AFM-BASED MACHINE DESIGN FOR FINISHING INJECTION MOLDING TOOLS

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This research delves into challenges within injection molding, particularly the struggle to maintain uniform cooling in complex product shapes. Additive manufacturing, like conformal cooling, is explored as a potential solution but faces surface quality issues. The study investigates Abrasive Flow Machining (AFM) as a means to refine surfaces within cooling channels, crucial for injection molds. The research presents the design and assembly of an AFM-based machine and its potential in addressing the requirements for machining internal surfaces created through additive technologies, highlighting its universality and potential applications in future research on conformal cooling within injection molding technology.

KEYWORDS

Injection molding, Abrasive Flow Machining, cooling channels, additive manufacturing, machine design

1 INTRODUCTION

The injection molding technology is one of the most widespread and continually evolving methods for processing plastics. Products manufactured using this technology find applications in several industrial sectors, particularly in the automotive, aerospace, and defense industries. The main advantage of this technology, which subsequently translates into its application potential, is the ability to produce complex-shaped components with high dimensional and shape accuracy. This includes the production of both thin-walled and thick-walled components, as well as products with specific shapes. However, complications related to the quality of the injection can arise during the production of some of the aforementioned products, and these need to be considered.

Partially, this issue can be solved by using some special injection molding methods, such as water-assisted injection (WIT) or gas-assisted injection (GIT). However, in cases where traditional injection molding technology must be used, attention should be focused on the design of the injection mold, especially on the design of the cooling system, to ensure a more uniform temperature field on the surface of the injected product. The uniformity of the temperature field is a key factor in ensuring the dimensional stability of the product and reducing residual stresses as much as possible. Failure to meet these criteria can result in significant deformations of the injection-molded parts, which may also become apparent in the period after the injection molding cycle is completed. Unfortunately, in some cases, using conventional methods for manufacturing injection molds cannot ensure temperature field uniformity for uniquely shaped products. A possible solution is to use so-called conformal cooling, which can be created using some additive manufacturing technologies.

In researching the field of injection mold cooling, it has been found that the current research is primarily focused on conformal cooling, with efforts aimed at increasing the efficiency of cooling systems. A significant portion of the studies conducted in recent years by Venkatesh et al. [Venkatesh 2017], Deepika et al. [Deepika 2020], Jahan et al. [Jahan 2016], Dimla et al. [Dimla 2018], Park et al. [Park 2020] and Shen et al. [Shen 2020] compares the differences between the conventional cooling method and methods created using additive manufacturing technologies. The majority of these studies address this issue solely through simulations rather than real-world cases. This may be due to the fact that additive manufacturing of individual steel parts is still relatively expensive.

From the perspective of additive manufacturing itself, a major drawback is that products prepared in this way exhibit low-quality surfaces and high roughness; this fact is proven by authors Han et al. [Han 2020], Galati et al. [Galati 2019] and Babu et al. [Babu 2022]. Furthermore, research by Galati et al. [Galati 2019] and Babu et al. [Babu 2022] declares that surface roughness in additive manufacturing can range from tens to hundreds of micrometers. In the case of cooling channels, this worsened surface quality can lead to restriction of flow, which, in combination with small channel diameters (channel diameter < 6mm), can potentially lead to their blockage by dirt. High channel roughness can also impede heat transfer and cause stress concentrations, resulting in lower fatigue strength. These facts are discussed by Han et al. [Han 2020], Günther et al. [Günther 2018], and Dumas et al. [Dumas 2018]. To fully harness the potential of additive technologies in the cooling of injection molds, it is therefore imperative to further process channel surfaces to reduce roughness. In terms of suitable technology for these applications, the Abrasive Flow Machining (AFM) method appears suitable, as recent studies by Han et al. [Han 2020], Chawla et al. [Chawla 2019], François et al., [François 2021] Kumar et al. [Kumar 2022] and Uhlmann et al. [Uhlmann 2018] suggest it can be used effectively for machining internal surfaces. Along with the possible use of AFM for finishing internal channels produced using additive technologies in the context of injection mold cooling, the proper selection of abrasive materials is also crucial, all of which are areas that have not yet been fully explored.

