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NEW UNCONVENTIONAL PROCESSES OF PLASTIC FORMING OF THE INTERNAL TOOTHING OF COUPLING SPLINE SLEEVES

The article explores the possibility of using the authors' three new methods of unconventional extrusion of deep hollows to be used for the manufacture of spline sleeves intended for internal toothing couplings. Two invention patents, PL206466 and PL224121, and one patent application, P.416772, were used for this purpose. Numerical computations were made in the Forge®3D program for the conceptual schemes of forming sleeves. The aim of those computations was to determine the extrusion forces and to compare them with the conventional indirect and direct extrusion methods. Then, on models based on the authors' plastic forming schemes, numerical computations were made, from which the actual energy and force parameters were determined in the form of the relationship of extrusion force versus forming tool path. Also, the degree of fill of the passes, in which spline sleeve toothing is formed, was determined.

Keywords: forging, extrusion, spline sleeves

1. Introduction

Spline sleeves are manufactured mainly of steel St 52.3 or 16 MnCsS 5 [1]. One of their major functions is linear guiding in plotters and another one is the protection against rotation and assuring the axiality 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 [2]. The last, but not least of the significant applications is the construction of safety disengaging couplings in many types of machines [3-5]. These parts are manufactured in three versions: as cylindrical or flanged, or as a clamping ring [1]. Some of the varieties are made of bronze Rg7 (GC – CuSn 5/7 ZnPb). The spline sleeve is manufactured according to standard DIN ISO 14 [6].

Fig. 1. A spline sleeve with a flange [1]

Figure 1 shows a view of a sample spline sleeve product, whose production processes were subjected to numerical studies.

The article has proposed the implementation of new methods of plastic forming of internal toothing in flange spline sleeves to be used for, e.g., couplings. The authors' plastic forming methods being the subject of invention patents PL206466 [7], PL 224121 [8] and patent application PL P.416772 [9] have been used for this purpose. These methods consists of a combination of the scheme of direct extrusion of a cone hollow with die press forming of the wall, simultaneous rolling and mandrel extrusion, and hobbing extrusion and pressing. All the processes take place in a single technological operation. Numerical modelling of the processes was carried out in a finite element-method (FEM)-based program, Forge®3D [10]. The model material used for numerical computations and intended for subsequent laboratory verification was aluminium bronze in grade CuAl10Ni5Fe4 (BA1054). The main characteristic of the BA1054 grade bronze

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is high strength and ductility, both at ambient temperature and at elevated temperatures, and good abrasion and corrosion resistance (e.g. by seawater). Aluminium 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 [1].

The first to be subjected to analysis was the process of bar extrusion by rotating rolls. A schematic diagram of the process is shown in Fig. 2. The second process is the method of hobbing extrusion of cylindrical products. A schematic diagram of this process is shown in Fig. 3. The third investigated process is complex sleeve extrusion. The run of this process is illustrated in Fig. 4.

The aim of the numerical studies was to assess the possibility of using the authors' developed methods of plastic forming of bottomed deep hollows for the production of inner toothing and splines especially in long sleeves intended for, e.g., couplings. The basic criterion in assessment is the effect of combination of different deformation schemes on the force needed for plastic forming, materials flow and, as a consequence, the fill of tool impressions, where the toothing or splines are formed.

2. The essence of the proposed production methods

a) The process of extrusion of a hollow in a die with rotating rolls is the subject of Patent [7]. It involves placing stock 1 in container 2 on mandrel 3 between rolls 4. Punch 5 presses on stock 1 to pierce it on mandrel 3. The material is forced between rolls with a round impression and the working portion of the mandrel. Hollow 6 is formed. The schematic diagram is shown in Fig. 2.

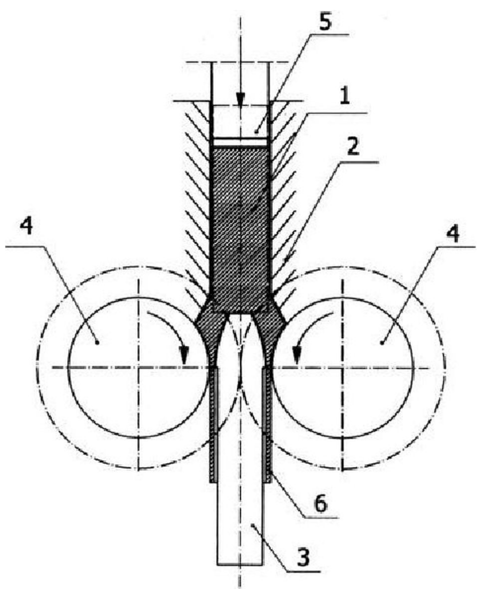

Fig. 2. A schematic diagram of the extrusion and rolling process according to [7]

b) The combined envelope pressing and extrusion is the subject of Patent [8].

