Arch. Metall. Mater. **63** (2018), 4, 1981-1986

DOI: 10.24425/amm.2018.125133

J. MICHALCZYK*[#], S. WIEWIÓROWSKA*, Z. MUSKALSKI*

THE DEVELOPMENT AND MODELING OF AN INNOVATIVE PROCESS OF FORMING THE INTERNAL TOOTHING OF FLANGE COUPLING SPLINE SLEEVES

The article proposes the implementation of a novel method of plastic forming of internal toothing in flange spline sleeves. A method being the subject of Polish patent application P.416772 has been used for this purpose, which involves a combination of the scheme of the direct extrusion of a cone hollow with the die press forming of the wall to obtain a flange. The entire process takes place in a single technological sequence. The operations come one after another, so that there is no need for reheating the stock or carrying out intermediate soft annealing. The proposed method is assumed to be an alternative to the operation of press forming of internal spline sleeve toothing in a conical die [1] and to the operation of swaging on rotary swaging machines [2]. It is assumed that this method, too, is alternative to other technologies known from the literature and industrial practice, whose specifications and literature references will be indicated later on in this paper. Computer simulations of the flanged sleeve plastic forming process were performed using the commercial numerical program Forge®3D. During the numerical computations, the distributions of temperature fields were determined on the cross-section of the plastically formed product. The computations enabled also the visualization of the plastic flow of metal, especially in the toothing forming regions, and the determination of the energy and force parameters of the process.

Keywords: forging gears, FEM analysis, Heat extrusion

1. Introduction

The forging or extrusion method can be economically used for manufacturing toothed gears or pinions with either external or internal toothing for production runs of much more than 1000 pieces [3]. Like in other plastic working methods, the potential for rational applications is limited to some types of gear wheels. There is a certain number of gear wheels, especially in the automotive industry, whose manufacture through extrusion may bring about economic benefits [4]. They include gear wheels with one or more straight tooth rims and gear wheels with an additional internal spline toothing [1]. It can also be advantageous to combine extrusion with subsequent press forming – cold burnishing of toothing in a multi-operation process, which is used, e.g., for production of hole bevel gears [4]. Using such complex extrusion-press forming processes creates room for the ingenuity of the designers of technologies and tooling [5-10].

Engineering design in plastic working processes, apart from seeking to obtaining a good quality product, is also oriented to production economy. An important economic aspect influencing the overall production cost is the material output, energy intensity and labor intensity. The material output is associated with the type of stock used and a possible production waste. The energy intensity of a process is the lower, the smaller the forces needed for the plastic forming of a product, the lower the stock heating temperature and the smaller the number of technological operations or treatments are [5-7]. The process energy intensity is also influenced by possible heat treatments, or intermediate reheating or stock softening operations. The labor intensity of a production process, on the other hand, is related to the preparation of the stock, and primarily, with the need for the cutting, machining or plastic working of the preform. Repairing or replacing tools or their parts during series production, due to their poor durability, also contributes to an increase in process labor intensity as well as time-consuming, which clearly translates into process economy [1,3].

Flanged spline sleeves are manufactured of steel St 52.3 or 16 MnCsS 5. One of their major functions is linear guiding in plotters and another one is the protection against rotation and assuring the rectilinearity of travel. This takes place during motor-gear power transmission under heavy loads. Also, it should not be forgotten that sleeves assure backlash-free operation at a variable rotation direction. The last, but not least of the significant applications is the construction of safety disengaging couplings in many types of machines. These parts are manufactured in three versions: as cylindrical, flanged or as a clamping ring. Some varieties are made of bronze Rg7 (GC – CuSn 5/7 ZnPb). The flanged spline sleeve is manufactured according to standard DIN ISO 14.

Figure 1 shows a sample flanged spline sleeve product.

