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Original Research

MODULAR INJECTION MOULD WITH A CONFORMAL COOLING CHANNEL FOR THE PRODUCTION OF HYDRAULIC FILTER HOUSINGS

MODUŁOWA FORMA WTRYSKOWA Z CHŁODZENIEM KONFORMALNYM DO WYTWARZANIA TYPOSZEREGU OBUDÓW FILTRÓW HYDRAULICZNYCH

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Abstract

The article presents the idea, design, construction, and implementation of a production technology for hydraulic filter housings using a modular injection mould. The annual demand for filters for specialised marine hydraulics systems by HYDROMEGA averages about 1,000 pieces. Two sizes of filters with the same housing connection dimensions are used. Due to the small scale of production, the modular injection mould was designed and manufactured to press two types of a polyamide housing. Changing the shape of a moulded part requires removing or installing modules that change the die and punch dimensions, which reduces the costs of production of a single tool compared to the costs of production of two separate tools. The mould design process was supported by the numerical analyses of operation and processes of plastic injection, cooling, moulded part shrinkage, and mould cavity deaeration. A mould and a series of moulded parts were manufactured and verified positively for dimensions and durability.

Keywords: injection mould, moulded part, modular mould, mould cooling

Streszczenie

W publikacji opisano koncepcję, proces projektowania, budowę i wynik wdrożenia technologii wytwarzania typoszeregu obudów filtrów hydraulicznych z zastosowaniem modułowej formy wtryskowej. Zapotrzebowanie na filtry do specjalistycznych systemów hydrauliki siłowej wykorzystywanych w gospodarce morskiej, budowanych przez firmę HYDROMEGA, wynosi do 1000 szt./rok. Stosowane są filtry w dwóch rozmiarach o takich samych wymiarach przyłączeniowych obudowy do pozostałych elementów instalacji. Ze względu na niewielką skalę produkcji zaprojektowano i wykonano modułową formę wtryskową do prasowania dwóch rodzajów obudowy z poliamidu. Zmiana kształtu wypraski wymaga usunięcia lub zainstalowania modułów zmieniających wymiary matrycy i stempla, co zmniejsza koszt wykonania oprzyrządowania w porównaniu z budową dwóch osobnych przyrządów. Projektowanie formy było wspomagane analizami numerycznymi działania oraz procesów wtrysku tworzywa, chłodzenia, skurczu wypraski i odpowietrzenia gniazda formującego. Wykonano formę i wyprodukowano serię wyprasek, które przeszły kontrolę wymiarową i wytrzymałościową z wynikiem pozytywnym.

Słowa kluczowe: forma wtryskowa, wypraska, forma modułowa, chłodzenie formy

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1. Introduction

Plastic injection moulding technology is commonly used to manufacture everyday products, toys, household appliances, medical devices, and machine parts. The combination of excellent material properties of modern plastics and composites (including good mechanical and sliding properties, lower density, good corrosion and chemical resistance) with the development of processing methods means that plastic parts are increasingly replacing expensive and labour-intensive metal parts. Compared to moulded metal parts which require labour-intensive machining, complex moulded parts with high dimensional accuracy and good condition of the surface can be obtained with well-planned part manufacturing processes and properly designed instruments. The decision to apply the injection moulding technology is made based on a financial calculation, in which the design and manufacture of special manufacturing equipment, i.e. an injection mould, constitutes a high cost. This means that the technology is most economically viable particularly in the case of batch and flow production. Another way to make the manufacturing process more cost-effective is to maximise performance by using multiple moulds and shorten the cycle time (i.e. the time of mould filling and moulded part cooling, with the latter accounting for up to 80% of the total cycle time). However, it must be remembered that the cycle time may not be shortened at random, as the mould cooling rate critically impacts on the product's dimensional accuracy stability, residual stresses (in the plastic and in the components of the mould), and on the product's surface quality and smoothness (Sołtysik & Moczała, 2020; Wang et al., 2023) The design of the cooling circuit and its distance relative to the mould cavity have a great impact on the efficiency of mould cooling and on the course of the heat transfer from the moulded part (Arman & Lazoglu, 2023; Hassan et al., 2010; Muszyński et al., 2016.) Moulds intended for the manufacture of parts of products with complex shapes in which the circulation of the coolant through drilled channels does not ensure even cooling of the moulded part are particularly problematic. The development of 3D printing technology, namely selective laser melting technology (Strzelec, 2020), allows the design and manufacture of mould components with optimised cooling channels adjusted to the shape of the moulding surfaces (Dimla & Miani 2005; Gotlih et al., 2023; Kazmer 2007; Strzelec 2020) On the other hand, computer-aided design tools enable the development of spatial models of products and moulds used for their manufacture, as well as simulation of the processes of mould filling with plastic (Heneczkowski, 2016) and heat flow at each stage of the production cycle. A special modular injection mould for batch production of oil filter housings used in large hydraulics systems was designed and developed at the Łukasiewicz – Institute for Sustainable Technologies. The work involved the development and implementation of a new polyamide filter housing to replace costly housings made of aluminium alloys.

