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THERMOMECHANICAL ANALYSIS OF THE POSSIBILITY OF USING NEW METHODS OF COMPLEX EXTRUSION FOR MANUFACTURING THE INNER TOOTHING OF SPLINE SLEEVES

In the paper presents two new patented of unconventional methods author's and sleeve-type products of extruding [PL219182, PL221425]. The extrusion methods have been developed with the aim of reducing the energy and force parameters during the plastic forming of material. Traditional methods of extruding similar products are characterized by considerably higher extrusion force magnitudes. This results in substantial limitations and problems of an engineering nature. Moreover, the proposed methods of producing bottomed and bottomless sleeves are distinguished by the capability to minimize or totally eliminate the waste. The author's methods of extruding long bottomless sleeves, presented herein, were used for developing a method for shaping inner toothing in spline sleeves. The theoretical analysis is based on thermomechanical simulation of the possibility of applying such processes to the extrusion of spline shafts with inner toothing. Next, the obtained results were compared with analogous parameters for classical indirect extrusion. The possibility of shaping inner toothing over the entire product length according to the proposed spline sleeve plastic forming methods was also explored.

Keywords: complex extrusion, spline sleeves, forging gear, new method extrusion

1. Introduction

Forging or extrusion methods can be used for manufacturing products with either outer or inner toothing with production volumes much larger than 1000 pieces [1,2]. Like in other plastic working methods, the potential for applications is limited to some types of gear wheels. There are gear wheel types, especially in the automotive industry, whose manufacture via extrusion may bring about economic benefits [3]. They include gear wheels with one or more straight tooth rims and gear wheels with an additional inner spline toothing [4]. It can also be advantageous to combine extrusion with subsequent press forming – cold burnishing of toothing in a multi-operation process, to be 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 [5-7].

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 labour 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 labour 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 tools or replacing their parts during series production, due to their poor durability, also contributes to an increase in process labour intensity as well as time-consuming, which clearly translates into process economy [1,3].

Spline sleeves are most often manufactured of steel St 52.3 or 16 MnCsS 5. One of their major functions is linear guiding in plotters. Protection against rotation and ensuring feed evenly linear is also important. 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

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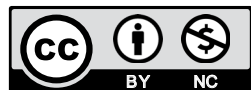
cylindrical, flanged or as a clamping ring. Some varieties are made of bronze Rg7 (GC – CuSn 5/7 ZnPb). The flanged spline sleeve is manufactured according to standard DIN ISO 14.

Figure 1 shows examples of spline sleeve and ring products.

Fig. 1. Spline sleeves and rings [1]

This publication has proposed processes for the manufacture of spline sleeves with inner toothing. The proposed processes are based on the author's extrusion concepts protected by the Polish Invention Patent [PL219182, PL221425] [9,10]. The proposed method is assumed to be an alternative to the operation of the press forming of inner spline sleeve toothing in a conical die [1], to the operation of swaging on rotary swaging machines [1] and to forward and backward push broaching processes [4].

2. The concept and purpose of the proposed complex extrusion methods

The complex extrusion method [9] consists in that the stock material is put in cylindrical die 2 on a slidable forming sleeve 3. The material is subjected to the complex process of extrusion with punch 1 until a shank sleeve has been extruded (Fig. 2b). Then, a further sleeve extrusion process is performed with punch 1, while pushing out forming sleeve 4 and cut-off sleeve 3 from the die. The extrusion process is continued until cut-off sleeve 3 is locked (Fig. 2c). The bottom of the sleeve being extruded is cut off using punch 1 and cut-off sleeve 3. Waste formed is removed using knock-out 6. Thus obtained sleeve has a through hole of a diameter corresponding to that of punch 1. The main advantage of the process is the fact that, as compared to the conventional solutions, it enables the production of long sleeves. No additional technological operations, such as annealing or heating up the stock, are needed. At the same time, a much smaller pressure force is applied, and the metal excess is automatically cut off by the extruding tool and removed from the container. There is no need for mechanical cutting off the sleeve bottom after the extrusion process.