2 EXPERIMENTAL

2.1 *Overview of the experiment*

The experimental part of the study deals with the analysis of the injection mold cooling channels and the design of the testing machine which works on the AFM principle. The machine is useful in areas where there is a need to finish internal surfaces such as cooling channels of the injection mold made by additive technology. However, for successful verification of the machine functionality the test specimens had to be designed.

2.2 *Cooling channels analysis*

Analysis of the cooling channels made by additive manufacturing technology should confirm the hypothesis that the finishing of the cooling channels positively changes the flow behavior of the coolant media and its pressure drop. Analysis has been done on real thick-walled optical part. The mold of this part contains a conformal cooling system.

2.3 *Materials and equipment*

Materials such as tool steel, stainless steel, or copper alloys (e.g., Ampcoloy 85) are commonly utilized in today's manufacturing of mold cavities for injection molding. When selecting materials for the fabrication of test specimens, it was crucial to choose types that are currently in common use for designing mold cavities and also can be processed using the selected technologies and available equipment - EOS M 290 (Direct Metal Laser Sintering - DMLS technology). For these reasons tool steel 1.2709 was chosen.

2.4 Test specimens design

The design of the test specimens, including individual channels, is devised to best correspond with real cooling channels in injection molds. In addition to the technology and material used, the test specimens also vary in channel diameter and pitch.

2.5 AFM Technology

AFM technology is currently primarily used for finishing internal openings, most commonly in automotive industries, particularly in the case of intake and exhaust manifolds, turbocharger stators, and wherever precise inner contouring is required. The abrasive medium is composed of polymer and SiC abrasive particles. These two components, when mixed, form a unified substance (Fig. 1), which is subsequently placed in the machine's bottom cylinder. [Han 2020]

Figure 1. AFM medium [Han 2020]

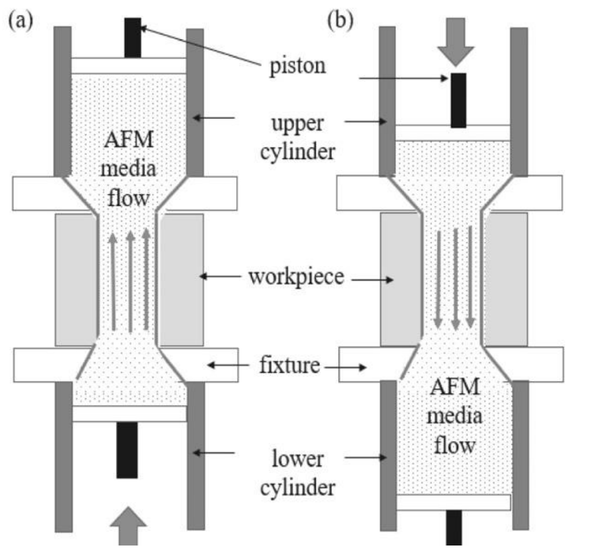

Figure 2. A schematic illustration of a two-way AFM: (a) up-stroke, (b) down-stroke [Han 2020]

The product that needs to be machined is appropriately secured using a fixture to the bottom cylinder. The medium then flows up and down the machined channel with the assistance of the piston's movement within the cylinder. One cycle is completed after the medium moves upwards and then back downwards (Fig. 2 b, c). During this process, an abrasive medium grinds against the channel, thereby reducing the channel surface roughness. [Goyal 2022], [Cheema 2012]
The AFM technology can be categorized into three groups based on the equipment configuration and the flow of the abrasive medium:

- One-way AFM: An Abrasive medium is pushed in only one direction.
- Two-way AFM: An Abrasive medium is pushed between two working cylinders (upper and lower). The medium is pushed back and forth through the workpiece placed between the two working cylinders (Fig. 2 b, c).
- Orbital AFM: Similar to the two-way system, except the workpiece undergoes an orbital oscillating motion. [Goyal 2022]

2.6 Software

Cooling system flow analysis has been performed using Moldex3D.
All the parts and assemblies of the machine were designed using software Catia V5R19 in the part design module and the drawings module has been used as well.