---

* CZESTOCHOWA UNIVERSITY OF TECHNOLOGY, INSTITUTE OF METAL FORMING AND SAFETY ENGINEERING, 19 A. KRAJOWEJ STR., 42- 200 CZESTOCHOWA, POLAND

[#] Corresponding author: jm@wip.pcz.pl

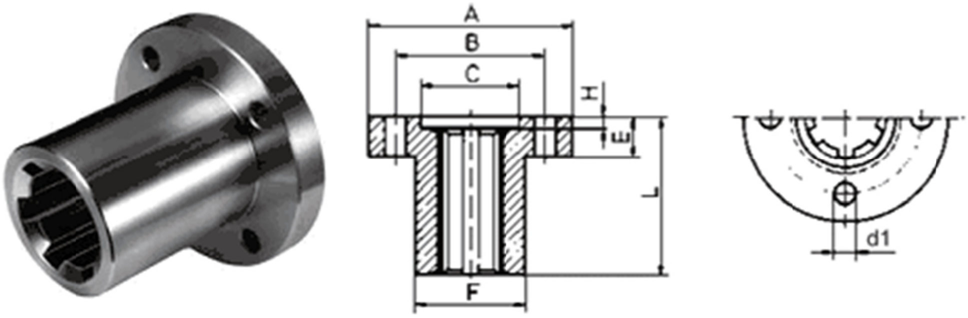

Fig. 1. A flanged spline sleeve [1]

This publication has proposed a process for the manufacture of spline sleeves with internal toothing. The proposed method is assumed to be alternative to the operation of the press forming of internal spline sleeve toothing in a conical die [1], to the operation of swaging on rotary swaging machines [1] and for forward and backward push broaching processes [4]. However, using the above-mentioned processes does not ensure a flange to be made through plastic working, therefore, an additional machining operation may be necessary.

The proposed process is based on the author's idea known from Polish patent application P.416772 [11]. According to aforementioned patent application, a thick-walled conical hollow is initially extruded, and then it is subjected to die forging with a movable die. The die moves along the wall of the hollow, reduces its thickness and then forms the flange by press forming at the end of the process.

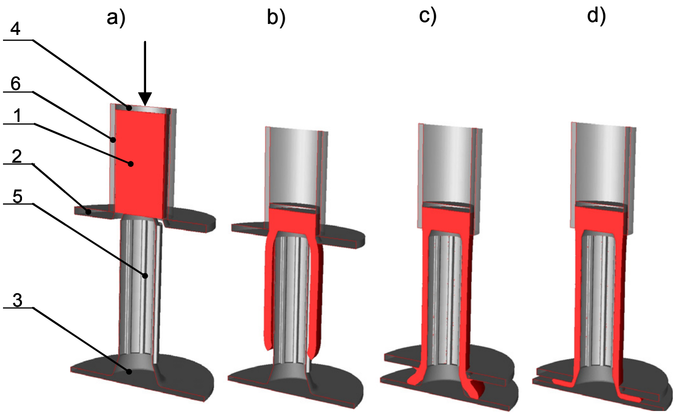

Fig. 2. Schematic diagram of the process of manufacturing the internal toothing flanged spline sleeve 1. stock 2. die, 3. mandrel base, 4. punch, 5. mandrel, 6. container

2. The essence of the process and the computation assumptions

Numerical analysis aims to explore the potential for the application of the combined scheme of the direct extrusion, sizing and stretch forging of the internal toothing sleeve and the press forming of the flange to produce a flange coupling spline sleeve. The numerical modeling was also aimed at making comparison with another, in the authors' view competitive method of manufacturing similar products [12]. In order to ascertain whether the examined process is competitive or not to the already developed single-operation flanged sleeve extrusion method, the determined energy and force parameters and the plastic metal flow were compared with those obtained according to the method [12]. Figure 2 shows the conceptual schema of the examined process based on the invention being the subject of patent application P. 416772. Figure 3 shows the schematic diagram of the process of complex extrusion of the internal toothing flanged spline sleeve based on the author's patented hollow extrusion method (PL 221425), which is the subject of comparative analysis in this study.

At the first stage (Fig. 2b), the process involves the direct extrusion of a conical thick-walled hollow. The second stage includes the die press forming of the sleeve wall on a mandrel with impressions, as a result of which the wall thickness is reduced. At the final third stage, the die presses the flange formed at the second stage on the mandrel base.

The process of extrusion at the first stage (Fig. 3b) involves the simultaneous extrusion of a hollow and a stem. Then, at the second stage (Fig. 3c), through the travel of movable sleeve 3 and punch 5, a bottomed hollow is extruded and a flange is formed under die 6. At the final stage (Fig. 3d), die 6 under the pressure of punch 5 forms the finished flange of the spline sleeve.

