CALCULATION OF FIXING ELEMENT OF METAL-POLYMERIC MOLD-FORMING SURFACE OF MOLD IN METAL CAGE

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***Abstract*—The article describes a technique to calculate the reliability of a fixing element of a metal-polymer insert of a combined mold for casting products from thermoplastics. To do this, the stress-strain state of the metal-polymer fixing element is calculated by the force of ejection. The characteristics of ejection systems intended for removing molded products from a mold are given. The scheme for removing the product from the punch of a metal-metal-polymer mold, as well as the pressure distribution scheme for the metal-polymeric part of the die punch of the shrink-formed product, is shown. An algorithm is given for calculating the ejection force required to remove a mold from a punch. A special case of the ejection force for an "asterisk" product is calculated. The technique for obtaining the initial data for the calculation is described, in particular, the measurement of the change in the geometry of the article, subject to shrinkage of its material, was carried out using CAD simulation. By the example of the metal-polymer forming part of the mold for the star-shaped product, the reliability of the metal-fixing element in the cage was tested using finite element analysis. Calculations of the stress state of the metal-polymer insert for the "star" product are given. The article specifies a particular problem of finding stress concentrators in a metal-polymer insert, which allows designers to decide on the optimal shape and location of the fixing element. Finite element analysis is carried out using a free application FreeCAD, which enables one to accomplish the task. A step-by-step calculation algorithm in FreeCAD is presented with the description of built-in modules used in the calculations. A technique is proposed to calculate the reliability of a fixing element of a metal-polymer part of a mold for any design of a metal-polymer insert, provided that the design model is parameterized.**

Keywords—mold; metal-polymer; ejection force; form-forming; fixing element; finite element analysis.

I. INTRODUCTION

When designing molds to cast thermoplastics, one of the main tasks to be solved by the designer is to ensure an effective way to remove a molded product from the mold cavity. After being formed, the product usually remains in a movable part of the mold - the punch, on which side the elements of the ejection system of the mold are most often located. Ejection systems are divided into mechanical, pneumatic or combined. The technology [1, 2] developed by the authors focuses on manufacturing mold-forming parts of molds for casting products from thermoplastics with the mechanical ejection system to be applied. Its main elements ejecting and dropping the product are special ejectors or push plates. As a rule, the force generated by ejecting devices of a die casting machine and displayed to the ejectors of the mold to remove the product is sufficiently large. So the main criterion to be accounted for to design a metal mold is to ensure the distribution of forces so that to protect the product from losing its shape and size (no traces of ejectors on the product, no distortion during removal that can entail product deformation). Techniques and recommendations to construct ejection systems are described in [3, 4, 5].

The developed technological process for manufacturing metal-metal-polymer molding parts of molds implies the presence of a metal-polymer forming part in a metal cage [1, 2]. Caused by the friction between a cast product and a metal-polymeric forming element, ejection forces P_B are displayed to the metal-polymer part of a forming element, so it is important to ensure a reliable fixation of a metal-polymeric part in the metal cage of a forming element. The volumetric shrinkage of the metal polymer makes up 0.01% [6] and can not affect the dimensional accuracy or some relative displacement of surfaces of the forming part. However, a shrink-formed gap between the metal cage and the metal-polymer mold-forming part leads to the reduction of friction between them, which necessarily requires some special fixing elements referred to locking hooks in the metal-polymer forming part.

II. METHODS

To ensure reliable fixation of the metal-polymer mold-forming part in the metal cage, there are undercuts poured with liquid metal-polymer that after curing forms a locking hook (pos.5, Fig. 1).

The ejection force for products like bushings and those of rectangular shape that shrink on the punch is calculated by the normal stress and friction coefficient (1) [7].

$$P_E = f * \rho_A * S_P,\ Pa/m^2 \qquad (1)$$

where f is the coefficient of friction; ρ_A is the pressure in the gap between the mold and the punch, Pa/m^2; S_P is the surface area of the punch, m^2.