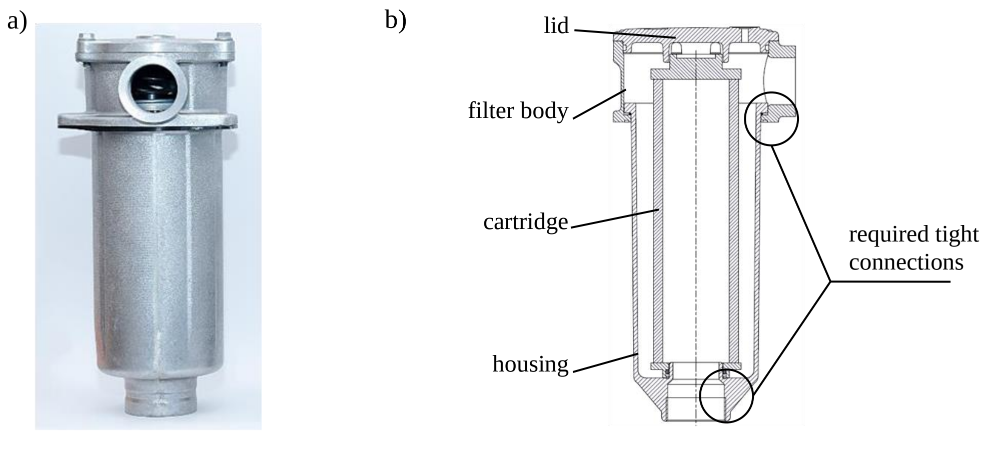

Fig. 1. Oil filter: a) with an aluminium housing; b) with a housing made of pressed polyamide

Figure 1 presents an image of a filter with a housing made of cast aluminium alloy and a technical drawing of a filter with a housing made of pressed plastic. Both filters (Figure 1) have the same structure and contain identical filter cartridges. However, they differ in terms of shape and the material of which the housing is made. Due to the conditions in which the hydraulics system operates, the housing must meet the following technical requirements: the working pressure of the hydraulic agent – 0.2 MPa; the maximum non-destructive pressure – 1 MPa; and the operating temperature between -25ºC and +80ºC. The requirements concerning the dimensional accuracy of the moulded part stem from the necessity to ensure connection between the filter housing and the body, and between the body and the cartridge (Figure 1b). The type of the plastic to be used (PA6 polyamide) was agreed and the technical documentation of the finished product was developed in consultation with the industrial client (HYDROMEGA, a Polish company based in Gdynia). The authors assumed that the design of the instrumentation would allow easy modification of the height of the moulded part, and thus enable the production of two sizes of housings (RF100 and RF150), without the need to build two separate injection moulds.

The PA6 polyamide[1] has high tensile strength and stiffness at high temperature, good resistance to hydrocarbons, high humidity absorption, moulding shrinkage of approximately 2%, very good flow properties in a liquid state, and a high solidification rate during injection moulding. The thickness of the moulded part walls of minimum 6 mm, resulting from the strength requirements, and the large weight of about 1,350 g called for an in-depth analysis of thermal processes occurring at the time of pressing and for a proper design of the mould cooling system [10], and efficiently cooled to achieve favourable production cycle time.