The process of envelope extrusion of cylindrical products consists in placing stock material 1 in the form of a bar in die 2. The die has a flange situated on the punch 4 side. The stock material is subjected to extrusion with punch 3 with simultaneous enveloping motion of punch 4. During the enveloping motion of the punch, die 2 is positioned in the punch seat not deeper than at the height of its flange. The schematic diagram is shown in Fig. 3.

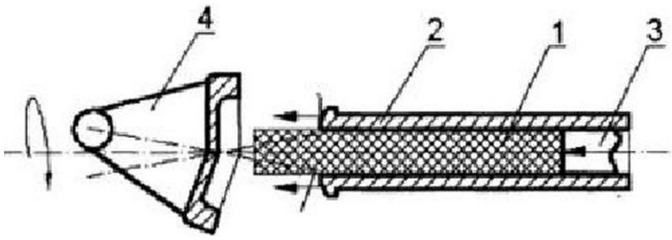

Fig. 3. A schematic diagram of the process of hobbing pressing with extrusion according to [8]

c) The method of direct extrusion of a flanged sleeve [9] consisting in placing the stock on pressure mandrel 3 with flanged base 5. The mandrel has a bevelled upper edge. The stock is pressed on by upper punch 4 until a sleeve of appropriate bottom thickness is extruded through the aperture of the annular conical die. Then, the stock material is pressed with annular die 2 along pressure mandrel 3.

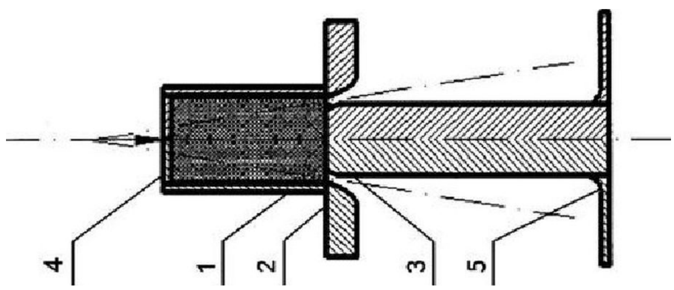

Fig. 4. A schematic diagram of the extrusion and pressing process according to [9]

3. Model material and assumptions for numerical studies

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 [11,12] that can be expressed with the equation below:

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

where: S_{ij} – stress tensor deviator [12,13], $\dot{\varepsilon}$ – 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:

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

where: T – temperature, ε – true 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 and were taken from the Forge®3D database. Because of considerable plastic deformations occurring in the processes under analysis, the Tresca friction model with the value $\mu = 0.8$ was adopted for computation. The initial temperature for new process was T_0 = 600°C, and the speed of tool travel for the examined processes was V = 25 mm/s. The AlMgSi and Al99,6 material models were downloaded from the Forge3D computer program database.

4. Numerical computation for the proposed plastic deformation processes

In the first place, the values of energy and force parameters were determined. The results for the dependence of extrusion force on the tool path were compared. The comparison was made with the force parameters of the direct and indirect extrusion processes. The aim of the comparison was to verify whether it was justifiable to implement the proposed spline sleeve plastic forming methods from the point of view of forces needed for plastic forming.

4.1. Verification of the extrusion force

Figure 5 shows diagrams of force as a function of punch path for extrusion in the three-roll die.

Figure 6 shows a diagram of extrusion force as a function of punch path for coextrusion.

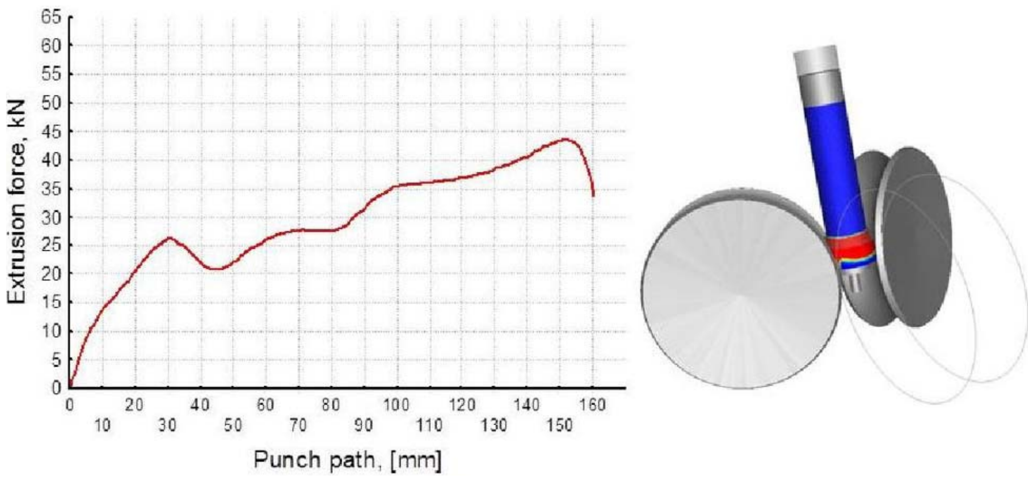

Fig. 5. Extrusion force as a function of punch path. Material, Al 99.6; roll rotational speed, ω = 5 rpm; punch travel speed, 25 mm/s; T_0 = 400°C