3 RESULTS

3.1 Cooling system flow analysis

To prove the necessity of the machine design, an analysis of the cooling channels was carried out.
Following that fact, two analyses have been made for comparison. Only the channel roughness was variable, and all other parameters were the same.
Fig. 3 shows coolant pressure throughout the circuit with average channel roughness of 20 μm which is roughness made by additive manufacturing technology [Babu 2022].

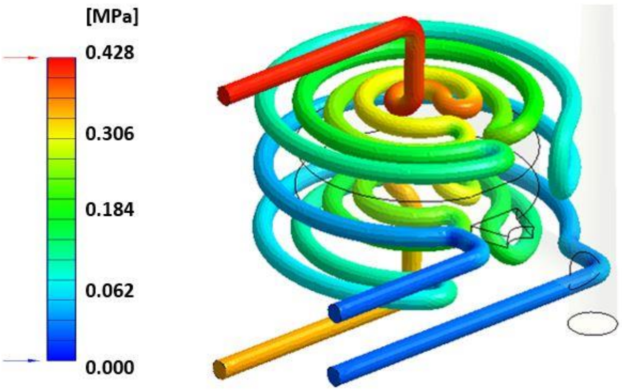

Figure 3. Visual pressure drop interpretation (Ra = 20 μm)

As can be seen in Fig. 3, the maximum value of the coolant pressure is 0.428 MPa.
Fig. 4 shows coolant pressure throughout the circuit with average channel roughness of 1.6 μm which is roughness usually made by conventional technology such as drilling. [Habib 2021]
For the analyses the surface roughness parameters were chosen with acceptance of studies mentioned above. [Babu 2022], [Habib 2021]

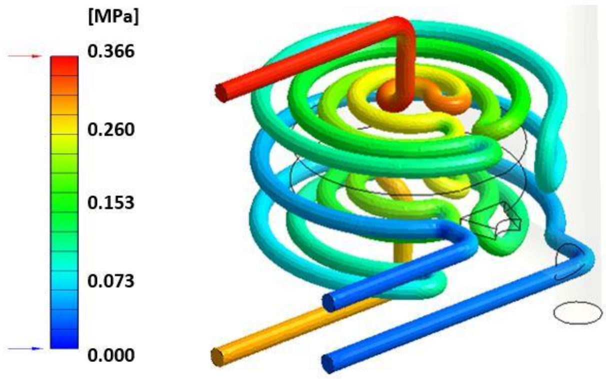

Figure 4. Visual pressure drop interpretation (Ra = 1.6 μm)

The maximum pressure value of the coolant in the channel with an average roughness of 1.6 μm is 0.366 MPa. This can be seen in Fig 4 and it's obvious that in this case, the maximum value is smaller than the maximum pressure value in Fig. 3.

Parameter	Ra = 20 μm	Ra = 1.6 μm
Pressure [MPa]	0.428	0.366
Reynolds nr. [-]	96 606	110 300
Flow velocity [cm/s]	605	691

Table 1. Analysis results summary

Tab. 1 shows results such as Reynolds nr. and flow velocity. Besides pressure, all the values are average values. As can be seen in Tab. 1 after the finishing process (Ra = 1.6 μm) values of Re and flow velocity are higher which may improve cooling efficiency.

3.2 Machine design

The ability to finish the internal surfaces of the conformal cooling channels is one of the specific requirements of the machine. However, during the finishing process, there is an operating pressure in the AFM media and this pressure is also transmitted to the frame of the machine. This fact must have been in mind at the time of design because the stiffness of the machine frame has to be sufficient enough to the applied pressure.