The schematic diagram of the process is shown in Figure 2, where Fig. 2a represents schematically the initial state of the

process prior to the through-sleeve extrusion operation, Fig. 2b and Fig. 2c show schematically the through-sleeve extrusion process, and Fig. 2d illustrates schematically the final state of the through-sleeve extrusion process – the finished product.
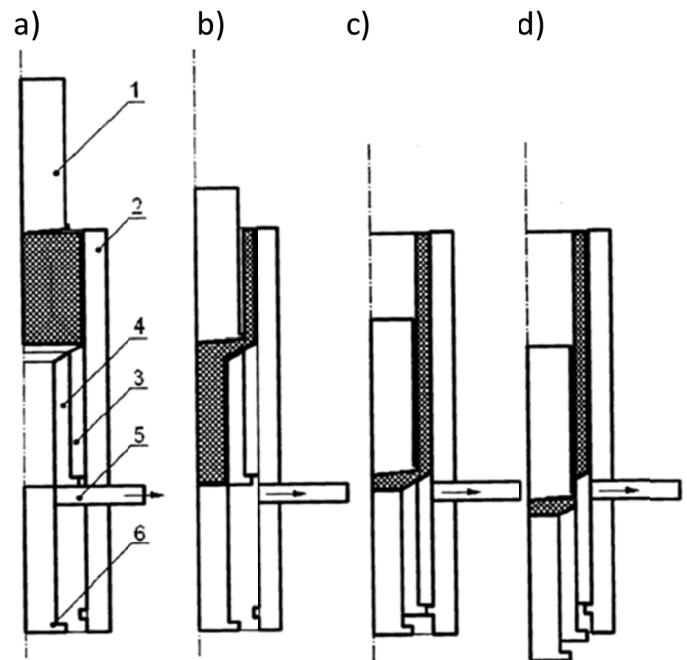

Fig. 2. Schematic diagram of the complex through-sleeve extrusion process [9]: 1. punch, 2. container, 3. cut-off sleeve, 4. forming sleeve, 5. lock, 6. knock-out

The complex double-side extrusion method [10] consists in that stock 4 positioned in cylindrical die 2 is subjected to the process of double-side extrusion. At this stage, punch 1 is movable, while lower punch 2 is a fixed tool. A double-sided sleeve of different inner diameters is formed (Fig. 3b). Next, the further process of sleeve extrusion is performed with upper punch 1. At the same time, knock-out 6 is retracted from die 2 and pilot sleeve 5 until upper punch 1 has entered the pilot sleeve. A sleeve with a through-hole diameter identical to that of upper punch 1 is thus formed.

The schematic diagram of the process is shown in the figures below, where Fig. 3a represents schematically the initial state of the process prior to the through-sleeve extrusion operation, Fig. 3b and Fig. 3c show schematically the through-sleeve extrusion process, while Fig.3d illustrates schematically the final state of the through-sleeve extrusion process – the finished product.

The aim of the numerical studies was to assess the possibility of using the developed author's methods of plastic forming of deep bottomless sleeves for the production of inner toothing in spline sleeves. The analysis concerned long products intended for the manufacture of, e.g., couplings. The basic criterion in the assessment of manufacturing possibility is the effect of the combination of different deformation schemes on the force needed for plastic forming, material flow and, as a consequence, the fill of tool impressions, where the toothing or splines are formed.
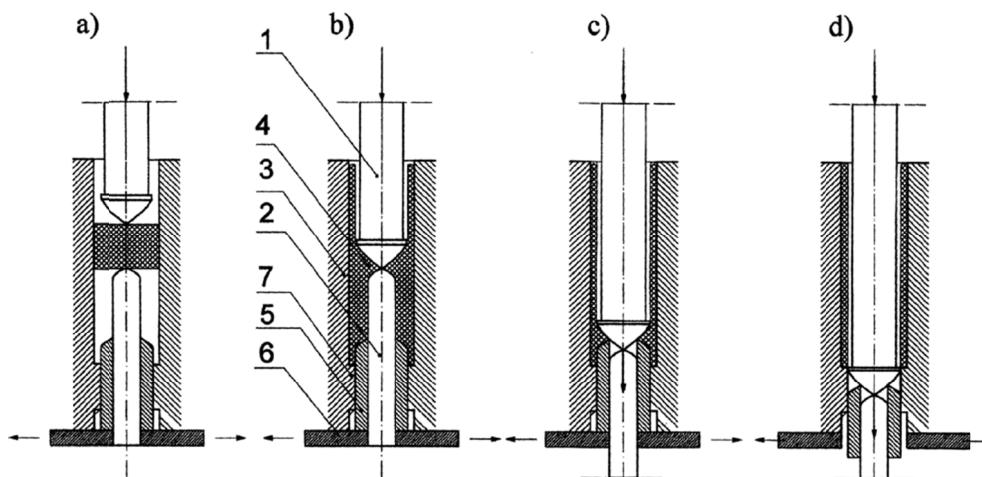
Fig. 3. Schematic diagram of double-side through-sleeve extrusion [10]