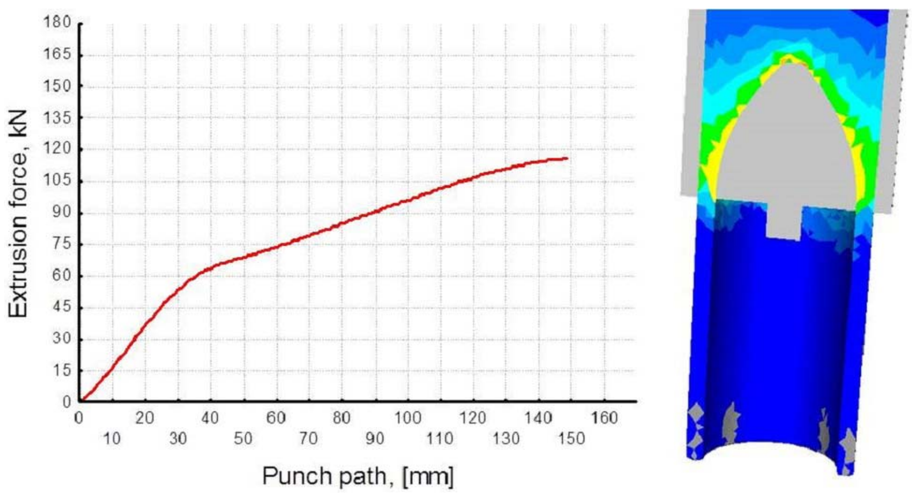

Fig. 6. Coextrusion force as a function of punch path. Material, Al 99.6; roll rotational speed; punch travel speed, 25 mm/s; T_0 = 400°C

With analogous temperature and speed parameters, the maximum force of extrusion in the die with rotating rolls is almost two times smaller compared to coextrusion. The average value was considered in the analysis. For extrusion according to Fig. 5 – 43 kN, and for extrusion according to Fig. 6 – 118 kN.

In the hobbing pressing method, comparison with indirect extrusion was made. Figure 7 shows a diagram of pressing force as a function of punch operation time

Figure 8 represents the dependence of the indirect extrusion force on the punch travel time.

The computation was made for analogous temperature and speed conditions. The magnitudes of extrusion force as a function of tool operation time show that the maximum force in hobbing pressing is 80 kN, while in indirect extrusion, approx. 120 kN.

Figure 9 shows a diagram of the extrusion and pressing force as a function of tool operation time [ ].

Figure 10 shows the dependence of the determined extrusion force on the punch path for indirect extrusion with temperature and speed conditions analogous to those in the process illustrated in Fig. 9.

The comutations have found that using the combined sleeve extrusion and pressing scheme (Fig. 9) will cause a drop in extrusion force, compared to indirect extrusion (Fig. 10), by about 250 kN. This yields a difference by almost 50%.

To sum up, the proposed methods of plastic forming of sleeve products are distinguished by lower force parameters compared to traditional extrusion methods. Therefore, it is justified to verify whether it is feasible to use these methods for the processes of manufacturing splined sleeves or inner toothing.

4.2. Numerical modelling of extrusion processes

Computer simulations of the processes were performed to evaluate the behaviour of stock material flow during the operation of the tools. Subject to evaluation was primarily the fill of the impressions where splines are formed, as well as the material flow (nor wall curvature) and the extrusion force for material BA1054. The computations were performed for an initial stock temperature of T_0 = 600°C.

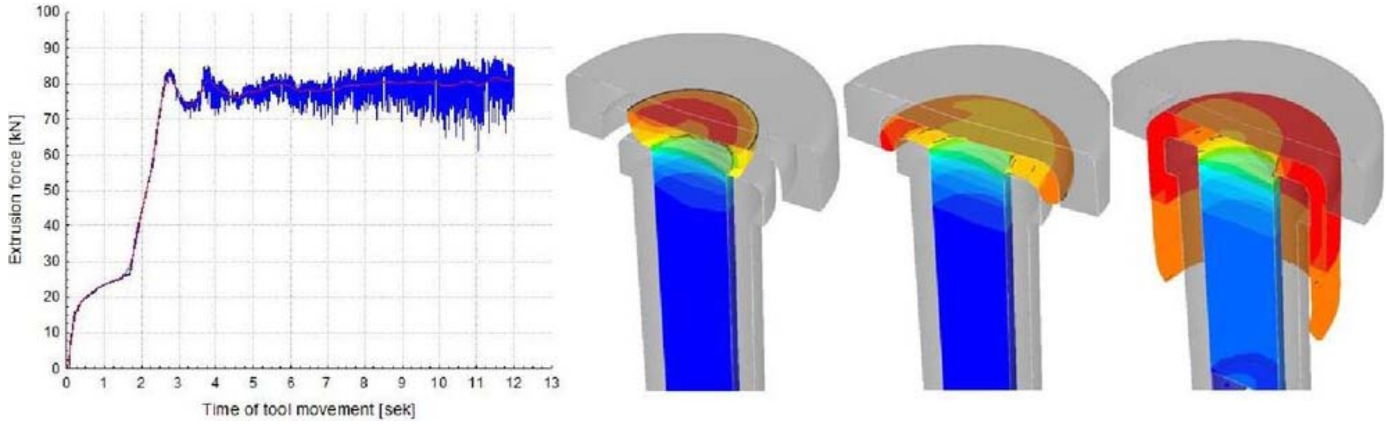

Fig. 7. Pressing force as a function of punch operation time. Material, Al 99.6; roll rotational speed, ω = 20 rpm; punch travel speed, 25 mm/s; T_0 = 400°C