2. Calculations and mould design

In the design of the mould, the capabilities of modelling the structure and simulating thermal and flow processes in a virtual environment (Jaskulski, 2020; Zbrowski et al., 2012; Zbrowski et al. 2012) were used to the greatest extent possible, to eliminate costly and labour-intensive modifications and corrections at the test run stage. The authors used Autodesk INVENTOR Professional to build a 3D model of the injection mould (Figure 2), which is composed of a punch and die with replaceable modules that can be removed from the mould to change the shape of the moulded part. The bigger RF150 filter housing is pressed in the fully configured mould (Figure 2a) and the smaller RF100 filter housing – after the replaceable modules have been removed (Figure 2b).

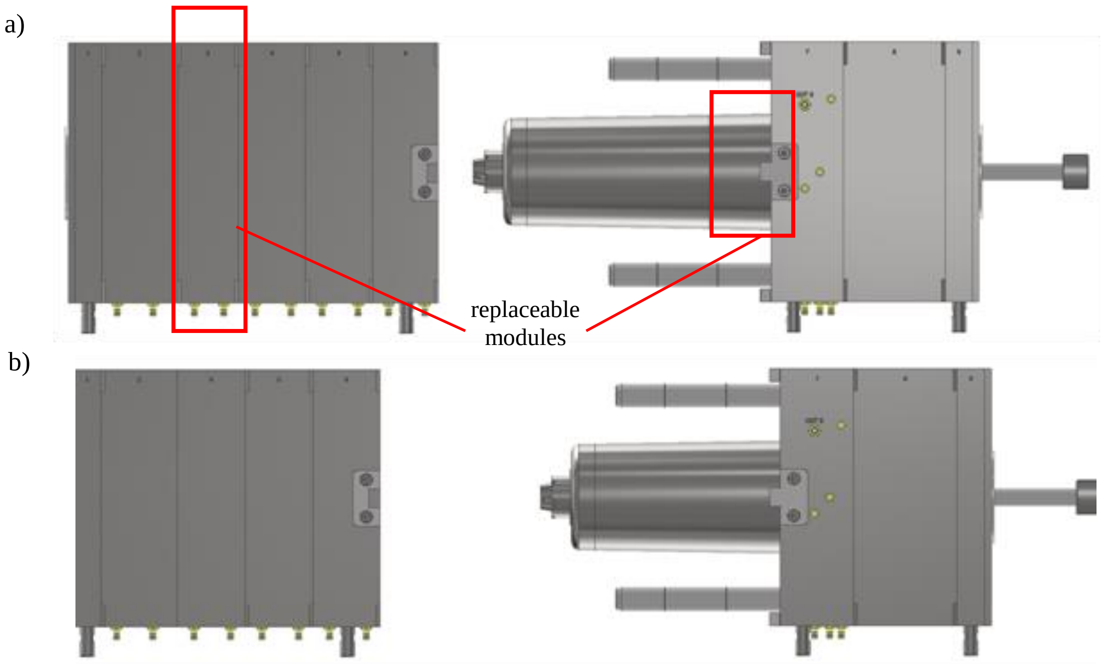

Fig. 2. 3D model of the modular mould: a) configuration used to make RF150 filter housings; b) configuration used to make RF100 filter housings

In the mould, a conformal cooling system with cooling channels evenly distributed near the moulding cavity of the die and outer surface of the punch was used (Figure 3).

The design of such a cooling system, using classic processing methods, was facilitated by the axisymmetric shape of the moulded part and the modular structure of the mould. In the case of the punch,

[1] Grupa Azoty, Tarnamid T-27 MCS 850 Poliamid 6 (PA6) – product data sheet

removing the replaceable modules (Figure 2) in no way modifies cooling channels, and in the case of the die, the removed module has its own cooling circuit connected separately to the chiller. Such a system ensures even cooling of the moulded part and effective control of the heat transfer process.