3. Assumptions for computer simulations

Computer simulations of the process of extrusion of spline sleeves with inner toothing were performed using the Finite Element Method (FEM). The commercial computation package Foge®3D was used for carrying out the theoretical studies.

For performing the numerical modelling of the spline sleeve *complex extrusion process*, a tool built in the CAD environment was used, which included punch 1 and container 2 that had inside it two slidable sleeves 3 and 4 blocked with lock 5. Sleeve 3 forms a cut-off sleeve for the stock material, while sleeve 4 is a forming sleeve. Knock-out 6 of the tool is used for pushing out the waste and, after completion of the process, it sets sleeves 3 and 4 in the initial position.
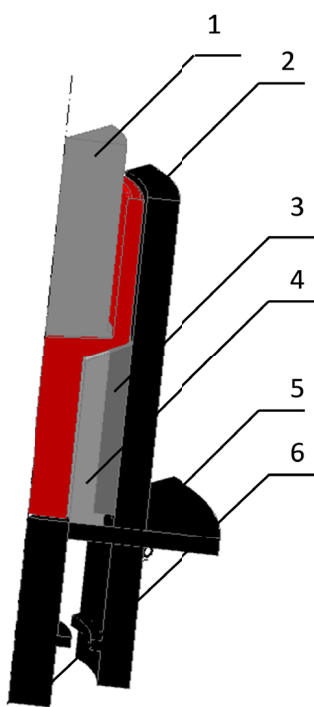
Figure 4 shows a CAD visualization of the tool, using which the computations were made in the Forge®3D numerical program.

For carrying out the numerical modelling of the spline sleeve *two-side complex extrusion process*, a tool built in the CAD environment was used, which had punch 1 and container 4 with punch 2 and pilot sleeve 3 inside it. Pilot sleeve 3 forms a cut-off sleeve for the stock material. Knock-out 6 of the tool is used for pushing out the waste and, after completion of the process, it sets sleeve 3 in the initial position.
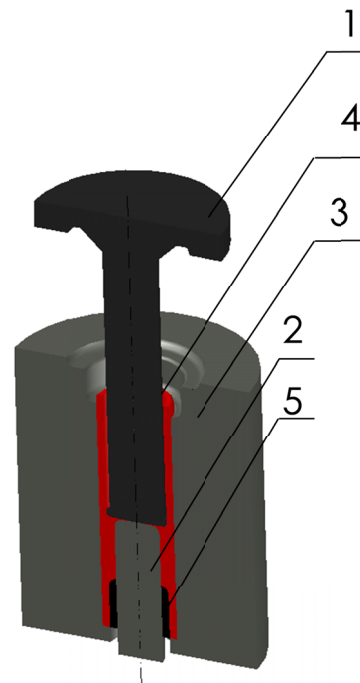

Fig. 4. The CAD model tool scheme for computer simulation of the complex extrusion process

Fig. 5. The CAD model computer simulation tool scheme of the double – side extrusion process

Figure 5 shows a CAD visualization of the tool, using which the computations were made in the Forge®3D numerical program.