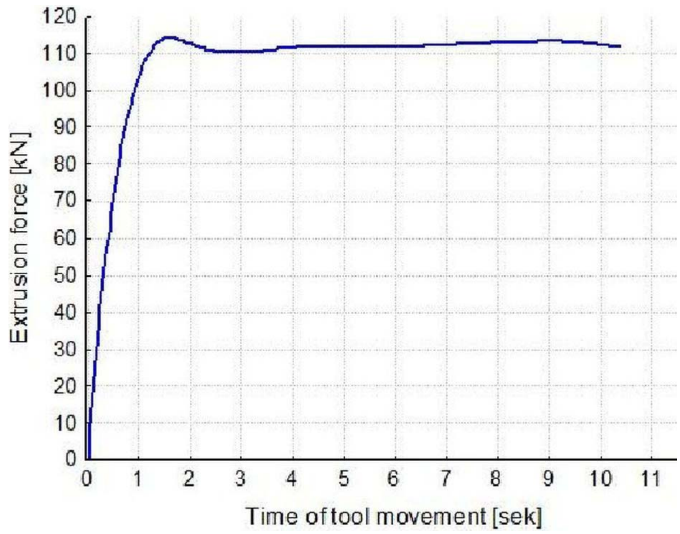

Fig. 8. Indirect extrusion force as a function of punch operation time. Material, Al 99.6; punch travel speed, 25 mm/s; T_0 = 400°C

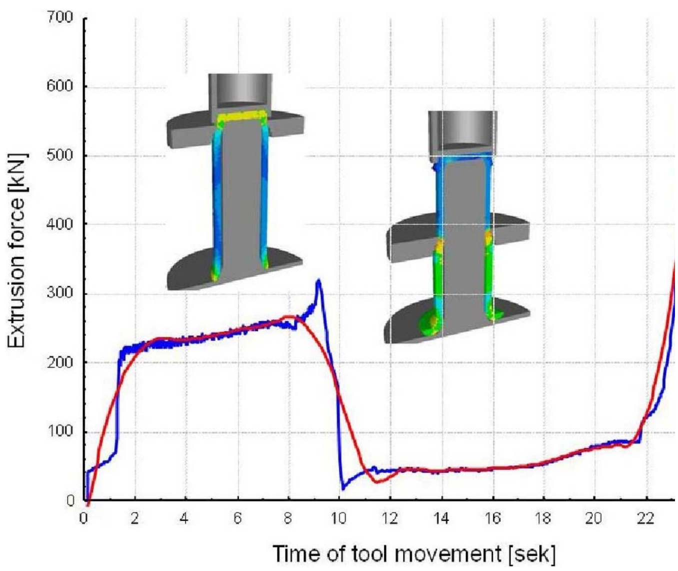

Fig. 9. Extrusion and pressing force as a function of tool operation time. Material, AlMgSi; punch and die travel speed, 25 mm/s; T_0 = 400°C

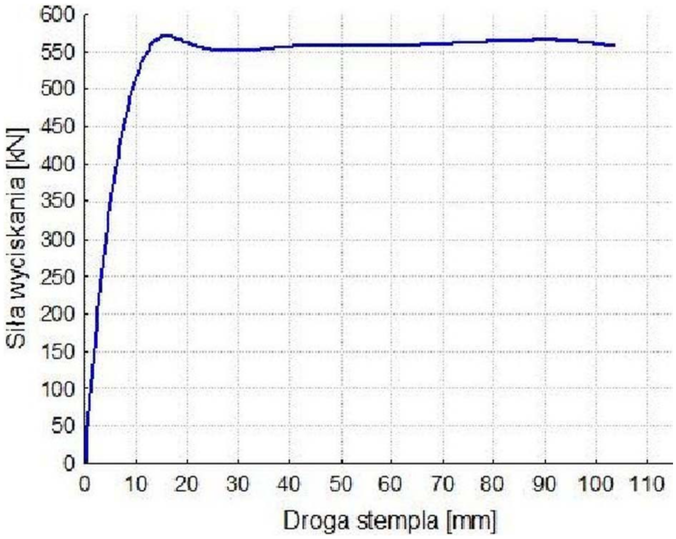

Fig. 10. Indirect extrusion force as a function of punch operation time. Material, AlMgSi; punch travel speed, 25 mm/s; T_0 = 400°C