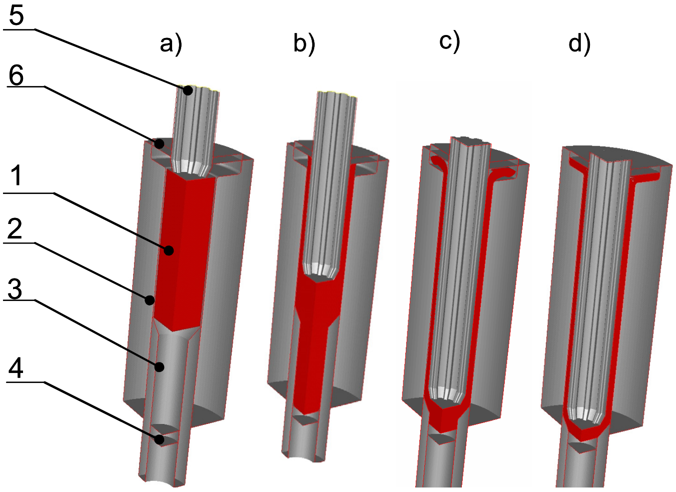

Fig. 3. The method of complex extrusion of the internal toothing flanged spline sleeve 1. stock, 2. container, 3. movable die, 4. mandrel, 5. punch, 6. die

Numerical modeling of the processes was carried out in a finite element-method (FEM)-based program, Forge®3D. The model material used for numerical computations and intended for subsequent laboratory verification was aluminum bronze in grade CuAl10Ni5Fe4 (BA1054). The main characteristic of the BA1054 grade bronze is high strength and ductility, both at ambient temperature and at elevated temperatures, and good abrasion and corrosion resistance (e.g. by seawater). Aluminum bronzes exhibit also high resistance to erosion and cavitation and, above all, to variable loads, as well as abrasion. They are also characterized by susceptibility to cold plastic working. This material is most often used for heat exchanger perforated bottoms, shafts, bolts, parts exposed to abrasion, valve seats, bearings, bushings, slides, and gear wheels.

Cylindrical stock of dimensions of ϕ49 mm × 90 mm was used for numerical studies. The dimensions of the obtained spline sleeve were as follows: length, L = 200 mm; outer diameter, 50 mm; inner diameter, 40 mm.

For solving the problems of three-dimensional plastic metal flow, a mathematical model was used, in which the mechanical state of the material being deformed is described using the Norton-Hoff law [13,14], which can be expressed with the equation below:

$$S_{ij} = 2K(T, \dot{\varepsilon}, \varepsilon)(\sqrt{3}\varepsilon)^{m-1}\dot{\varepsilon}_{ij} \tag{1}$$

where: S_{ij} – stress tensor deviator, [11,15]; $\dot{\varepsilon}$ – strain rate intensity; ε_{ij} – strain rate tensor; ε – strain intensity; T – temperature; K – consistence dependent on the yield stress, σ_p; m – coefficient characterizing hot metal deformation ($0 < m < 1$).

The yield stress value is determined from the following formula:

$$\sigma_p = Ae^{m1T}\varepsilon^{m2}\dot{\varepsilon}^{m3}\varepsilon^{\frac{m4}{\varepsilon}}(1+\varepsilon)^{m5T}\varepsilon^{m7\varepsilon}\dot{\varepsilon}^{m8T}T^{m9} \tag{2}$$

where: T – temperature, ε – actual strain, $\dot{\varepsilon}$ – strain rate, A + $m9$ – coefficients describing the rheological properties of the material. For the computation of the yield stress value, the coefficient values were taken from the material database of the Forge3® program. For the CuAl10Ni5Fe4 alloy, individual coefficients take on the following values, respectively: A = 11582.76, $m1$ = –0.00686, $m2$ = 0.03602, $m3$ = 0.089, $m4$ = 0.24482, $m5$ = 0, $m7$ = 0, $m8$ = 0, $m9$ = 0 and were taken from the Forge®3D database. Because of considerable plastic deformations occurring both in the examined process and the comparative process, the Treska friction model with the value m = 0.8 was adopted to computation. The initial process temperature was T_0 = 700°C, and the speed of tool travel for the examined processes was V = 20 mm/s.

The internal toothing of the flanged spline sleeve is finally formed at the second stage of the process (Figs. 2c,d), when the die sizes the sleeve wall and stretches the sleeve. At the first stage, the recess is filled in about 30% of the depth. To form the internal toothing in the sleeve, recesses responsible for making the toothing were provided on mandrel 5 (Fig. 2). Figure 4 shows a mandrel model with sample recesses.