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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 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.

For the numerical studies, ϕ49 mm×90 mm cylindrical stock was used. 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 [8,11], which can be expressed with the equation below:

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

where:

S_{ij} – stress tensor deviator, [12],
$\dot{\varepsilon}$ – strain rate intensity,
ε_{ij} – strain rate tensor,
ε – strain intensity,
T – temperature,

K – consistence being dependent on the yield stress σ_p,
m – coefficient characterizing hot metal deformation $(0 < m < 1)$ [13].

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, $m5$ = 0, $m7$ = 0, $m8$ = 0, $m9$ = 0 and were taken from the Forge®3D database. Because of considerable plastic deformations occurring in the processes under analysis, the Treska friction model with the value m = 0.8 was adopted for 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.

4. Modelling and numerical computation results

Figure 6 illustrates the computer simulation of the bottomless spline sleeve complex extrusion process. This is a thermomechanical analysis of plastic forming. In the longitudinal section, the distribution of temperature at individual stages is shown. A characteristic feature of such a deformation scheme
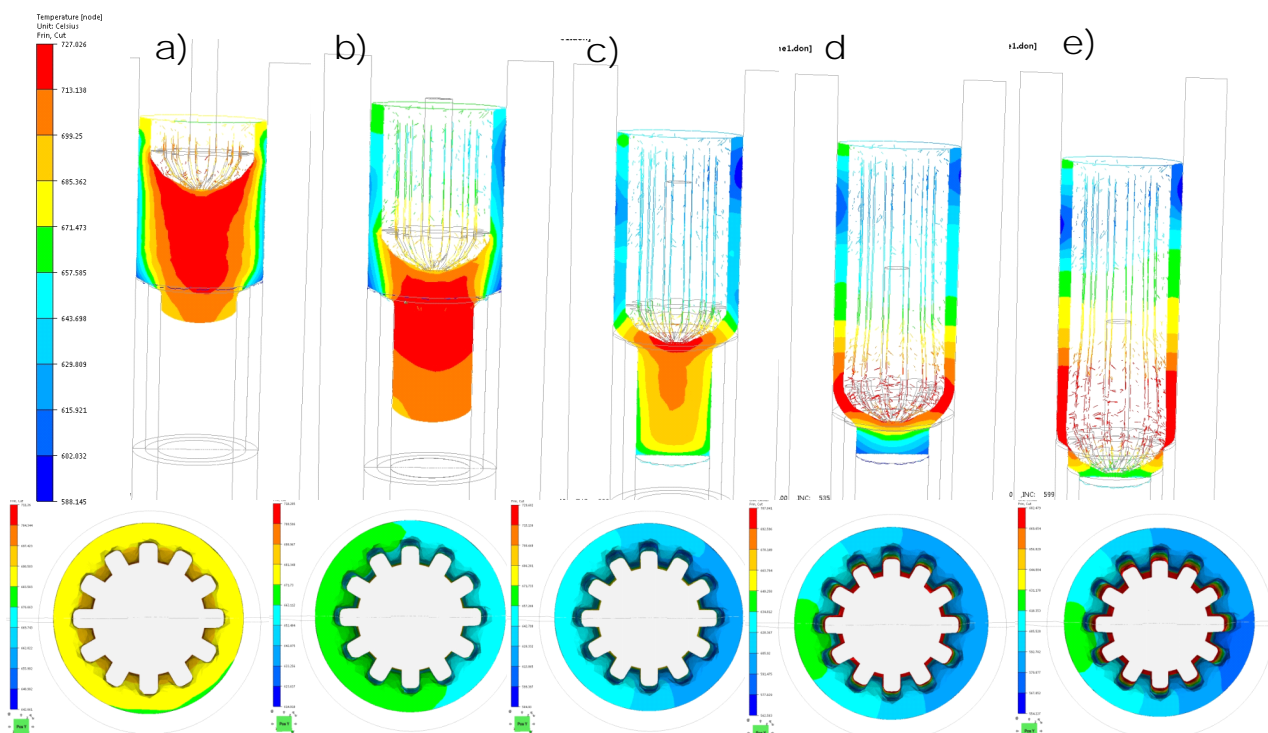