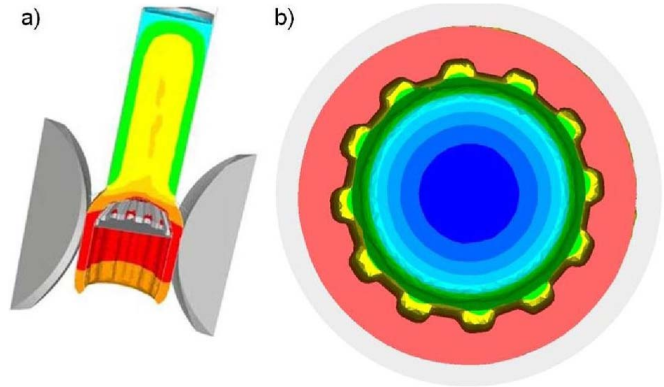

Fig. 11. Computer simulation of the process of spline sleeve extrusion in a three-roll die. a) steady extrusion state, b) view of the spline sleeve through the cross-section of the mandrel working portion – the fill of the mandrel impressions

Figure 11 shows the run of computer simulation for a steady extrusion process in a three-roll die. As can be seen in the diagram shown in Fig. 11b, the fill of the impression in the mandrel in its working portion is correct. The material has completely flown into the toothing impressions, whereby the spline sleeve geometry conforms to the geometry of forming tools. This is certainly caused by an increase in temperature in the roll region. The material in that region has better ductility and, in addition, is pressed on by the rotating rolls and forced into the impressions on the mandrel.

Figure 12 shows a diagram of the dependence of force on the punch path. The diagram is presented in the form of raw data generated by the Forge®3D numerical program, therefore the force magnitude is shown in tons. As the punch acts downwards, oppositely to the Z axis, the punch path is reverse.

The diagram of the extrusion force as a function of punch path (Fig. 12) confirms also that the rolls have an advantageous effect on the material flow. A mild increment in extrusion force signifies that the rolls greatly facilitate the flow of material in the mandrel working portion. Also the absence of a dead zone and a retarded material flow are undoubtedly the cause of the smaller extrusion force.

Figure 13 illustrates the run of computer simulation for the steady process of spline sleeve hobbing pressing with simultaneous extrusion.

The envelope pressing process is characterized by the fact that, while performing enveloping motion, the die introduces additional tangential stress to the material. Such stress increases the material plasticity by refining the structure of the metal. Computer simulations will not give a definite response to this; however, the clearly lower plastic resistance of the material and the complete fill of the mandrel impressions suggest that this may be the case, as can be seen in Fig. 13b.

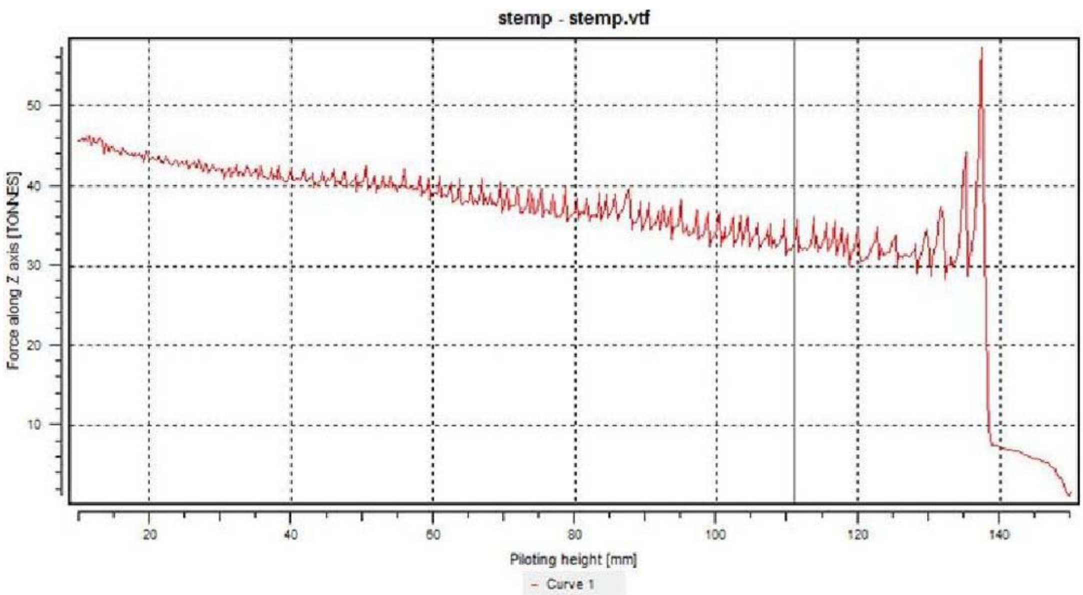

Fig. 12. Extrusion force as a function of punch path in the three-roll die extrusion process . Material, CuAl10Ni5Fe4; roll rotational speed, ω = 8 rpm; punch travel speed, 25 mm/s; T_0 = 600°C