The coefficient of friction between metal-polymer and polymer is affected by the surface roughness of the mold-forming part. Metal-polymer surface of the mold has roughness parameters inherited from the master model used to produce the mold-forming part [8]. Besides, according to the developed method, the master-model is produced on a 3D printer using SLA technology [9] and has a surface roughness equal to *Ra* 0.20 μm. Accordingly, the coefficient of friction between the metal polymer and polypropylene for the surface roughness of the metal polymer *Ra* 0.20 μm is equal to f = 0.47 [7]. The static coefficient of friction can be reduced by applying lubricating materials and the temperature of mold cavity walls. The higher the temperature, the greater the plasticity of the product and the higher the risk of defects arising during the ejection.

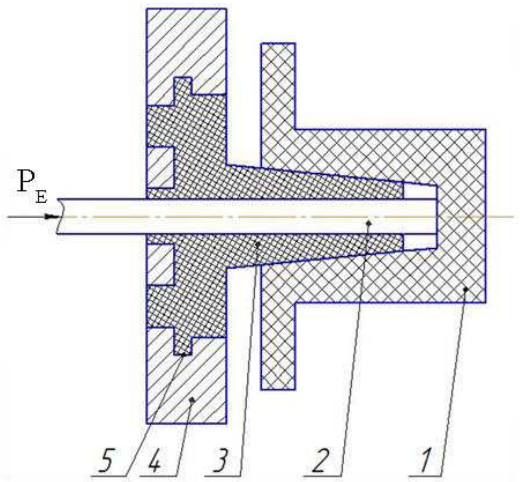

Fig. 1. Scheme of removal of the product from the combined metal-metal-polymer molding part of the mold: 1 – product; 2 – pusher; 3 – metal-polymer part of the mold-forming part of the mold (punch); 4 – metal case; 5 – undercut in a metal plate / Locking hook for metal-polymer

Owing to their nature, products like bushings require the most significant forces while being removed. Let us consider the calculation of the ejection force by the example of bushing.

Shrinkage of material, the article is made of, exerts pressure on the punch, which leads to an increase in internal stresses in the product that form a force normal to the punch surface. When removing the product from the punch, the accumulated stresses are also removed and lead to the reduction in the inner diameter of the bushing. This change in the diameter (2) can be measured in Fig. 2

$$\Delta d_E = (d_P - d_b)/ d_P,\ m \qquad (2)$$

where d_P is the diameter of the punch, m; d_b is the diameter of the bushing after its removal, m.

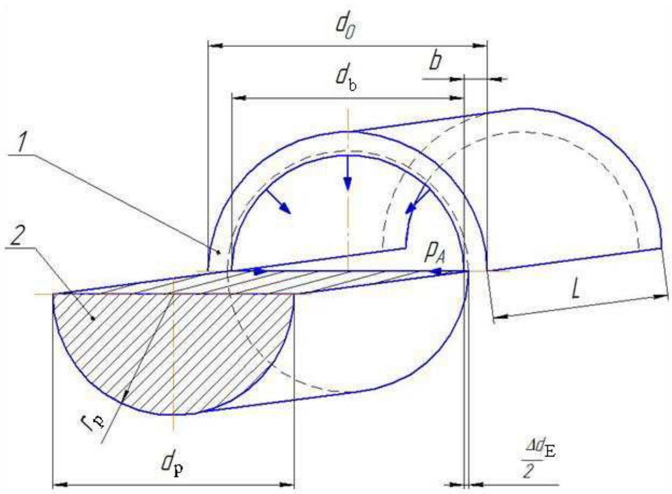

Fig. 2. Scheme of the direction of pressure on the punch 2 of the shrink-formed material of article 1.

where d_0 is the bushing outside diameter, m;

L is the length of product and punch contact area, m;

r_p is the punch radius, m;

b is the wall thickness, m.

With Hooke's law, it is possible to calculate the stress arising due to the deformation of the article (3):

$$\sigma_\varphi = \Delta d_E * E(T),\ Pa/m^2 \qquad (3)$$

where E(T) is Young's modulus of material at temperature T.