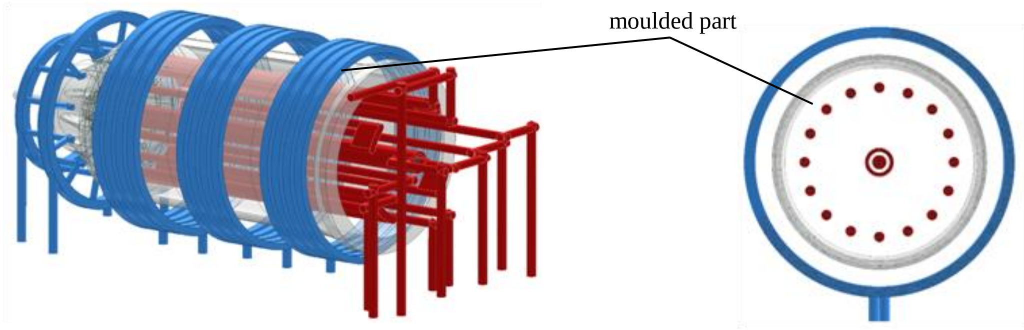

Fig. 3. 3D model of mould cooling: blue – cooling of the die; red – cooling of the punch

Numerical calculations of the injection moulding process of the designed product were done in Autodesk Moldflow Insight Ultimate 2021.2, which is based on the finite element method and allowed simulation of the cavity filling process, to obtain information about pressure and temperature distribution in the injection mould, and deformation of the injection moulded parts. The simulations were carried out for a 3D mesh of the housing. They included the filling, pressing, and cooling phases as well as the determination of the deformation of the moulded part as a result of the anisotropic plastic shrinkage. All calculations were made for PA6, Tarnamid T27.

Given the conformal cooling system used in the mould, a 3D cooling simulation module was required (Frenkler & Zawistowski, 1984; Jaskulski, 2020). It differs from the basic module in that it uses a 3D mesh instead of 1D beams to represent cooling channels, which allows the study of more complex flows. The 3D model of the injection mould contained 5.8 million tetrahedral elements, the cooling system – 2.2 million, and the moulded part – 0.8 million. The analysis of the injection mould cooling assumed averaging the mould temperature distribution during the cycle. The software used Fourier equation to determine the temperature distribution in the injection mould. On the other hand, the filling of the cavity using a 3D mesh as well as the injection mould cooling process using the conformal module were based on a Navier-Stokes equation.

Simulations were carried out for the following carefully calculated parameters:

- the temperature of the plastic: 270°C;
- the mould opening time: 5 s;
- the full cycle time (injection, packing, cooling): 90 s;
- the cavity filling time (calculated automatically): 8 s;
- the V/P-switch over (based on the value of pressure changes in the cavity, the algorithm automatically determines when to switch from the injection phase to the pressing phase in order to avoid a drastic pressure change as a result of uneven filling of the cavity): 99.9%;
- the packing profile: 80% of the maximum injection pressure for 10 s.

Figure 4 presents the result of the cavity filling simulation. The simulation showed the order in which the mould was filled and allowed the prediction of the filling time and evaluation of the correctness of the design of the channels through which the plastic is injected. The resulting mould filling time met the requirements of the adopted technological cycle. Figure 5 presents the result of the simulation of the coolant temperature distribution in individual circuits intended to transfer heat from the mould. The simulation allowed the assessment of the effectiveness and evenness of the moulded part cooling. The resulting coolant temperature distribution, the values of which were similar for each section, indicates the correct selection of cooling channel geometry and fluid flows. Figure 6 presents the plastic temperature distribution at the time of injection. The simulation enabled the identification of areas in which the temperature of the plastic could significantly increase as a result of, among other things, air compression in the closed parts of the mould cavity separated at the time of injection. The detection of such areas through simulation enabled the authors to introduce at the design stage channels to remove air from the mould during the plastic injection.