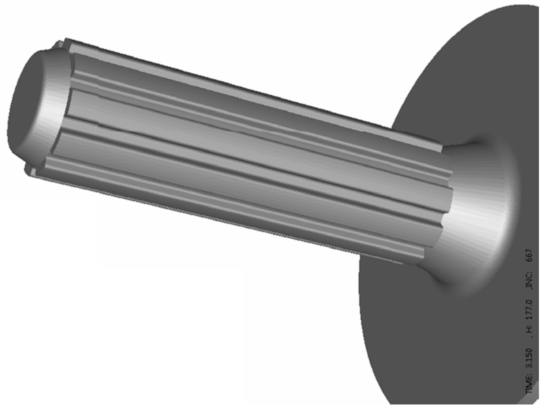

Fig. 4. A model of the tool for forming the internal toothing of a flanged spline sleeve

3. Results of numerical computations

The main advantage of the proposed flanged spline sleeve extrusion process is that, at its first stage, the surface area of contact between the deformed stock and the tool is relatively small. While extruding the conical hollow, punch 4 pushes stock 1 through container 6 and die 2, thus causing a temperature increase. Beyond the region of clearance between mandrel 5 and die 2, the conical wall of the hollow has no contact with the much cooler tool, and therefore it does not lose its temperature so fast. This has an undoubtedly considerable effect on the yield stress and plastic flow of the metal. Figure 5 shows the distribution of temperature fields in the plastic forming of the product by extrusion and die press forming.

As can be seen from the presented temperature distribution, at the first stage of the process during direct extrusion, the metal has been heated up to a temperature of approx. 750°C by friction and plastic deformation (Fig. 5a). No material transitions are observed in the temperature distribution of the conical hollow formed, as there is no contact between the metal and the tool. Then, while moving down, the cooler die (T = 250°C) presses the sleeve wall and forms the toothing. The temperature changes (decrease) gradually, because the metal also gradually gives up heat to the much cooler mandrel.

At the last stage (Figs. 5c,d), thanks to this temperature distribution, the flange is pressed at a temperature of about 700°C.

Figure 6 illustrates the distribution of temperature fields in the plastic forming of the product by complex extrusion.

The flanged spline sleeve complex extrusion process relies on the author's method of bottomed hollow plastic forming. The method has proved very effective for extruding products, especially deep hollows. However, as compared to the proposed extrusion and pressing process, as shown in Fig. 2, this method is clearly ineffective from the point of view of temperature distribution. There are numerous overcooling zones occurring in the metal due to a considerable metal-tool contact surface area. Large friction surface areas and considerable temperature drops cause the material to be much more overcooled in the regions of the largest plastic deformations, compared to the new proposed process. During forming the sleeve from the metal shank in the ring channel (Fig. 6a), the temperature does not exceed 600°C. This is the key stage of sleeve forming and, as a result, considerable metal to punch pressure forces arise there. Also, the temperature in the flange formation region (Figs. 6c, d) is by approx. 150°C higher than during die pressing (Figs. 5c, d).

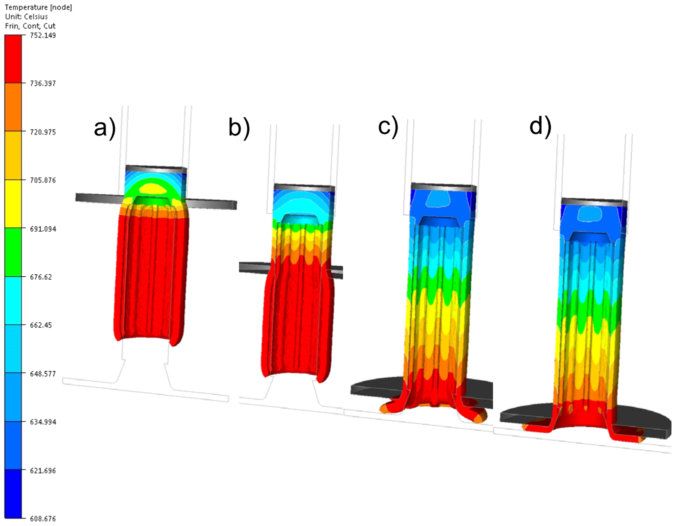

Fig. 5. The distribution of temperature fields on the product cross-section in the process of extrusion of a flanged spline sleeve

