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Structural analysis of molds with conformal cooling channels: a numerical study

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Abstract: This article presents noteworthy discoveries pertaining to molds featuring innovative conformal cooling channel designs. The aim of this study is to determine the upper limit of pressure that the components can endure in a real-world injection molding scenario. The resistance and stiffness properties of the examined geometries are assessed by linear structural analyses conducted in the ANSYS Workbench 2020 R2 Finite Element Method Software. Multiple metrics are employed to analyze the outcomes. Upon thorough examination and analysis of the obtained results, it was determined that specific configurations exhibit a high degree of compatibility with the prevailing operational parameters inherent to the injection molding procedure.

Keywords: Structural analysis; Finite Element Method; ANSYS; Computer Aided Engineering

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1. Introduction

Extensive research has been undertaken regarding the design and modeling of conformal cooling channels (CCCs) in the context of injection molds. Various simulation technologies are used to analyze mold and channel designs. Dimla et al. (2005) employed I-DEASTM moldflow analysis to ascertain the most favorable channel position [1]. (Dimla, Camilotto, & Miani, 2005). In their study, Saifullah and Masood (2007) conducted an investigation on the concept of "part cooling time" by using the thermal analysis program ANSYS [2]. In a study conducted by Saifullah et al. (2009), it was observed that when assessing conventional and quadratic CCC profiles through the use of MPI simulation software, conformal channels exhibited a cooling rate that was 38% faster compared to conventional channels [3]. In their study, Gloinn et al. (2007) employed a finite element method (FEM) analysis to ascertain the mold temperature. The analysis focused on the utilization of ABS polymer as the molten material and the intake of chilling water [4]. In 2007, a study conducted by [5] examined the thermal impacts of cooling channel design in injection molding using Moldflow Plastic Insight 3.1. The authors have put out a novel criterion for CC construction. In order to illustrate the advantages of a cooling loop, Wang et al. [6] employed identical modeling techniques to simulate the temperature of a singular segment. In 2017, Khan et al. conducted a comparative analysis of the cooling time, total cycle time, volumetric shrinkage, and temperature change associated with serial, parallel, and additive-parallel cooling channels [7]. Mayer (2010) succinctly establishes a correlation between four key design criteria for additive manufacturing. Previous studies have indicated that the utilization of noncircular channel cross-sections has the potential to enhance cooling efficiency [8]. The investigation of cooling tubes with varying spacing for mold tooling has been conducted by researchers [9]. The initial construction of the model involved the use of linear channels. However, a subsequent redesign was implemented, replacing the linear channels with CCCs. This redesign was carried out by employing a meticulous conformal channel design method. The researchers investigated the spatial relationship between the wall and duct, the spacing between pitches, and the diameter of the duct. Only two published articles that present novel research on the topic of structural modeling of molds, including conformal cooling channels, were found [10,11]. The primary objective of doing structural analysis in the context of these two injection molding experiments was to validate the geometric aspects relevant to structural design. A comprehensive investigation comparing the stiffness, resistivity, and other pertinent attributes of different injection mold geometries has not been conducted. As evidenced, the literature on numerical simulation holds significant importance. The assessment of the structural integrity of molds incorporating internal reinforcement and a cellular structure was not conducted. This study proposes various cooling channel layouts for injection molds that possess internal cavities. The efficacy of specific forms was assessed using a structural static analysis conducted under typical loading conditions encountered in injection molding. The present study assessed the safety geometry of injection molds. The outcomes of this study can be employed to assess and evaluate the tolerance levels of different geometries under injection molding pressures.

2. Procedure

2.1. Material properties

The material used in the simulations was steel P20. It is assumed that the material behaves as orthotropic. The properties of the steel used are shown in Table 1.

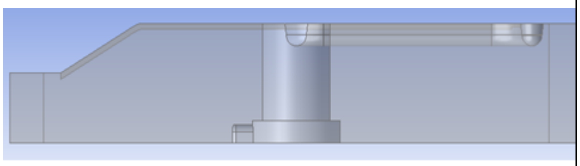
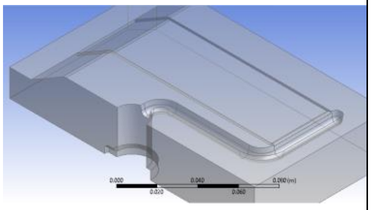
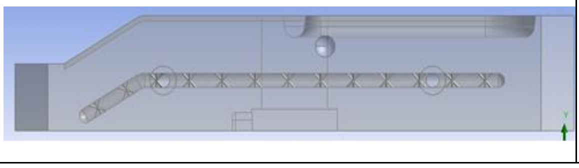
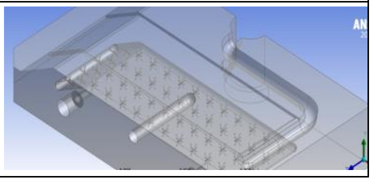
Table 1. – Material properties.