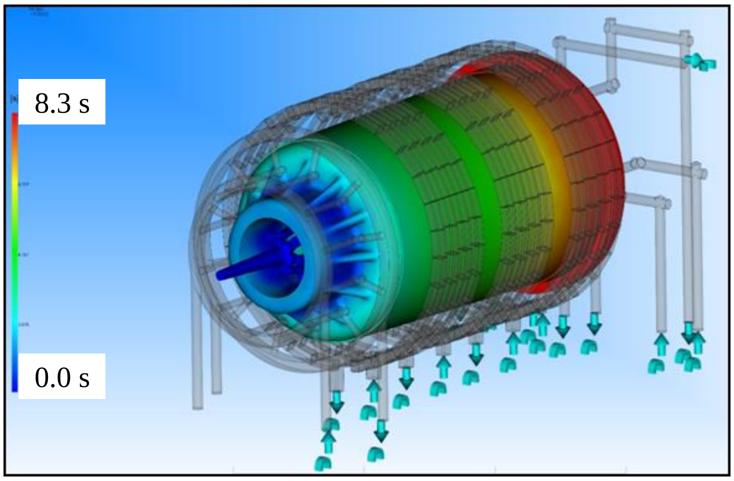

Fig. 4. Simulation of mould cavity filling as a function of time

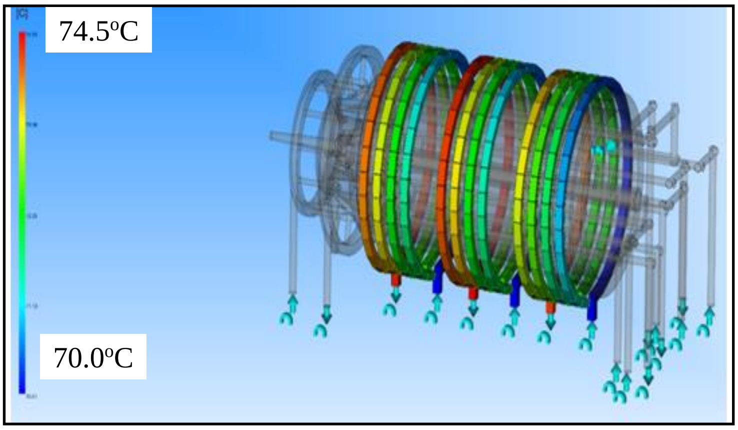

Fig. 5. Simulation of the cooling liquid temperature distribution in individual sections of the die

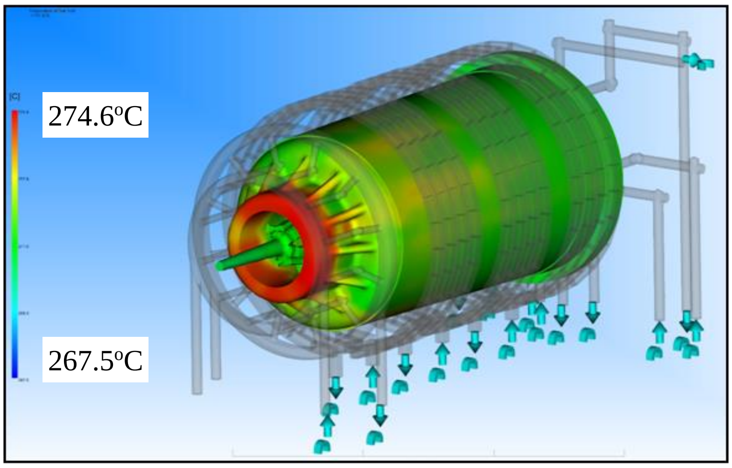

Fig. 6. Simulation of the plastic temperature distribution during the injection phase

Based on the results of calculations and numerical simulations presented in Figures 4, 5, and 6, the authors developed the technical documentation of the mould. All structural solutions were provisionally verified in the form of virtual 3D models, kinematic simulations, and on the basis of the thermal and flow processes during mould operation.

3. Manufacture of the injection mould and analysis of the pressing of the housing

The housing (Figure 7) was made based on the developed design documentation. The injection mould elements were made of dispersion-strengthened M261 BÖHLER (X13NiCuAlS4-1-1)[2] steel intended for such applications. The structural elements of the mould were made of tempered 40CrMnMoS86[3] steel supplied by FCPK Bytów in the form of finished machined semi-finished plates (Feldhausen et al., 2023). Additionally, typical structural elements (pillars, bushings, and locks) offered by FCPK Bytów were also used. The total weight of the mould amounted to 723 kg. In the housing there are areas which require a high degree of manufacturing precision, and which are important for the installation of the housing in the metal filter body and for the tightness of the hydraulic connections. Moulding surfaces were intentionally cut oversize to allow for dimensional changes after the verification of the dimensions of moulded parts and actual part shrinkage.

a) b)