The expression for calculating ρ_A (4,5) looks like

$$\rho_A = \sigma_\varphi * ((d_0 - d_b)/ d_P),\ Pa \qquad (4)$$

or

$$\rho_r = \sigma_\varphi * r_p/b = \Delta d_E * E(T) * r_p/ b,\ Pa \qquad (5)$$

The required ejection force associated with static friction f, needed to start the removal of the product (6):

$$F_{req} = f * \Delta d_E * E(T) * r_p * d_p * \pi * L/ b,\ N \qquad (6)$$

Production experience shows that to ensure the ejection of products from molds, the ejection force is increased by a safety factor of 15% [10].

To calculate the force needed to remove the product from the mold, it is also necessary to take into account frictional forces in the ejection system, but within the framework of the problem being solved here, given that gaps between the metal-polymer forming part and pushers are equal to 0.02 mm, they can be neglected. As a consequence, the ejection force for a product with n mold-forming cavities is obtained from the equation:

$$F_d=1.15\cdot\sum^{n}_{i-1}\cdot F_{req\,i}\ ,\ N \qquad (7)$$

Having derived the expression for calculating ejection force, it is possible to proceed to calculating geometric parameters of the undercut serving as a locking hook. It is obvious that the metal-polymer fixing element formed by the corresponding undercut should withstand the ejection force.

Using the expression (7), let us calculate the force exerted on the metal-polymeric fixing element of the combined mold for the "asterisk" article (Drawing of the "asterisk" Z17 CS 3270.03.03.00.007).

Using CAD modeling tools, let us calculate the surface area of each element of the product across which friction occurs. If the material of the product is polypropylene, its volumetric shrinkage (up to 2.5%) and the temperature of removal are known, it is possible to calculate the diameter of the product after its removal from the mold. Fig. 3 and 4 show the modeling of product shrinkage and the measurement of the enclosing dimensions in CAD application.

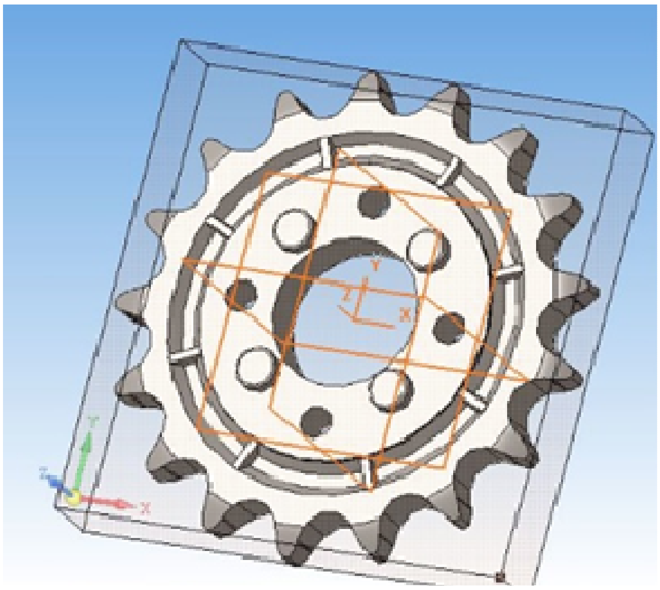

Fig. 3. Results of the geometric modeling of part shrinkage

Fig. 4. Results of geometric modeling, size measurement after shrinkage

The initial values for calculation will be depicted in Table 1. Young's modulus for polypropylene is 1500 MPa [11].

TABLE I. DATA FOR CALCULATING THE EJECTION FORCE FOR ASTERISK

Friction element	**Bore Nominal value Ø6.2 mm**	**Bore Nominal value Ø28.5 mm**	**Groove Nominal value Ø69.68 mm**
Number of elements, pcs.	4	1	1
Surface area of a friction element S_P, m^2.	0.000093	0.000425	0.000514
Diameter change of the product Δd_E, m.	0.00016	0.00071	0.00175
Radius of the forming punch r_p, m.	0.0031	0.01425	0.03484
Wall width of the product b, m.	0.014	0.033	0.012
Calculated pressure ρ_r, MPa/m^2.	$212\cdot 10^{-6}$	$460\cdot 10^{-6}$	$7621\cdot 10^{-6}$
Break-off force F_{req}, MPa.	$9.26\cdot 10^{-9}$	$91.88\cdot 10^{-9}$	$184.11\cdot 10^{-9}$