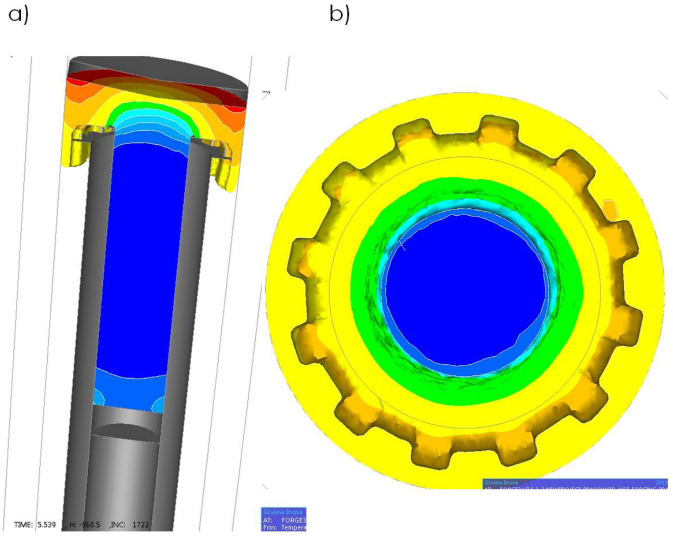

Fig. 13. Computer simulation of the process of spline sleeve hobbing pressing and extrusion. a) steady pressing and extrusion state, b) view of the spline sleeve through the cross-section of the die working portion – the fill of the mandrel impressions

Figure 14 shows a diagram of the relationship of pressing force as a function of punch operation time. The diagram is presented in the form of raw data generated by the Forge®3D numerical program, therefore the force magnitude is shown in tons.

Initially, the magnitude of pressing force is not high. The bar portion outside the die is pressed. In the next process phase, the force increases and the material becomes pressed out on the die and then forced between the die impressions and the hobbing punch. At that time, the process is steady in character (Fig. 14).

Figure 15 illustrates the run of computer simulation of the steady process of spline sleeve coextrusion followed by pressing.

In the process of conical sleeve extrusion followed by pressing (Fig. 15a,b), the deformation scheme is unconventional, but very advantageous. At the first stage (Fig. 15a), a sleeve is extruded through the skew aperture. Its diameter is larger than that of the mandrel. An initial toothing profile is formed. At the second stage (Fig. 15b), the die presses the sleeve wall against the mandrel, and presses and deepens the impressions in the spline sleeve.

Figures 16a and 16b show the diagram of the relationship of the extrusion and pressing force as a function of tool path. The diagram is presented in the form of raw data generated by the Forge®3D numerical program, therefore the force magnitude is shown in tons.

The diagram of the relationship of the sleeve extrusion and pressing force as a function of tool path has been split into two parts. The first graph (Fig. 16a) represents coextrusion, and this is a typical graph for this type of deformation scheme. The extrusion force magnitude is much lower than for the finished product with toothing. These are two causes. The first is that the hollow semi-finished product has a thick wall. And the second is that the toothing is made only to a small extent. Figure 16b shows the graph of force during die pressing. The force is relatively small, as the deformations mean pressing the sleeve wall into the final thickness and elongation.

5. Summary

The presented results of the numerical analysis of the spline sleeve extrusion process are preliminary in character and provide a basis for undertaking further analyses of the process aimed at establishing the optimal process conditions. The numerical computations have found that such processes are alternative, even for the already developed extrusion methods that are characterized by a considerable reduction in force parameters compared to traditional deep hollow extrusion method. The investigation has shown a possibility of, or even justification for using this plas-