Fig. 6. Computer simulation of the spline sleeve complex extrusion process on the example of temperature distribution; a),b) the first stage, c),d) the second stage, e) sleeve bottom cutting off

is the formation of internal heat sources. They are originated from friction inside the material due to plastic deformations and from the friction of the metal against the tool surface. This is visible especially at the first stage of the process (Figs. 6a,b). As a result of this, metal temperature decreases in some locations and plastic flow resistance decreases. This results in a reduction in energy and force parameters. This decrease in plastic flow resistance causes a faster and more accurate fill of the impressions where the inner toothing is formed (Figs. 6c,d,e).

The effect of the conversion of plastic deformation energy into thermal energy is visible on the graph of the relationship of press pressure force as a function of punch path (Fig. 7). At the first stage, the shank sleeve extrusion force reaches a value of (40 tons). The magnitude of extrusion force decreases at the second stage of the process due to an increase in material temperature in the largest plastic deformation zone and a reduction in deformation resistance. The extrusion force does not exceed the value of (20 tons) The force attains a maximum during bottom cutting off, this being only a momentary load of a magnitude of 65 tons.

Figure 8 illustrates the computer simulation of the bottomless spline sleeve complex extrusion process
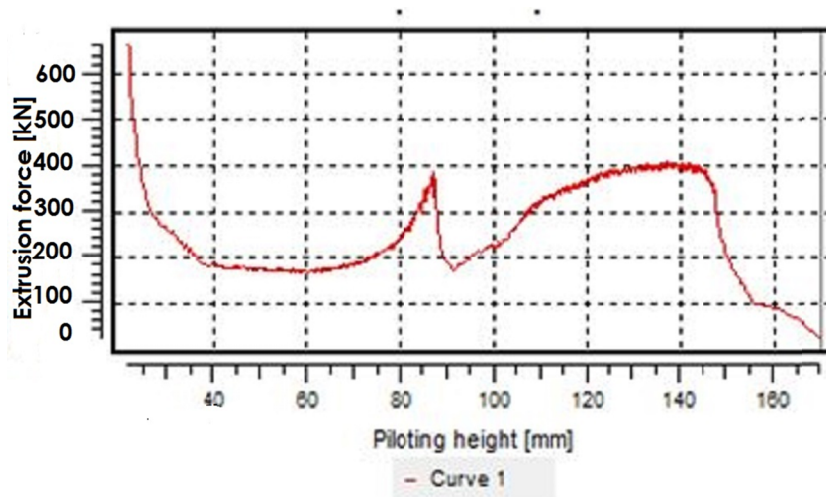