The whole concept is designed from individual subassemblies where every subassembly has its own purpose. All these subassemblies create one main assembly, and the scheme of this assembly is shown in Fig. 5.

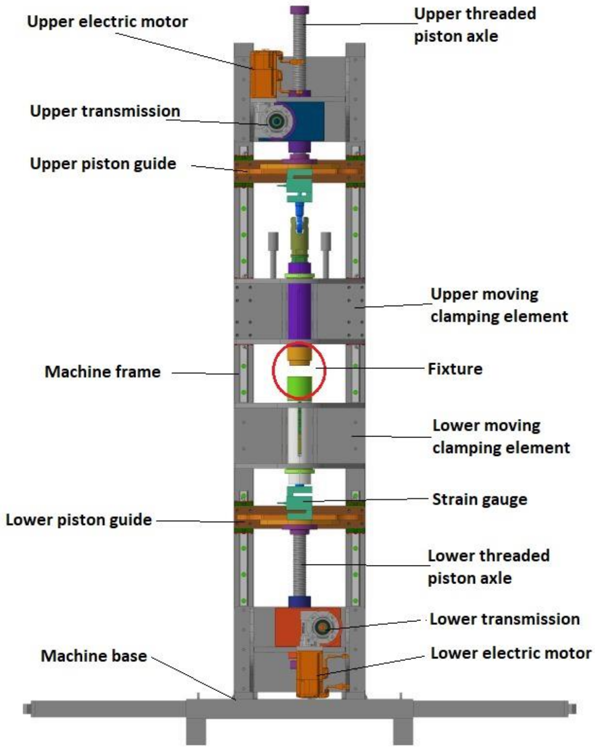

Figure 5. Assembly of the designed machine

It is important to mention the design of the upper moving clamping element. Due to simply insertion of the product upper clamping unit has to be movable to create space for inserting and manipulating the product.

The movement of the clamping element is generated by the same electric motor used for the working piston. Motion of the upper piston guide is transmitted by pulling rod (located on the back side of the machine) to the upper moving clamping element. The whole upper part of the machine is shown in Fig 6.