Property	Value	Units
E_y	180	GPa
E_x=E_z	185	GPa
n_x= n_y=n_z	0.29	[-]
G_{xz}	69.8	GPa
G_{yz}	71.7	GPa
G_{xy}	71.7	GPa
r	7900	kg/m^3

The values of G_{xy}, G_{yz}, and G_{xz} are required in ANSYS Workbench 2020 R2 and were not in [20,21]. Therefore, they were determined from Ez, Ex and Ey.

2.2. Numerical models

In fig. 1, one can see the CAD files (geometries) of the studied models.

ID	Side view (2D)	Isometric view
Bulk		
New1		

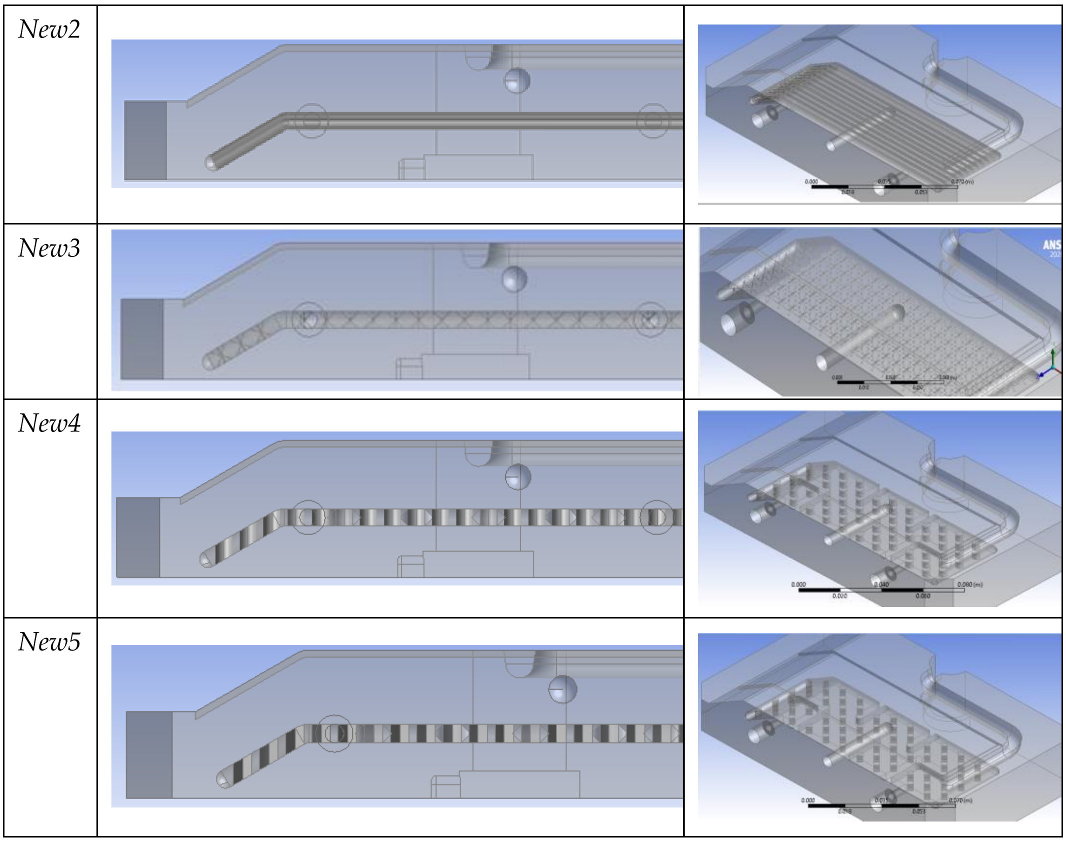


Figure 1. Geometries used in this work.

2.3. Conditions

In order to replicate the pressure exerted on the injected part during the injection molding process, a distributed load (pressure) was applied to the upper surfaces of the component, including the cooling channels, as shown in fig. 2. The pressure exerted was measured to be 100 megapascals (MPa). According to Rosato et al. (2004), the typical range of injection pressure is between 14 MPa and 310 MPa. The pressure falls within the permitted range. In the context of an injection molding machine mold, the object was securely immobilized to closely simulate real-world conditions. Fig. 2 illustrates the loads and boundary conditions imposed on numerical models.