Fig. 7. Press pressure force [kN] as a function of punch path [mm] for complex spline sleeve extrusion
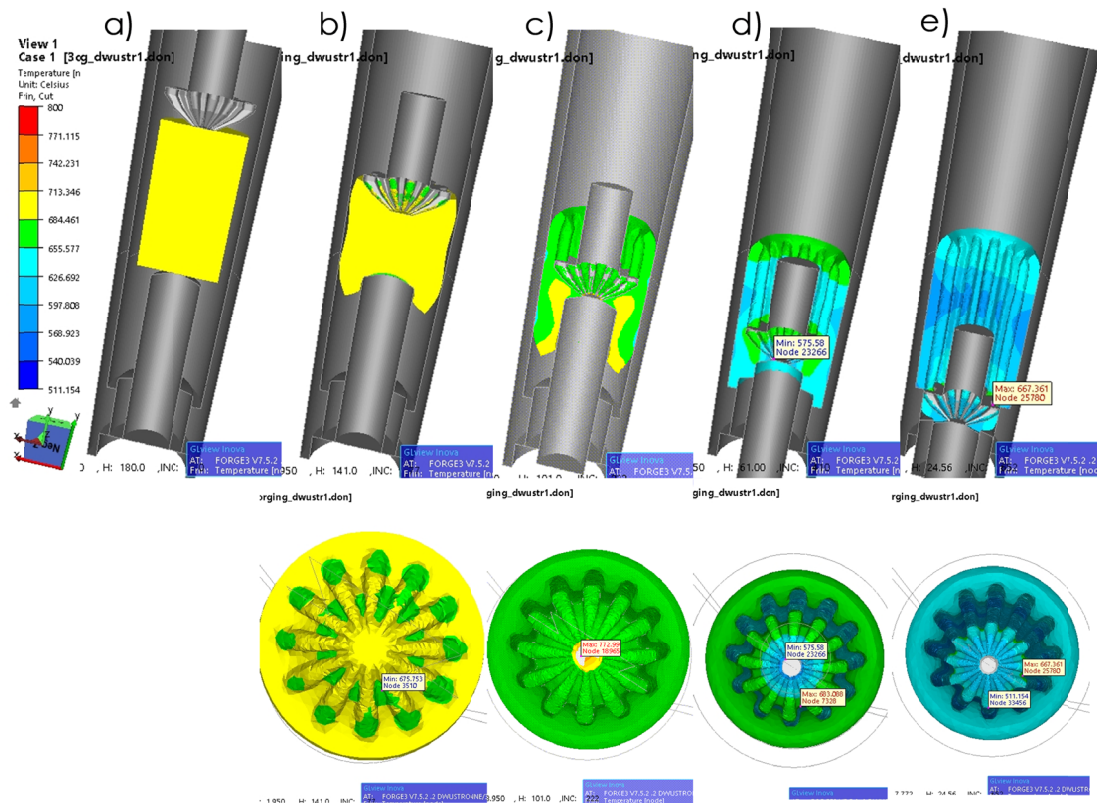

Fig. 8. Computer simulation of the spline sleeve two-side complex extrusion process on the example of temperature distribution; a),b) the first stage, c),d) the second stage, e) sleeve bottom cutting off

The thermomechanical analysis revealed relationships opposite to the ones occurring for complex extrusion. The extrusion force at the first stage is lower than at the second stage. In the region of forming the thick-walled sleeve, the temperature is maintained at the initial value level of $T_0 = 700°C$. The conditions for plastic forming in this extrusion method depend on the wall thickness of the sleeve being formed on the bottom punch.

At the second stage, the product is extruded from the thick-walled sleeve, which, combined with the effect of plastic deformation energy conversion into thermal energy and a larger friction surface area, results in a greater magnitude of extrusion force at the second process stage (Fig. 9).

From the point of view of the usefulness of the proposed methods for application to the extrusion of spline sleeves, plastic
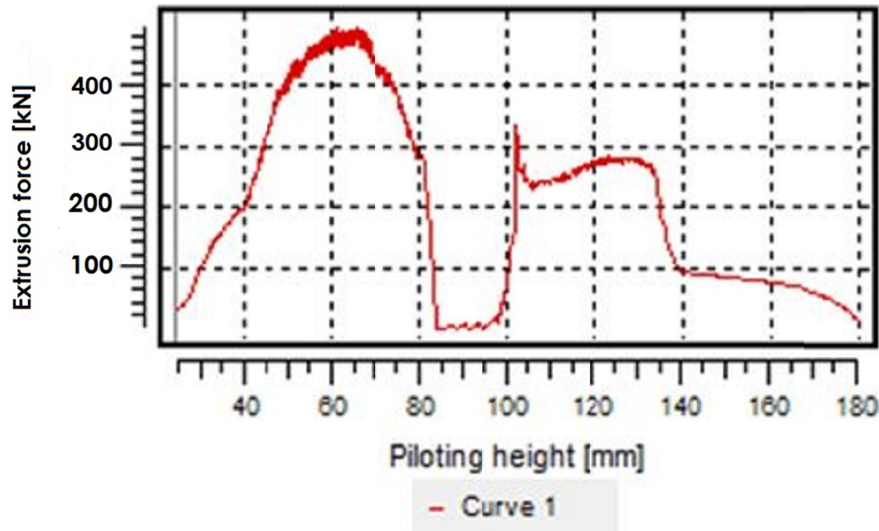