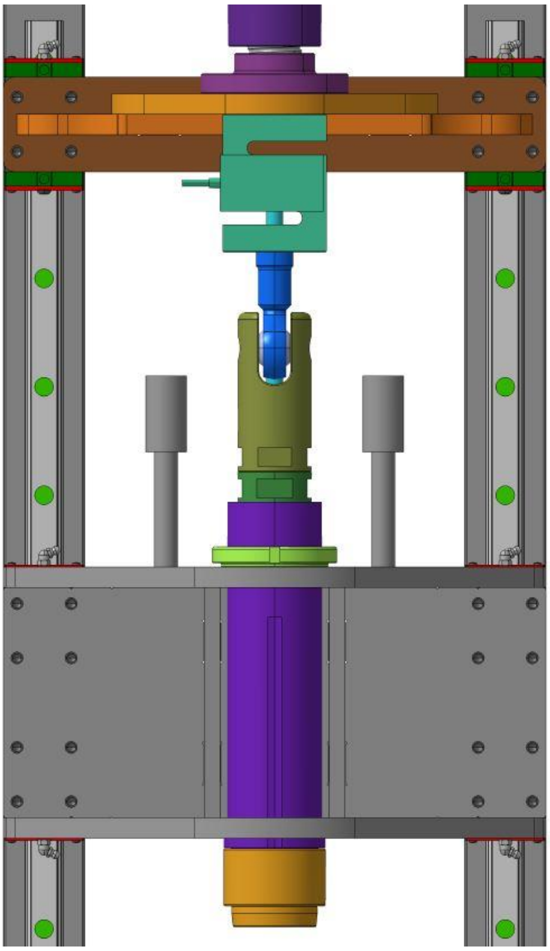

Figure 6. Upper subassembly of the designed machine

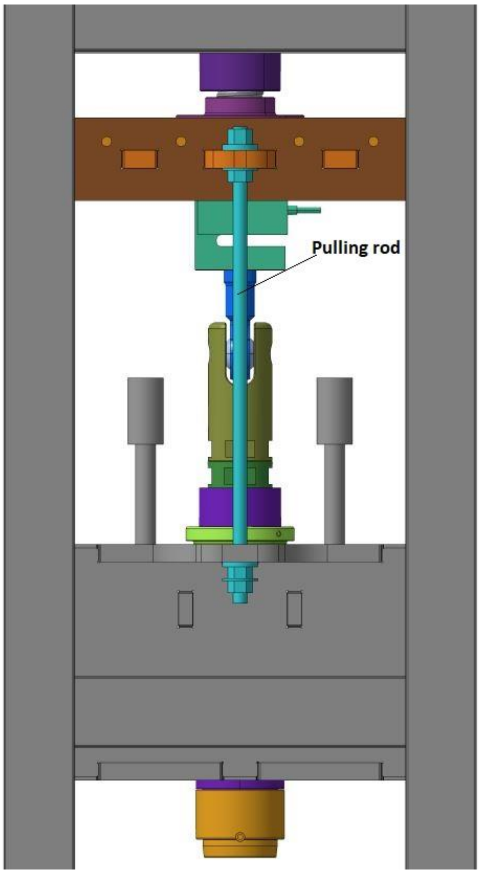

Figure 7. Visualization of the pulling rod

Fig. 7 shows the pulling rod located on the back of the machine. As mentioned earlier, the pulling rod transmits the movement of the upper cylinder guide to the clamping element by connection of these two parts as can be seen in Fig. 7.

On the other hand, the lower clamping element is stationary. This design of the lower clamping element helps to simplify the whole design of the machine and also helps with the stiffness of the machine frame. The stationary clamping element can be seen in Fig. 8.

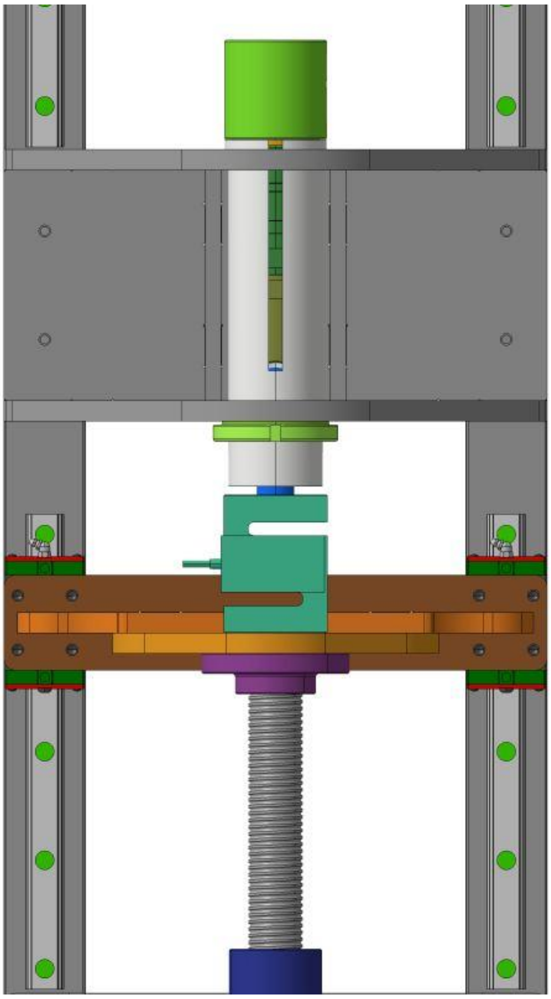

Figure 8. Lower subassembly of the designed machine

The machine is equipped with a cover for safety usage by the operator. The control panel is located on the left side of the machine. The mentioned covering and the control panel are shown in Fig. 9.