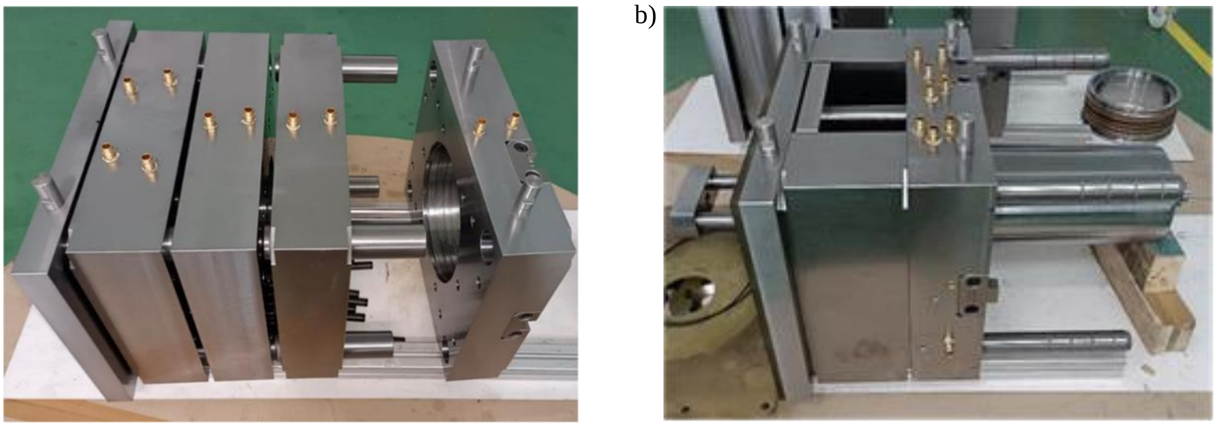

Fig. 7. Modular injection mould with a conformal cooling channel for the production of hydraulic filter housings: a) die (during assembly); b) punch

The technological performance tests of the mould involved producing a batch of several dozen of RF100 and RF150 filter housings. A TEDERIC TRX-650/8730 moulding machine was used for testing. During tests, the parameters of the injection moulding process (Table 1) were defined to achieve properly shaped and sized products. Images presented in Figure 8 show an example of a properly moulded part with visible directions of the plastic flow.

Table 1. Plastic injection parameters in the process of housing pressing

Parameter name	Calculated (assumed) values	Real values determined during tests	Unit
Injection temperature	251.1	250–270	[ºC]
Injection time	7.198	5	[s]
Cycle time	81.96	90	[s]
Injection pressure	131.66	160	[bar]
Clamp force (moulded part)	410	5,000	[kN]
Clamp force (mould)	3,140		

[2] https://www.bohler.pl/pl/products/m261/

[3] https://proplastica.pl/pl/korpusy-do-form/

a) b) c)

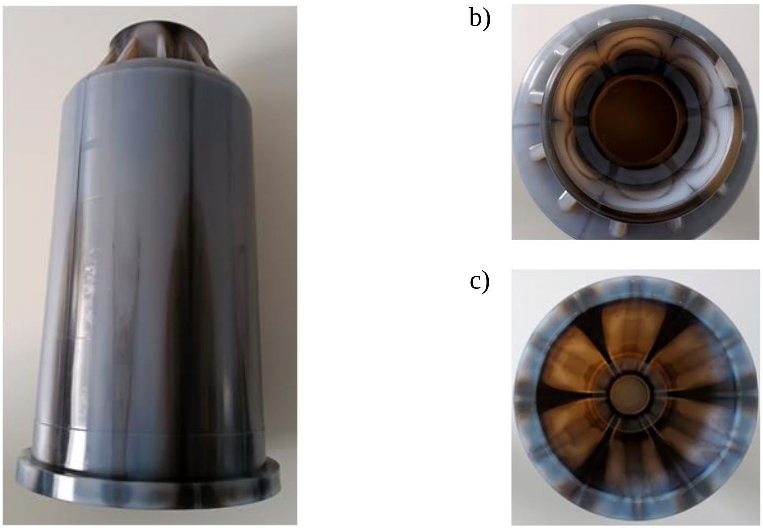

Fig. 8. Moulded filter housing: a) side view; b) external view, and c) internal view (plastic flow directions visible)

T27 polyamide[4] has high humidity absorption (2.5–2.8%) impacting on the dimensions of the product – they increase when humidity is absorbed. To prevent uncontrolled and long-term humidity absorption, once removed from the mould, moulded parts are immediately dipped in a hot water bath (60–80ºC) for 1–2 h. They achieve the desired stable end shape after 24 hours. The trial batch of moulded parts made as described above was verified for dimensional accuracy (Table 2). The authors also calculated the real total plastic shrinkage value, which averaged between 0.9% and 1.14%, with the value declared by the manufacturer between 1.0% and 3.0%.