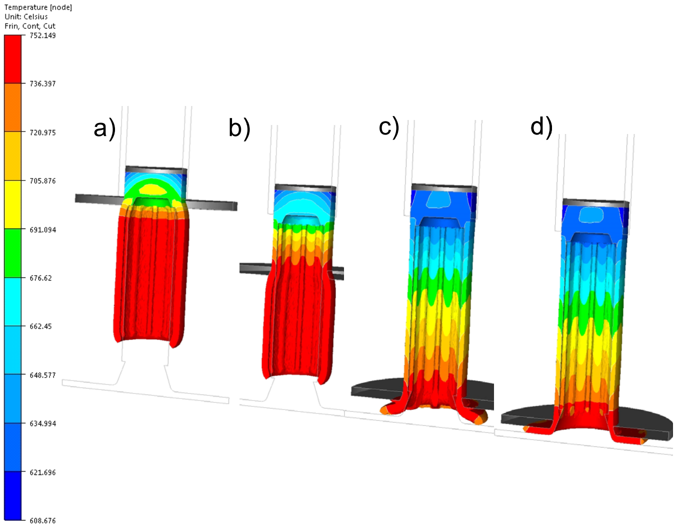

Fig. 6. The distribution of temperature fields on the product cross-section in the process of complex extrusion of a flanged spline sleeve

Figure 7 represents the diagram of the relationship of extrusion and pressing force versus tool path.

Force parameters in the processes of plastic forming of metal products are an extremely important indicator that shows whether the process is competitive from the technological and economic point of view, or not. The values of force parameters have an effect primarily on the durability and life of the tooling and equipment and on the energy intensity of the technological process. The proposed novel process of extrusion and pressing of flanged spline sleeves was designed to be distinguished primarily by low force parameters. The minimization of the tool to stock contact was supposed to reduce the friction forces during the process, but the main objective was to maintain the highest possible stock temperature. Also the kinetics of the tools was selected so that the plastic deformations were as low as possible, while generating the greatest possible amount of heat. In Figure 7, where the relationship of force parameters as a function of tool path is shown, a dramatic decrease in force can be noticed after classic direct extrusion. During the simultaneous sizing and stretching of the hollow wall and forming of the toothing, the die generates a force of a magnitude of 10 to 20% of that at the first stage. Only at the end of the process, where flange die forming takes place, does the force increase up to a level of approx. 800 kN due to material strain hardening.

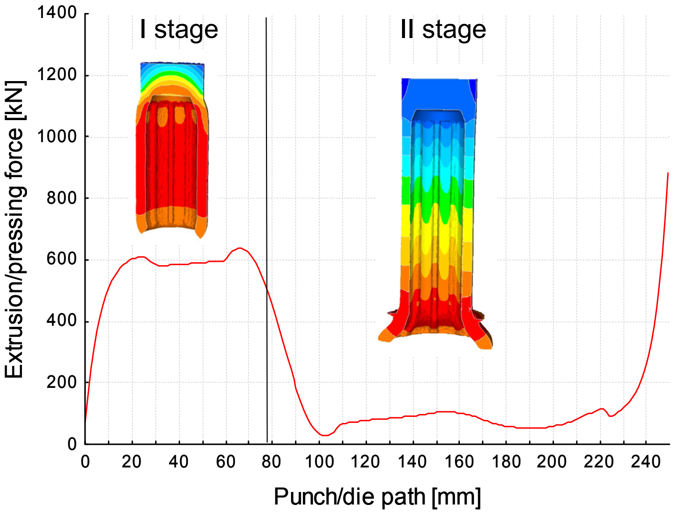

Fig. 7. Diagram of the relationship of extrusion force versus punch and die path for the flanged spline sleeve extrusion and pressing process

Figure 8 shows the diagram of the relationship of extrusion force versus tool path for the complex extrusion process.