Let us calculate the ejection force

$$F_d=328*10^{-9},\ MPa$$

Fig. 5 shows the metal-polymer part of the mold-forming part of the mold that has a structural element that ensures the fixing of the metal-polymer part in the metal cage. Following the recommendations [12], the diameter of the well in the metal cage for the "asterisk" product shall be 1 cm larger than the outer diameter of the product and will be equal to Ø104mm. To provide technological effectiveness of the groove that forms the fixing element, it has a diameter of 108 mm and its height is 2 mm.

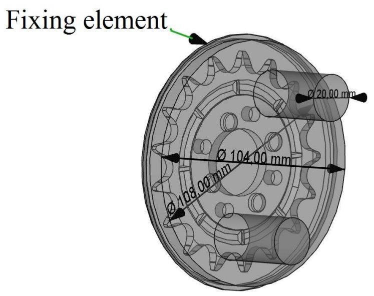

Fig. 5. The metal-polymer part of the mold-forming part of the mold

III. Discussions.

The definite value of maximum ejection force makes it possible to justify the minimum assignable size of the fixing element for the metal-polymer molding in the cage. For the designer, it is of interest to determine the exact area of the metal-polymer insert having maximum mechanical stresses, as in this case, it is possible to change structural geometric elements without full-scale tests. These studies can be performed within finite element analysis. The authors used a free application FreeCAD 0.17 that has a built-in FEM module. The results of modeling the stress-strain state of the metal-polymer insert are presented in Fig. 6.

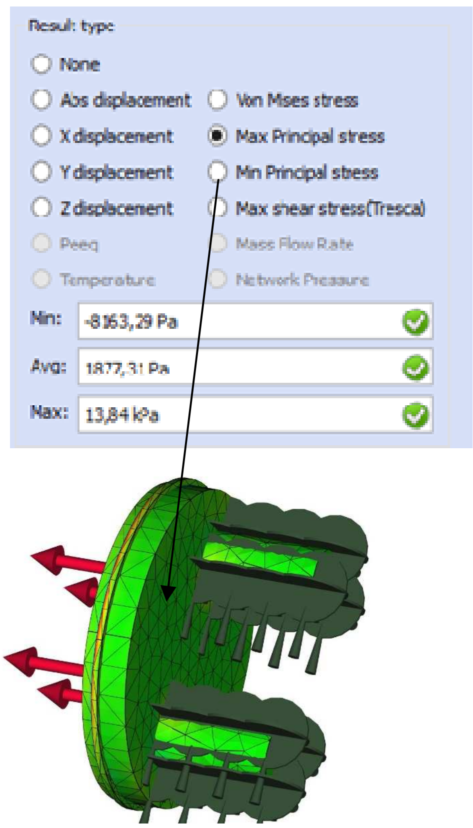

Fig. 6. Results of modeling the stress-strain state of a metal-polymer insert.

The estimated values and locations of stress concentrators enable one to change the design of the insert or make sure that strength of the insert is quite sufficient, which makes it possible to use it.

The use of FEM methods for solving stress-strain problems allows obtaining reliable results provided that the problem is properly stated and initial conditions are imposed in the form of constraints and loads, and a finite element grid is designed corresponding to the geometry of the object under study. In order to address challenges similar to those mentioned above, we will describe actions geared to solve the described problem in more detail.

The first step to solve the problem is to generate a finite element grid of the object. As a grid generator, the authors used *gmesh* installed with the FreeCAD package. In this case, the minimum element size assigned is no more than the minimum size of the geometric element of the object, as shown in Fig. 1. This element is the width of the protrusion in undercuts 5 of the metal cage of the mold-forming part. For the model under study, it is equal to 2 mm. Fig. 7 shows the purpose of the dimensions of the model elements in the grid generator *gmesh*. With FreeCAD, it is possible to use another grid generator, *Netgen* that enables one to overlay the adaptive grid.

