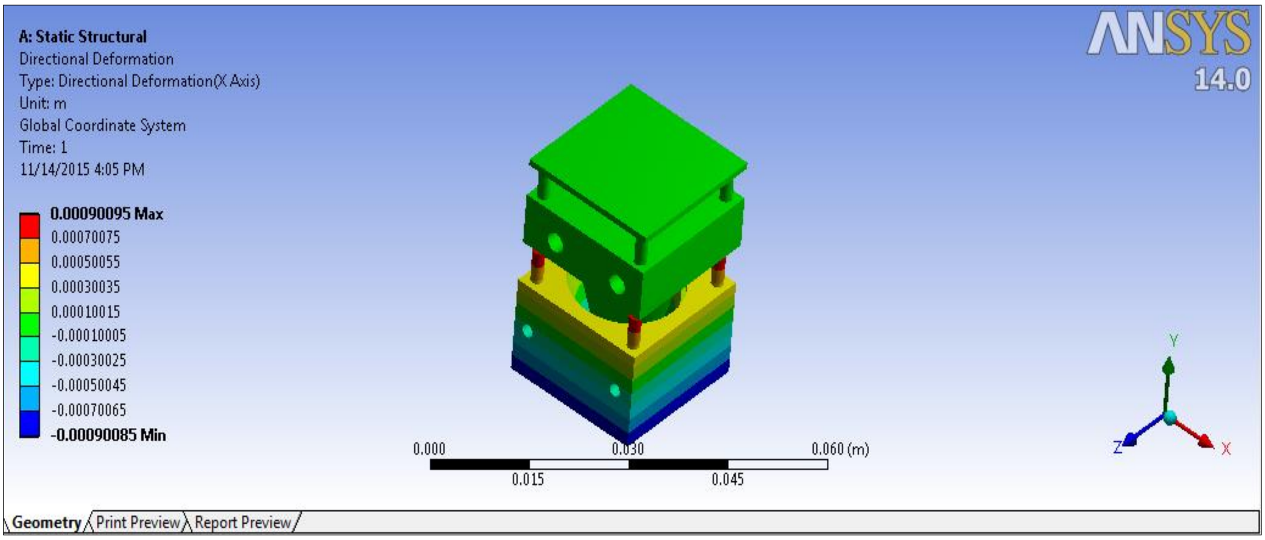

Figure 5: Directional deformation of the static analysis of the un-treated injection mold

Table 5: Simulation condition for the static structural analysis of the treated mold material

Density	**7900**	**Kg/m^3**
Clamping force	1826.2	N
Injection pressure	29420	Pa
Poisson’s ratio	0.291	
Young’s modulus	218	Gpa
Yield strength	2.5*10^8	Pa
Temperature of the molten polypropylene	250	ºC

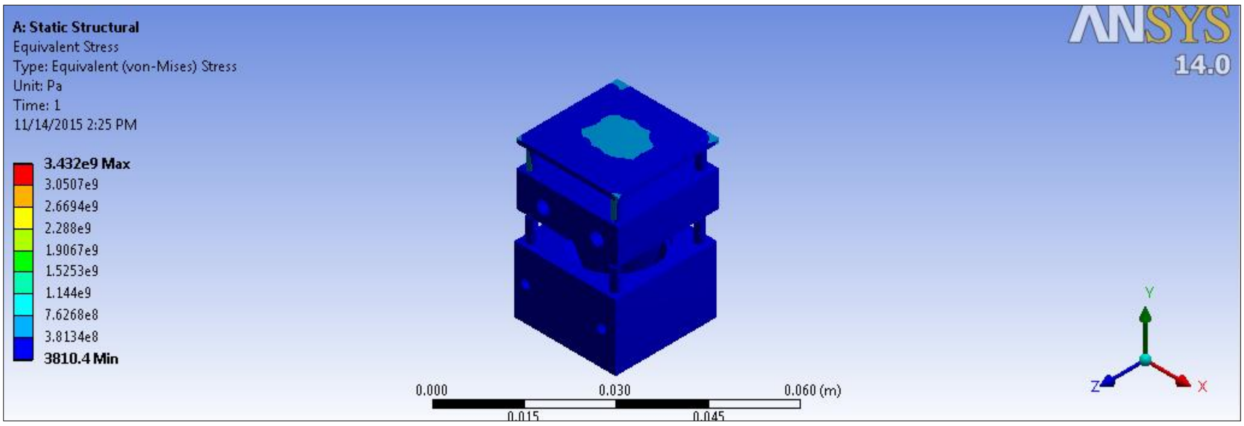

Figure 6: Equivalent Von mises of the static analysis of the treated injection mold