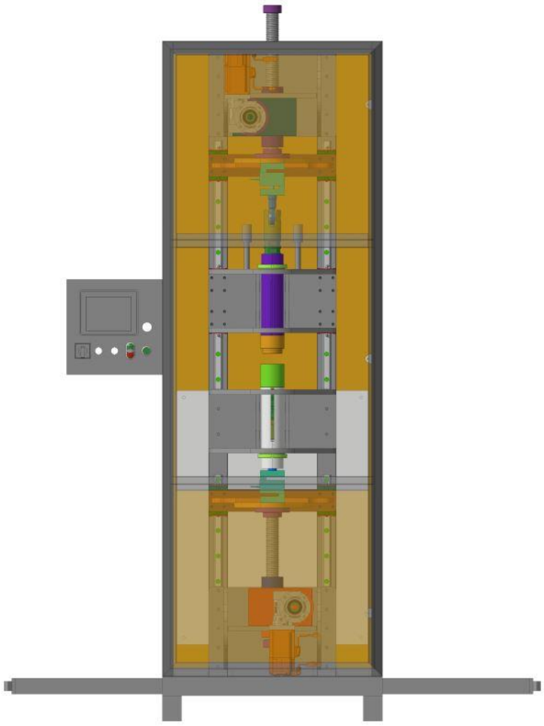

Figure 9. Complete visualization of the designed machine

3.3 Fixture design

Since the working cylinders are universal, it was necessary to design fixture for the test samples described in the experimental part of this paper. The fixture together with the test sample is shown in Fig. 10.

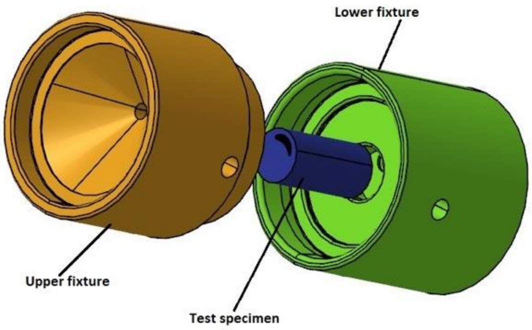

Figure 10. Exploded assembly of the test sample fixture, including the test sample

Dimensions of the test specimen mentioned in the experimental part are shown in Fig. 11. The test specimen is cylindrical and in the middle of the specimen is a helix-shaped hole simulating conformal cooling channel.

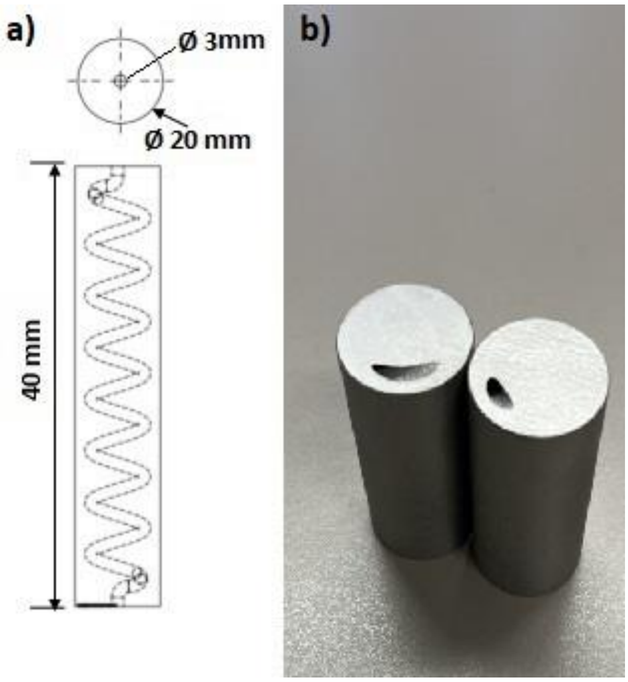

Figure 11. a) Dimensions of the test specimen, b) fabricated test specimen by DMLS

3.4 Structural analysis

All the parts under load caused by piston pressure have been subjected to strength analysis. Results of the analysis show that all designed parts of the machine frame can carry the necessary load of 25 000 N.