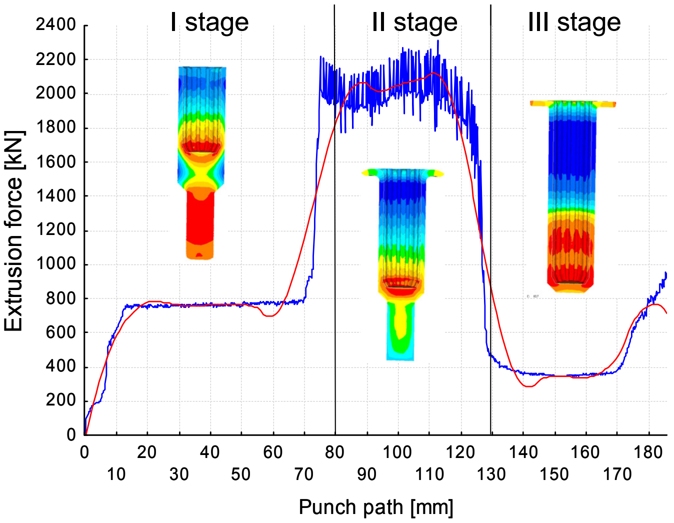

Fig. 8. Diagram of the relationship of extrusion force versus punch path for the complex flanged spline sleeve extrusion process

The graph obtained from numerical computations, representing extrusion force as a function of punch path, is characteristic of such a method of plastic forming of metal products. Initially, the extrusion force is relatively small and stabilized, but at the second stage, it increases. During the extrusion of the classic sleeve without a flange, the force increases at the second stage by approx. 50% compared to the first stage. However, in the case under examination, this rapid and substantial increase in force was as large as 120% of the first stage force. The cause if the gradual filling of the chamber, in which the sleeve flange is to be formed, with metal. Next, at the end of the process, the magnitude of the force decreases, after which its slight increase occurs at the time of flange finishing pressing.

To sum up the analysis of the energy and force parameters determined from the computations it can be concluded that, from the point of view of forces needed for the plastic forming of the product, the process of extrusion and pressing is much more energy intensive. The maximum computed extrusion force amounted to 850 kN, while that for complex extrusion, about 2100 kN.

The concept of the proposed flanged spline sleeve extrusion and pressing process, from the point of view of both computation and the plastic forming scheme, belongs to the realm of theoretical and preliminary studies. The proposed deformation scheme is very effective in terms of thermomechanical computation. However, to verify preliminary studies, such as FEM modeling, some changes to the kinetics of tooling operation need to be developed. It is possible to build the tool according to the schematic diagram (Fig. 2), but it will have a very complicated construction and will require additional connections of the die with the cross-beam. A tool for the verification of theoretical studies should be of possibly simple construction, thus eliminating any elements prone to damage. Figure 9 shows the concept of a tool for the verification of numerical computation.

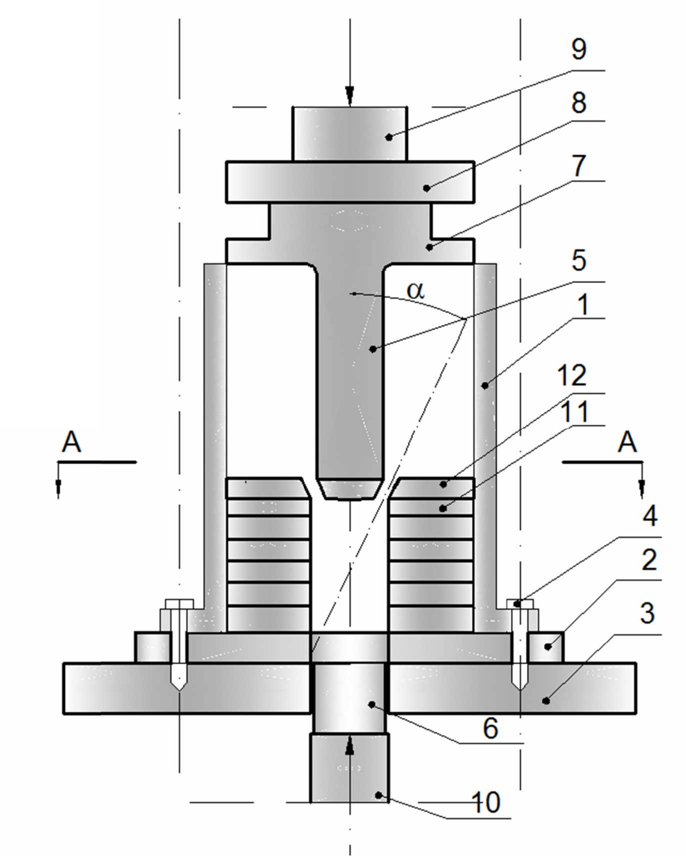

Fig. 9. The concept of a numerical computation verification tool. 1. body, 2. base, 3. press table, 4. clamping screws, 5. punch, 6. pusher, 7. plate, 8. cross-beam, 9. drive, 10. ejector, 11. sleeve, 12. die.