Fig. 9. Press pressure force [kN] as a function of punch path [mm] for spline sleeve two-side complex extrusion
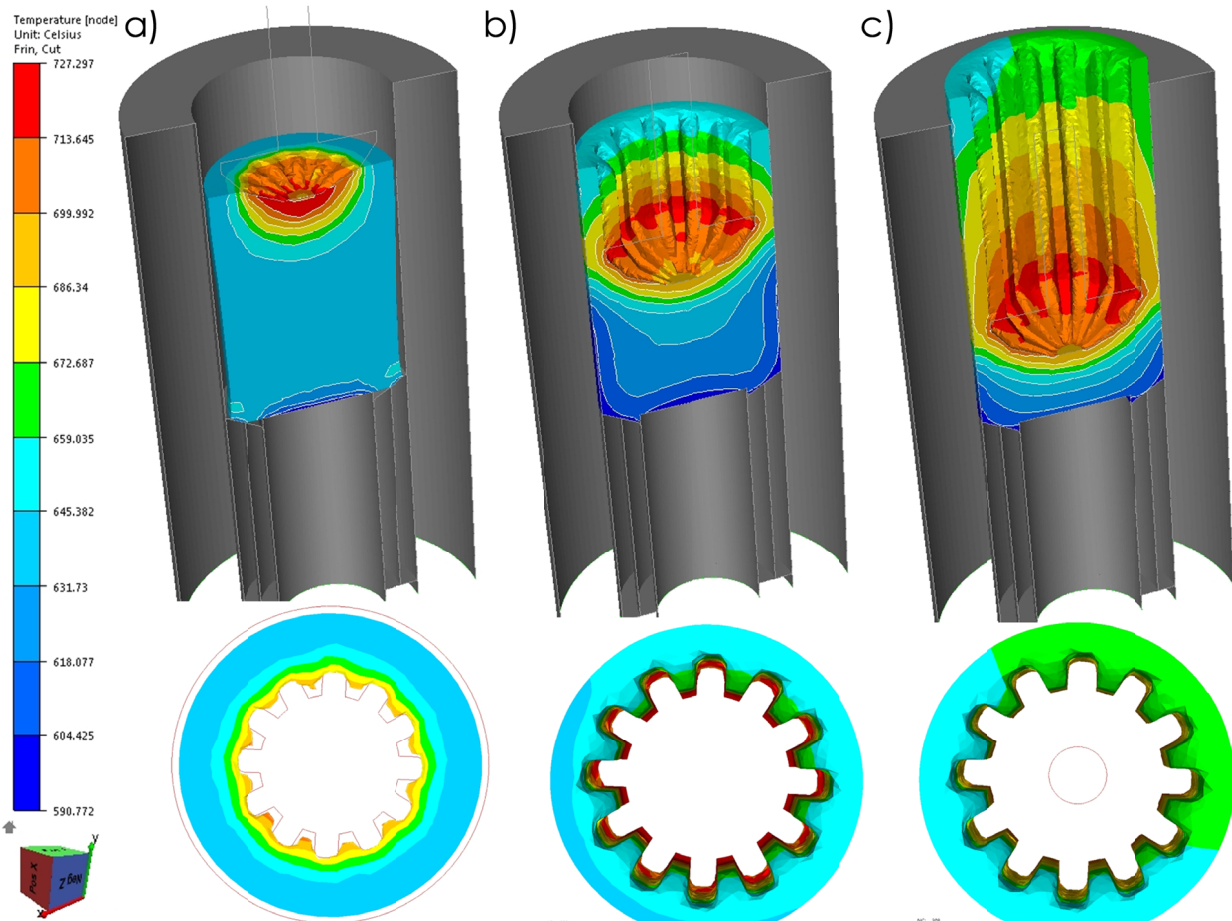