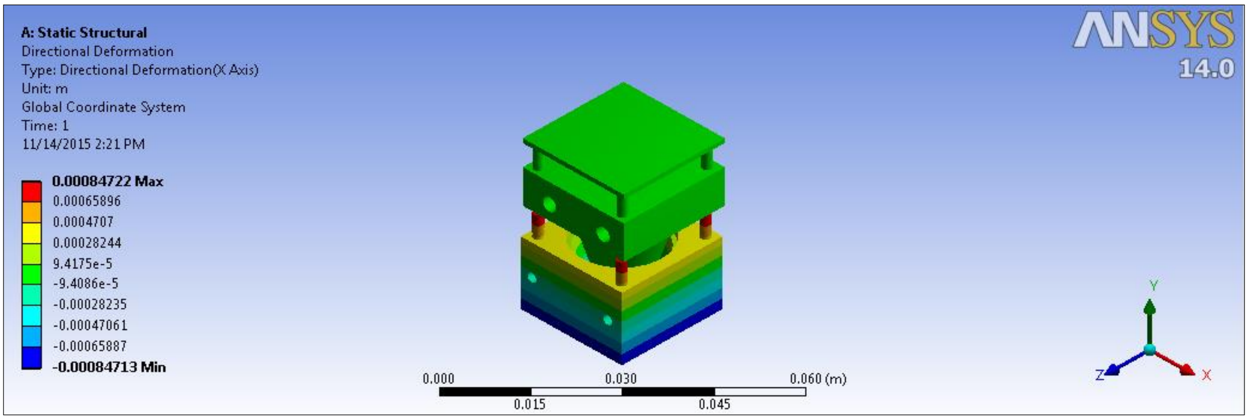

Figure 7: Directional deformation of the static analysis of the treated injection mold

5. DISCUSSION

In Figure 4 and Figure 5, the maximum equivalent von–mises stress and directional deformation of the structural analysis of the mold before heat treatment were $3.441*10^9$Pa and $9.0095*10^{-4}$m respectively. On the other hand, in Figure 6 and Figure 7, the maximum equivalent von–mises stress and directional deformation of the structural analysis of the mold after heat treatment were $3.432*10^9$Pa and $8.4722*10^{-4}$m respectively.

Accordingly,

1. It was observed that the maximum deformation obtained from Figure 4 for the untreated MCS mold material is higher than the maximum deformation of the treated MCS mold of Figure 7, this was as a result of the yield strength of the treated MCS which is presented in Table 3 is higher than the yield strength of the un-treated MCS mold which is found in Table 2, therefore, the higher the strength of a material, the lesser its response to deformation.
2. The process of banging/clamping, impact almost the same stress on the mold both before and after heat treatment, but comparing the yield strength of the material before and after heat treatment is an indication that, the yield strength of the material after heat treatment which is 810MPa will last long than that before heat treatment which is 508MPa.

6. CONCLUSION

In this research study, the structural analysis of a 0.32% carbon of medium carbon steel toilet brush cup injection mold was investigated. The Software solid works was crucial in designing all the necessary parts of the mold. As received medium carbon steel material was analyzed structurally for mold usage and results presented. On the other hand, same medium carbon steel material was heat treated at a temperature of 850°C, 900 °C and 950 °C respectively and was allowed to cool inside condemned oil (quenchant) for a period of 40 minutes. The heat treated medium carbon steel material was analyzed structurally for mold application, results were also presented. The results obtained during the analyses of the material (MCS) after heat treatment were better off compared to the un-treated material.

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