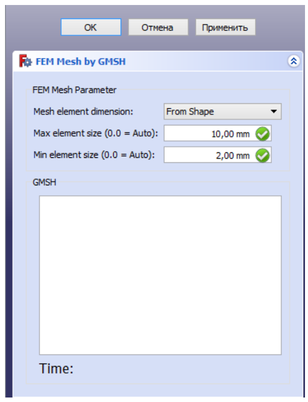

Fig. 7. Dialog box for assigning the minimum and maximum size of grid elements

The next step is to assign material properties, as shown in Fig. 8, which is important for obtaining reliable results of finite element analysis.

The values of those material properties necessary to perform calculations are entered in the form fields shown in Fig. 8. They include material density, Young's modulus of elasticity, Poisson's ratio, and heat transfer. As there is no material with the specified characteristics in the database of the package, the authors used the information given in [13, 14]. If it is difficult to obtain material characteristics, one can surf the Internet to find the database that can be called by choosing *MatWeb database* from the form in Fig. 8.

As it was described above, the load or force moving the metal-polymer insert in the cage is applied to its working surface, which in the finite element analysis is represented as a force applied to the face [15], which is shown in Fig. 9.

There are two constraints on the metal-polymer insert: protrusion surface constraint fixing this surface with the limit of six degrees of freedom, and constraints on the protrusions entering the wells, with four degrees of freedom, which allow the insert model to move along the *Z* axis and rotate on the same axis, as shown in Fig. 9.

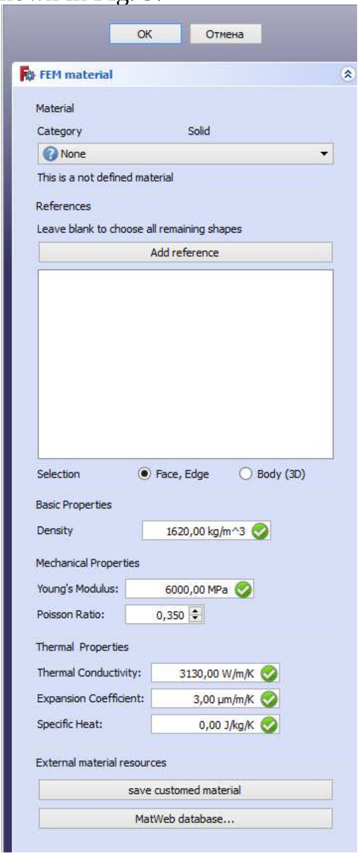

Fig. 8. Dialog box for assigning material properties

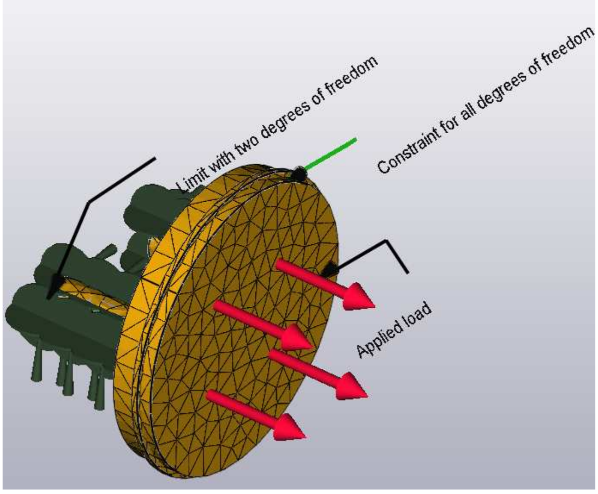

Fig. 9. The finite element grid, the load and the constraints of the model.

Following the process called preprocessing [16, 17], the Project Tree finite element analysis is formed, presented in Fig.10.

The software package uses Calculix as a calculator. It is possible to use both a built-in and plug-in calculator. The authors used Calculix v.2.12; the postprocessed results of its work are given in the paper.