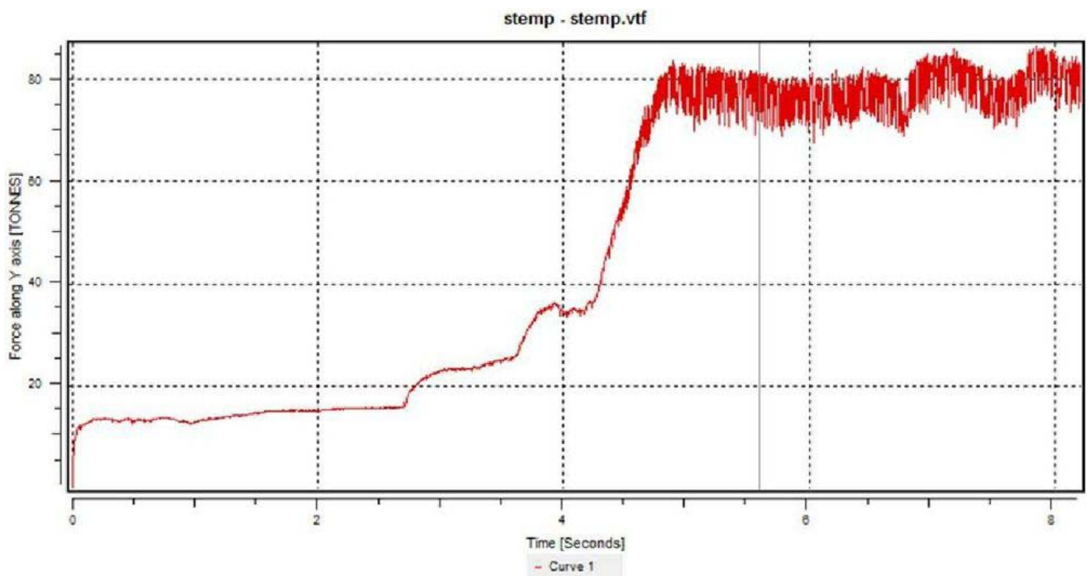

Fig. 14. Pressing force as a function of punch operation time for the hobbing pressing and extrusion and pressing process Material, CuAl10Ni5Fe4; punch angular speed, $\omega = 8$ rpm; lower punch path speed, 25 mm/s; $T_0 = 600°C$

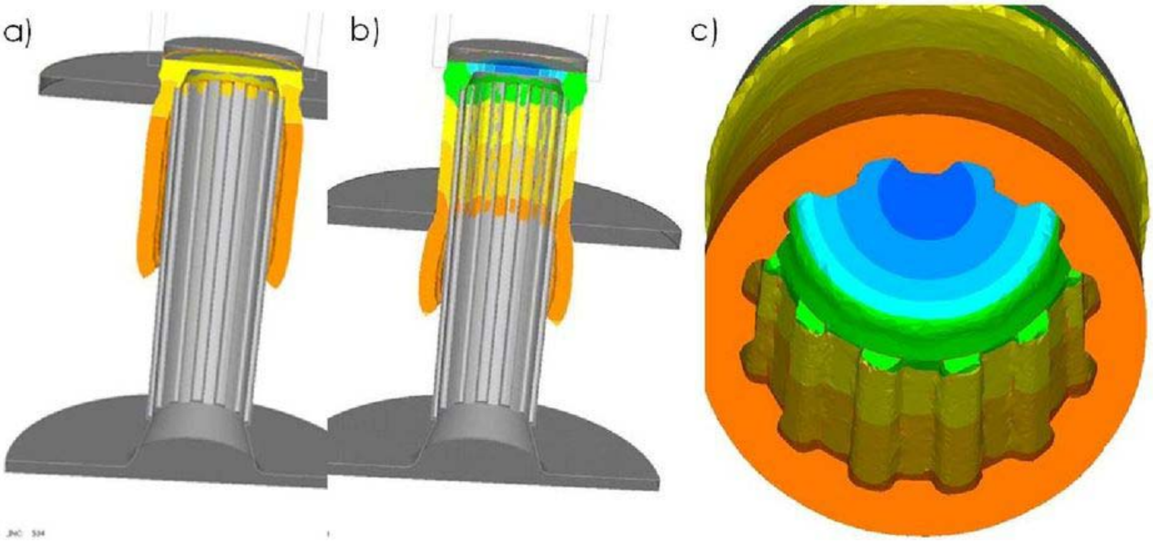

Fig. 15. Computer simulation of the conical sleeve coextrusion and pressing process; a) steady extrusion state, b) pressing with simultaneous elongation, c) view through the cross-section of the mandrel working portion – the fill of mandrel impressions