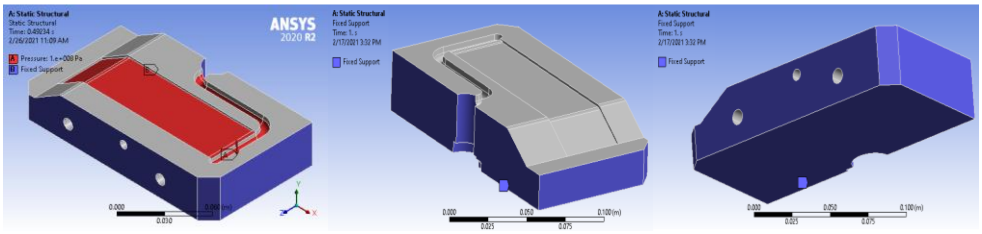


Figure 2. Loads applied to the FEM model (left) and degrees of freedom (DOF) constraints applied to all the FEM models (mid and right).

The mesh type is tetrangular free with a mean element size of 1.25 mm. The analyzed geometries were built in the computer-Aided Design (CAD) software Solidworks 2020. The geometries were exported in a neutral file format and imported into ANSYS Workbench.

3. Results and discussion

In order to evaluate the distribution of stresses and displacements, contours were created in ANSYS Workbench. In this situation, the goal of mechanical design and Computer Aided Engineering (CAE) engineers should be to lower critical stresses by reinforcing the part with the highest stresses and/or displacements. Alternatively, by reducing material on the points of lowest stresses, topology optimization principles can be used automatically (via software) or manually. Regarding the current study, the shapes could aid in the redesign of the components to achieve the least amount of displacement and stress. The Huber-Mises criterion equivalent stresses for the Bulk model are graphically displayed in Fig. 3. The results are displayed in Fig. 3(left, a). Figure 3(left, b) is a larger version of Figure 3(left, a).

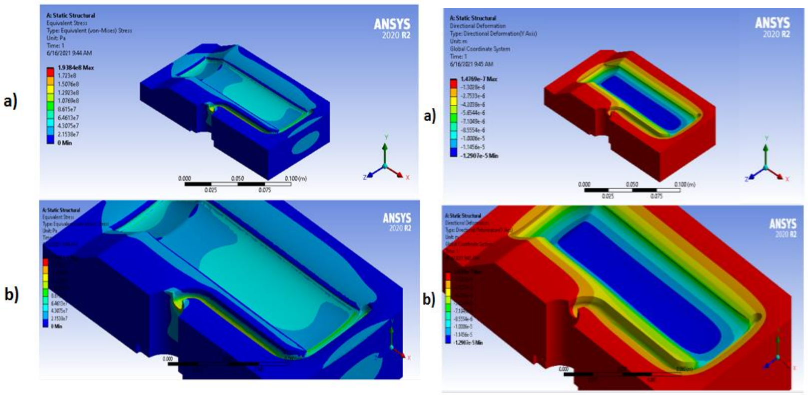


Figure 3. Contours of strength results (left) and contours of stiffness results (right).

The Huber-Mises stresses are highest around the center of the load application zones, as depicted by the contours in Figure 3. It is crucial to remember that this is an equivalent stress, which is determined using the major stresses, even though the contour may not show distinct gradients of results. The correlations among the primary stresses may give rise to outcomes with non-trivial contours, like the one in question. The Bulk model's graphical findings are displayed in Fig. 3 (right). in terms of displacement along the y axis. Refer to Fig. 3 (left, a)and fig 3. (right, a) for the coordinate system. The results are displayed in Fig. 3(right, a). Fig. 3(right, b) is a larger version of Figure 4(a). As would be predicted, the contour of Fig. 3 (right) displays substantial vertical deflections where the load is applied. The distance to the locations of load application results in a deflection gradient.

The Von Mises strength illustrated in fig. 4 (left). Fig. 4 (right) illustrates the representation of commonly used high-strength steels, exhibiting yield strengths of 300, 500, 700, and 900 MPa.

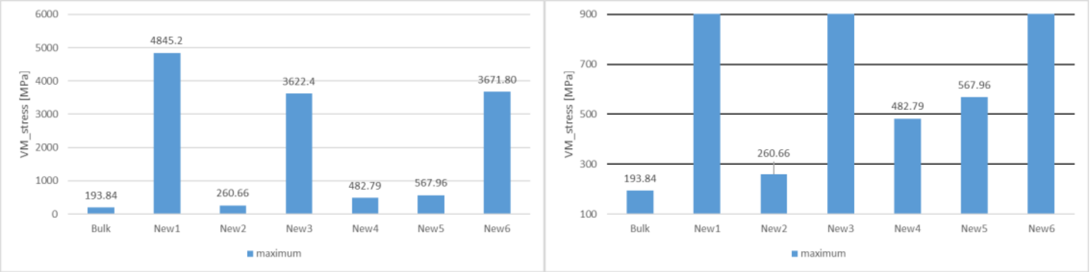


Figure 4. -Von Mises strength for all the studied geometries.