Table 2. Results of the dimensional inspection of a batch of 30 moulded parts

Dimension	Requirements			Dimensions of moulded parts		
	Nominal [mm]	**Deviations [mm]**		**Minimum [mm]**	**Maximum [mm]**	**Average [mm]**
Moulded part height	325	-1.8	0.0	323.63	324.96	324.65
Mounting diameter of the housing	165	-0.9	-0.2	164.22	164.82	164.35
Hydraulic seal diameter	68	-0.3	0.3	67.74	68.23	67.78

During technological performance tests, two dimensions of the moulded parts (i.e. diameters given in Table 2) were found to be outside the dimensional tolerance. To eliminate this problem and to adapt the shape to the dimensional requirements, the excess material was removed. The authors also found thermal discolouration ("burns") on the bottom surface of the moulded parts resulting from the insufficient deaeration of the cavity closed by the injected plastic. Additional deaeration channels were made on the contact surface of the end die modules.

Strength tests were performed on the manufactured filter housings and they involved the application of internal pressure to the hydraulic connection of a complete hydraulic filter. Pressure was applied to the inlet connection of the filter, with the outlet connection covered. During the test, pressure equal to the maximum working pressure (2 bar) and to the maximum non-destructive pressure (10 bar) was applied and the value of the destructive pressure was examined. The destructive load averaged 30 bar and its application resulted in the destruction of the aluminium body and lid of the filter (Figure 9). The described technological solution is now used for batch production of housings of filters by HYDROMEGA.

[4] Grupa Azoty, Tarnamid T-27 MCS 850 Poliamid 6 (PA6) – product data sheet.

a) b)

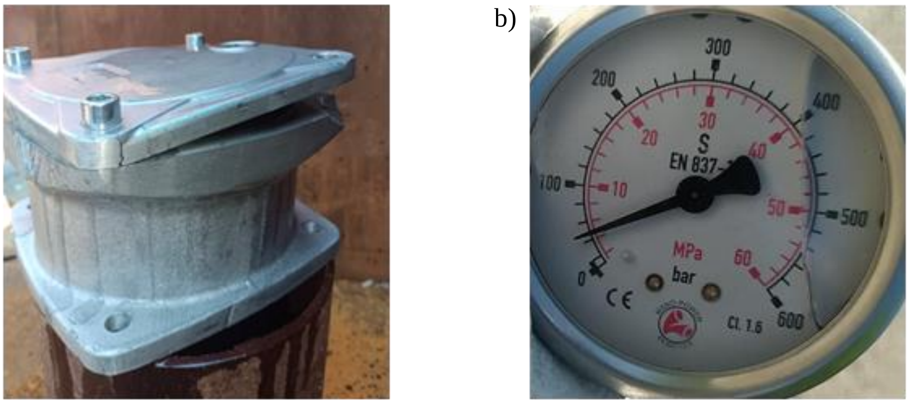

Fig. 9. Result of the pressure destructive test of the filter housing: a) image of the destruction of the housing, b) recorded value of the destructive pressure

4. Summary

The modular injection mould for the production of two types of large hydraulic filter housings was designed and developed at the Łukasiewicz – Institute for Sustainable Technologies in Radom, Poland. Changing the shape of the moulded part required removing or installing a replaceable structural module, which reduced the cost of manufacture and enabled cost-effective batch production. The mould uses a conformal cooling system that streamlines the heat transfer process and enables repetitive production of accurately shaped and sized polyamide moulded parts. In the mould design process, all available capabilities of structural modelling and simulation of thermal and flow processes in a virtual environment were used to eliminate costly and time-consuming corrections at the implementation stage. The design methodology used allowed direct and efficient implementation of the mould after the introduction of the planned adjustments to the moulding elements in compliance with tight dimensional requirements. The described technological solution is now used for batch production of housings of hydraulic filters by HYDROMEGA, a Gdynia-based company that commissioned the work described in the article.

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