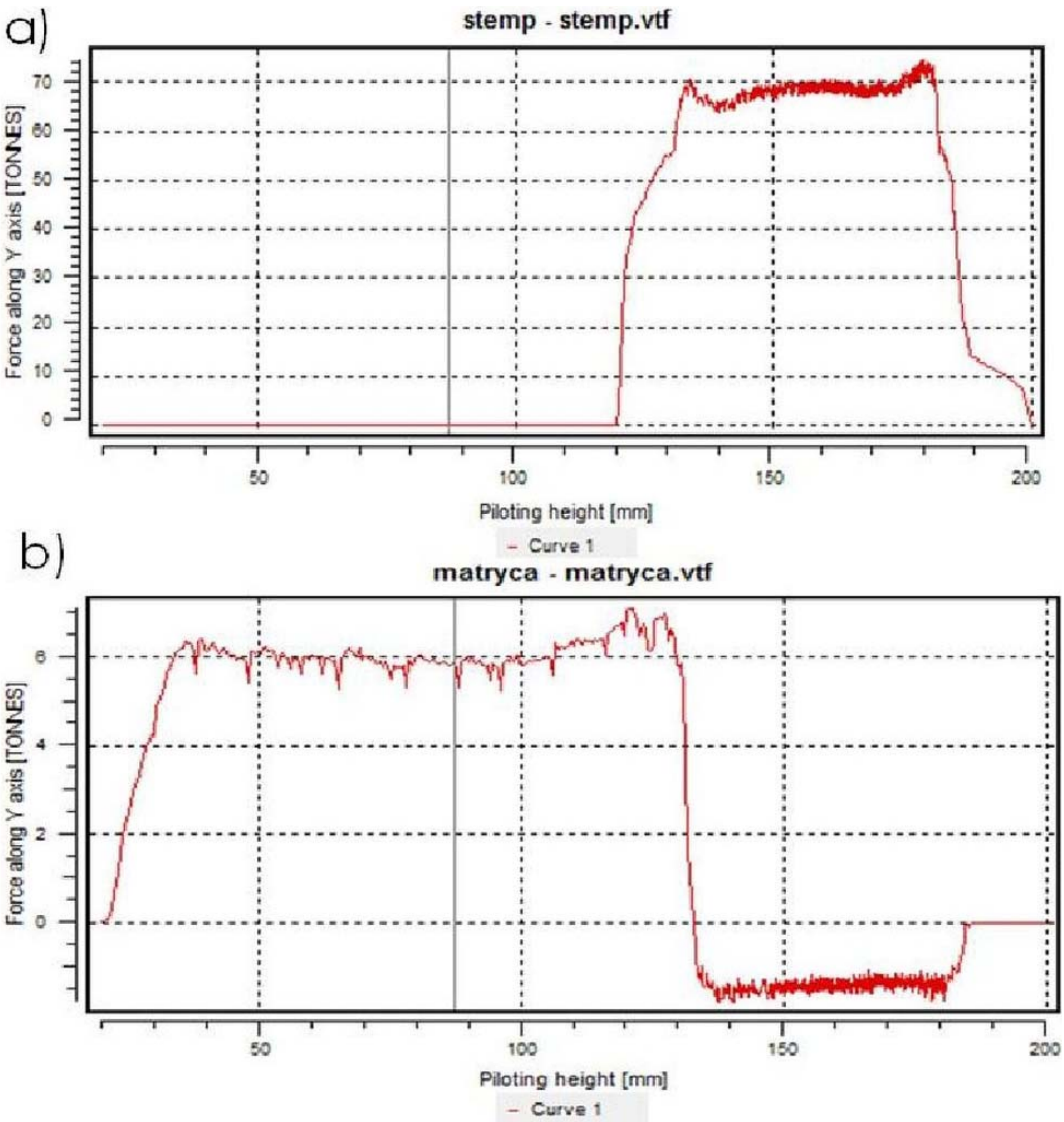

Fig. 16. Extrusion and pressing force as a function of punch and die path. Material, CuAl10Ni5Fe4; upper punch travel speed, Vs = 25 mm/s; die travel speed, Vm = 25 mm/s; T_0 = 600°C. a) extrusion force for stamp, b) pressing force for die

tic deformation configuration for conducting the spline sleeve manufacturing process. Moreover, as an important advantage of the presented extrusion, pressing and rolling methods, an uncomplicated form of the tools and equipment can be pointed out, which, coupled with relatively low force parameters and a single-operation run of the processes, allows the methods to be classified as economical processes of plastic forming of spline sleeve products.

The numerical studies, which were aimed at exploring the possibility of using the proposed processes for manufacturing spline sleeves, have also demonstrated that:

1. Using complex extrusion-pressing-rolling processes creates room for the ingenuity of the designers of technologies and tools.
2. Especially advantageous may be combining extrusion with subsequent sleeve wall pressing-burnishing and forming of inner toothing in a multi-operation process.
3. In view of the unconventional pattern of plastic deformations, the proposed processes are distinguished by much lower energy – force parameters(MES computation), compared to traditional direct and indirect extrusion.

REFERENCES

[1] A. Turno, R. Romanowski, M. Olszewski, Obróbka Plastyczna kół zębatych. Warszawa 1973.
[2] J. Sińczak, Kucie dokładne. Kraków 2011.
[3] A Gontarz, G. Winiarski, Arch. Metall. Mater. **60**, 3 (2016).
[4] G. Winiarski, A. Gontarz, A. Dziubińska, Arch. Civ. Mech. Eng. **17**, 4, (2012).
[5] J. Bartnicki, Arch. Metall. Mater. **57**, 4 (2012).
[6] G. Winiarski, A. Gontarz, Kształtowanie kołnierzy w wyrobach drążonych metodą wyciskania z ruchoma tuleją. Lublin 2017.
[7] J. Michalczyk, W. Dewiatow, Sposób wytwarzania wyrobów drążonych. Polish Patent 206466.
[8] J. Michalczyk, Sposób wyciskania obwiedniowego wyrobów cylindrycznych. Polish Patent 224121.
[9] J. Michalczyk, Sposób współbieżnego wyciskania tulei z kołnierzem. Apication Patent 416772.
[10] M. Pietrzyk, The numerical methods in plastic working metals. Kraków 1992.
[11] N.J Hoff, Quart, Appl. Mech. **2**, 49 (1954).
[12] F.H Norton, Creep of Steel at High Temperature. McGraw Hill, New York 1929.
[13] A. Stefanik, A. Morel, S. Mróz, P. Szota, Arch. Metall. Mater. **60**, 2A (2015).