Notably, the vertical axis of the graph is presented on a distinct scale, while the horizontal lines are emphasized with boldness.

According to the findings presented in fig. 4, it can be inferred that the existing configurations of the New1 and New2 geometries are deemed impracticable due to the inability of any steel material to endure the excessive stress levels associated with them. The Bulk, New2, New4, and New5 satisfy the specified criteria for structural yield strength, which is set at 700 MPa. The structural analysis reveals that the Bulk, New2, and New4 geometries exhibit a satisfactory performance, as they can withstand a stress level of 500 MPa. At a yield strength of 300 MPa, only the Bulk and the geometry New2 demonstrate maximum Von Mises strength below the yield point. Fig. 5 illustrates the maximum displacements in the y-direction for each respective shape. Results shown in fig. 5 were calculated from fig. 4, using eq. 1:

$$\left(\sigma_{VMx} - \sigma_{VMbulk} / \sigma_{VMbulk}\right)*100 \tag{1}$$

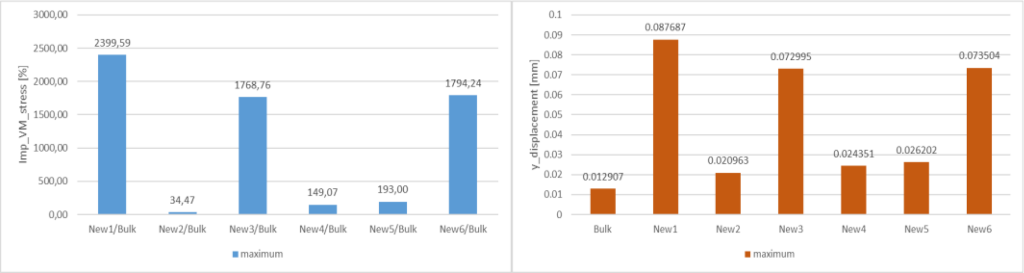


Figure 5. Improvement results in terms of strength (left) and Y displacement for all the studied geometries (right).

Based on the analysis conducted, it can be inferred that the geometries New2, New4, and New5 exhibit a plausible potential for viable implementation within operational environments and for the specific materials under consideration. While it is acknowledged that design alterations are required, it is worth considering the potential intrigue of the New1, New3, and New6 geometries. The stiffness results of Fig. 5 suggest that the upper surface undergoes the most deflections due to the distributed load applied to it and the larger distance to the restricted areas. The impact of these two parameters on the gradient of the deflections depicted in Fig. 5 is significant. Upon comparing the outcomes depicted in Fig. 4 and Fig. 5, it becomes evident that disparities exist between strength (fig. 4) and stiffness (fig. 5). The reason for this discrepancy lies in the fact that the Von Mises yield criterion incorporates primary stresses, but the deflections under consideration only consider a single direction. From fig. 4, it is shown that steel selection is an important design factor to consider, as steels with higher yield strength allow to obtain structural integrity, even in molds that are not high performers.

4. Conclusions

The following conclusions can be inferred from this work:

1. If the ANSYS APDL input files are appropriately configured, the procedure can be implemented on molds of any dimensions and with any number of cooling channels.
2. This study aimed to examine the structural behavior of molds that incorporate conformal cooling channels. Extensive research has been dedicated to the investigation of conformal cooling channels in recent years; yet limited knowledge exists regarding their structural behavior.
3. In the process of injection molding, it is common for the mold to experience pressures reaching magnitudes of several hundred MPa. The use of conformal cooling channels in injection molds under operational settings necessitates the use of static analysis as a crucial design tool for simulating structural behavior.

4. The advancement of additive printing technology will facilitate the development and experimentation of conformal cooling conduits. This approach enables the use of different mold diameters, cooling channel counts, and part temperatures.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Hugo Miguel Silva; methodology, Hugo Miguel Silva; software, Hugo Miguel Silva; validation, Hugo Miguel Silva; formal analysis, Hugo Miguel Silva; investigation, Hugo Miguel Silva; resources, Hugo Miguel Silva; data curation, Hugo Miguel Silva; writing—original draft preparation, Hugo Miguel Silva; writing—review and editing, Leandro Fernandes, João Noversa and Hugo Rodrigues; visualization, Hugo Miguel Silva; supervision, António José Pontes; project administration, António José Pontes; funding acquisition, António José Pontes. All authors have read and agreed to the published version of the manuscript." Please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: Authors declare no conflict of interest.

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