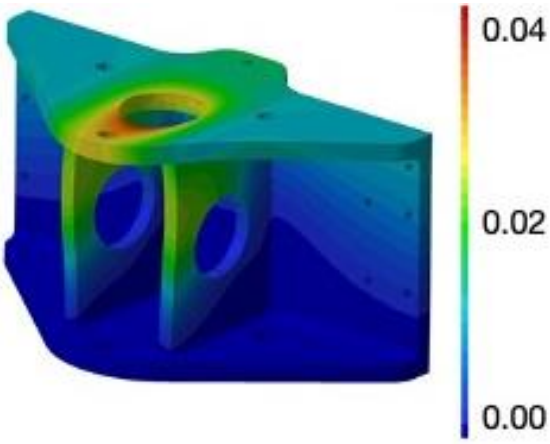

Figure 12. Displacement [mm] of the upper moving cylinder holder under load of 25 000 N

Fig. 12 shows the displacement of the upper moving cylinder holder and the maximum value is 0.04 mm.

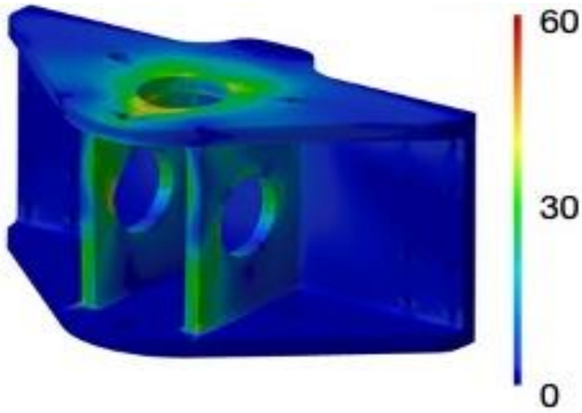

Figure 13. Von Mises stress [MPa] of the upper moving cylinder holder under load of 25 000 N

Fig. 13 shows Von Mises stress of the upper moving cylinder holder under the load of 25 000 N. The maximum value of this stress is 60 MPa.

4 DISCUSSION

The presented results show the evaluation of the cooling channels flow analysis (especially in the scope of pressure drop) as well as the design of the machine working on the AFM principle. A machine consists of multiple subassemblies when all together create one assembly. However, the great advantage of this design is its universality. Either test samples of the conformal cooling channels or real injection mold cavities used in the industry can be finished using this machine. This fact flexibly corresponds with the requirements for machining internal surfaces made by additive technology. All these aspects can help with future research in the area of conformal cooling in injection molding technology. Nevertheless, the functionality of the machine has to be done as the next research.

5 CONCLUSIONS

When designing an injection mold, there is always an effort to create it in the simplest and, consequently, cost-effective manner, with fewer production demands. Consequently, a significant number of molds are produced using traditional conventional techniques. However, there are cases where the use of additive manufacturing technology is necessary, especially in the context of core and cavity design. This solution is adopted due to the complexity of the product and the inability to ensure a uniform temperature field nearby the injected part surface, which is a fundamental prerequisite for eliminating deformation and residual stresses. As mentioned earlier, the complex shapes of injection mold components, together with the cooling system created using additive technologies, exhibit very low-quality surfaces. This, in the end, can cause numerous issues, such as increased demands on the cooling unit, blockage of cooling channels, poor heat transfer, or stress concentration, leading to reduced fatigue strength of the mold components. While the external surfaces can often be machined using conventional methods, the challenge arises in the context of cooling channel surfaces that cannot be conventionally machined, necessitating the adoption of an alternative technology. For these applications, the AFM technology appears to be a suitable method.
Therefore, this work is focused on the possibilities of finishing the surfaces of cooling channels in the context of conformal cooling. The study deals with CAE simulations and the design of

a machine on which cooling channels can be finished (the machine will operate based on AFM technology).

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