The tool operates with a double-sided press, where the stock positioned in sleeve 11 is co-extruded with ejector 10 and pusher 6 through the clearance between die 12 and punch 5. A conical sleeve forms with a preliminarily profiled internal toothing. Next, after pusher 6 and ejector 10 retract, the conical sleeve is drawn through die 12. Then, the sleeve is gradually stretched, the internal toothing is finish formed, and the sleeve flange is preliminarily formed by turning up on plate 7. After punch 5 has gone into sleeve 11, plate 7 will press the spline sleeve flange on the surface of die 12. The simultaneous return motion of pusher 6 and punch 5 will remove the finished product from the tool.

4. Summary

The performed numerical analysis of the process of extrusion and pressing of the flanged spline sleeve has confirmed the possibility of obtaining the product of the assumed shapes and dimensions. The implementation of the scheme of the combined direct extrusion followed by pressing of the conical sleeve showed that this configuration of deformation combined with the tool's construction resulted in a very advantageous distribution of temperature in the metal. The temperature increment in the first stage above the initial temperature across the entire length of the conical sleeve brought about very advantageous conditions for the second stage, where the sleeve flange was formed by turning up on the mandrel plate. Also, the comparative analysis of the alternative complex extrusion process has shown that the proposed method, by minimizing the metal-tool contact surface area, is more advantageous from the point of view of thermomechanical parameters. Moreover, the new manufacturing process is distinguished by considerably lower force parameters. The maximum force computed for the extrusion and pressing process at the final stage of the flange die press forming process amounted to approx. 8500 kN, while in the complex extrusion process, it was 2100 kN. The average force needed for the plastic formation of the product, as determined from the performed computations, is a good indication of the energy intensity of the entire process, as it includes force parameters from the whole extent of the process. In the proposed novel process, the averaged extrusion and pressing force amounted to 41 tons (410 kN). In the comparative complex extrusion process, it was as large as 98 tons (980 kN). This data confirms the prior suppositions about the advantage of the innovative flanged spline sleeve manufacture method over the method being the subject of the comparative analysis.

REFERENCES

[1] A. Turno, R. Romanowski, M. Olszewski, Obróbka Plastyczna kół zębatych, Warszawa 1973

[2] J. Sińczak. Kucie dokładne, Kraków 2011.

[3] W. Libura, Płynięcie metalu w procesie wyciskania, Kraków 2011.

[4] V.V. Dewiatov, H.S. Dyja, V.Y. Stolbow, Modeling mathematical and optimization processes extrusions, Częstochowa 2004.

[5] Z. Pater, A. Gontarz, J. Tomczak, T. Bulzak: Arch. Civ. Mech. Eng. 15, 4, (2015).

[6] G. Winiarski, A. Gontarz, A. Dziubińska, Arch. Civ. Mech. Eng. **17**, 4, (2012).

[7] J. Bartnick, Arch. Metall. Mater. **57**, 4 (2012).

[8] G. Winiarski, A. Gontar, Sposób i urządzenie do wyciskania wewnętrznego kołnierzy. Polish Patent PL 222169.

[9] G. Winiarski, A. Gontarz, Sposób i urządzenie do wywijania kołnierza rolkami prowadzącymi. Polish Patent PL 219935.

[10] Z. Pater, J. Tomczak, A. Gontarz, Sposób wytwarzania kołnierzy czołowych w kształcie rozety trójramiennej. Polish Patent PL 220525.

[11] M. Pietrzyk, The numerical methods in plastic working metals. Kraków 1992.

[12] J. Michalczyk, Sposób wytwarzania tulei przelotowej. Polish Patent 221425.

[13] N.J Hoff, Quart., Appl. Mech. **2**, 49 (1954).

[14] F.H Norton, Creep of Steel at High Temperature. McGraw Hill, New York 1929.

[15] H. Dyja, P. Szota, S. Mroz, J. Mater. Process. Tech. **153**, 115-121 (2004).