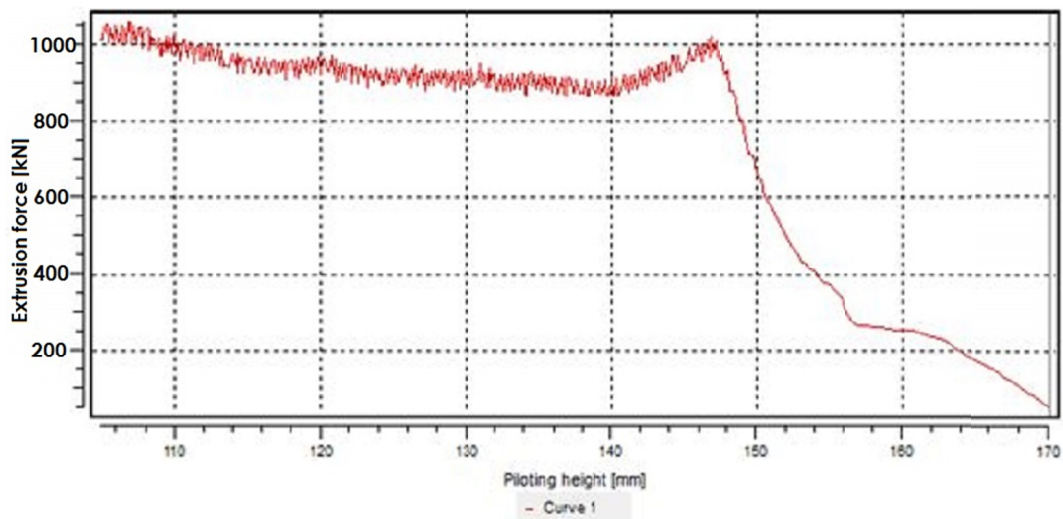Fig. 10. Computer simulation of the indirect extrusion process

Fig. 11. Press pressure force [kN] as a function of punch path [mm] for spline sleeve indirect extrusion

flow in punch impressions and the energy and force parameters were the most important. Numerical computations for complex and two-side extrusion showed that the punch impressions were filled up entirely. However, in order to demonstrate that the proposed methods are viable, a comparative analysis should be made for energy and force parameters.

To this end, numerical computations were performed for indirect extrusion (Fig. 10) to determine to what extent the energy and force parameters would differ from the ones in the proposed novel extrusion methods (Fig. 2 and Fig. 3). Figure 10 illustrates the computer simulation of the spline sleeve indirect extrusion process performed to determine the relationship of extrusion force as a function of punch path.

Figure 11 shows numerical computations that determined the pressure force as a function of punch path. The computations were made for similar temperature and speed conditions, where the punch travel speed was $V = 20$ mm/s and the initial temperature of the stock was $T_0 = 700°C$.

The pressure force, as a maximum value, determined from computations was 100 tons. The graph is characteristic of indirect extrusion, being ascending, because the metal gets overcooled in layers in the container bottom zone.

5. Summary and conclusions

Using complex extrusion-pressing processes creates room for the ingenuity of the designers of technologies and tools. Like for other plastic working methods, the potential for the rational applications of extrusion is limited to some types of toothing. These may include gears or sleeves with a single rim of outer straight toothing and inner spline toothing. Particularly advantageous might be combining familiar deformation schemes (such as direct extrusion, indirect extrusion, side extrusion, radial extrusion, etc.) in a multi-operation process. Such methods, due to a considerable degree of plastic deformation, will surely find application in cold plastic working.

This has been shown by the comparative analysis with numerical computation for press pressure force as a function of punch path. During the computations, the average press pressure force was determined from the entire span of the process. For the complex extrusion method, the average press pressure force was $F_{Nśr} = 35$ tons; for two-side complex extrusion, $F_{Nśr} = 30$ tons; while for classical indirect extrusion, $F_{Nśr} = 75$ tons. This means that the proposed extrusion methods are distinguished by force parameters smaller compared to indirect extrusion by around 50%.

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