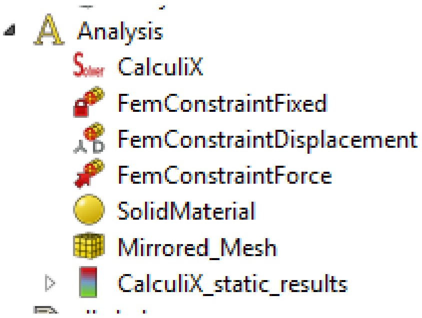

Fig. 10. Project Tree finite element analysis

FreeCAD is a parametric modeling package, which means that all project elements are linked together through geometric parameters. For example, the thickness of the protrusion for the undercut can be changed on a geometric model with the finite element grid for the geometric model to be changed as well. This results in the calculations aimed to acquire other values. The postprocessed results are given in Fig.11 in the form of finite element grid, with the diameter of the protrusion to be changed by 12 mm, the thickness to be increased from 2 mm to 4 mm, and the force to be increased 10 times.

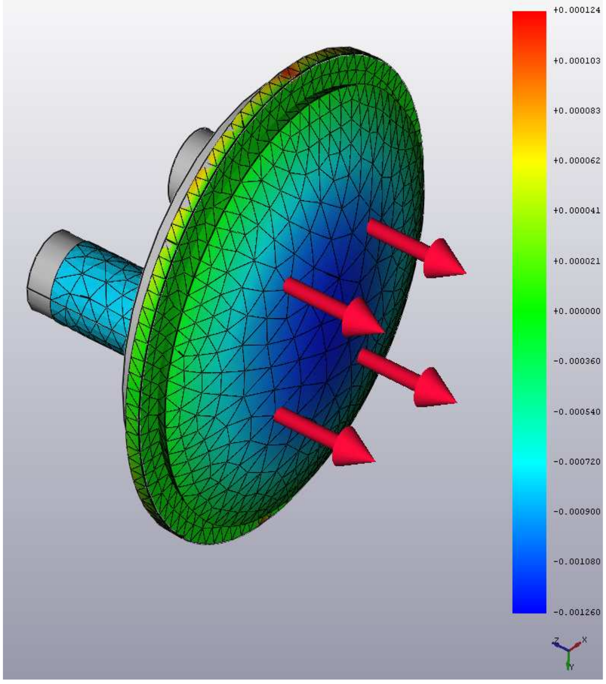

Fig. 11. The results of the calculation of the modified model, reflecting the values of the movement of the elements of the model

Postprocessing allowed visualizing the displacements in the model. Fig. 11 shows the displacement of the elements of the model and its initial position. The figure shows that the insert surface, supported by the metal cage, does not move, but the projections for the wells move, though not significantly. The largest displacements occur in that part of the insert that is exposed to force, which is quite natural for such construction and with a relatively low, as compared with steel, Young's module. The legend located on the right side of Fig. 11 is of significant information value as it gives a color representation of absolute displacement values. The displacements themselves are visually shown in a hypertrophied form, which is explained by the impossibility to represent displacements of tens of nanometers (see legend in Fig.11). In this case, they are derived with a factor of 1000, which can be set up in a window partially represented in Fig. 6.

The obtained results prove the feasibility of obtaining a metal-polymer insert of the mold-forming part of the mold. What is more, it is possible to vary geometric dimensions of the inserts, thus obtaining their optimum variant, both in size and location.

The proposed use of the FreeCAD package for calculating geometric parameters of the insert is the least expensive, as it is a free software product including *Calculix* and *gmesh* that are freely available on the Internet.

IV. Conclusions

The proposed design of the metal cage for making a metal-polymer molding part of a mold for a star-shaped product will ensure a reliable fixation of a metal-polymer part in the metal cage, and the metal-polymer mold-forming part is able to withstand ejection forces prior to failure, significantly exceeding the calculated ones.

The results of modeling the stress-strain state of the metal-polymer insert proved the feasibility of ensuring the reliability of the mold-forming part of the mold proposed by the authors, and the simulation technique itself, provided that the digital model is parameterized, is applicable to other designs of metal-polymer inserts.

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