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DEVELOPMENT AND MODELLING OF A NOVEL PROCESS OF MANUFACTURING CYLINDRICAL PRODUCTS WITH A VARIABLE LONGITUDINAL-SECTION STUB PIPE

The publication presents a novel concept of the process of plastic forming of variable longitudinal-section cylindrical products, being the subject of Patent Application P.427426 [1]. Additionally, these products are provided with a connection stub pipe. The plastic forming method proposed in the article combines many advantages and utilitarian benefits associated with the manufacturing technology itself, as well as with its further implementation. Using stock in the form of normalized bar commonly available in the metal product market as a finished product obviously reduces the process costs involved with stock preparation, i.e. casting, rolling, machining, etc. It also results in obtaining a much smaller surface area of stock contact with the tool and, as a consequence, a smaller surface of stock friction against the tool, which contributes to a reduction of force needed for the plastic forming of the product. The smaller contact surface area and the shorter time of stock contact with the cooler tool cause, above all, less intensive heat exchange and stock chilling. This has a significant effect on the plasticity of the cast material and, as a consequence, the plastic forming force. The proposed method enables also manufacturing cylinders with either a closed or open stub pipe with a regulated length and a varying section. In addition, unlike the method known from Polish Patent Specification PL 212062 [2], the proposed method does not require using a multi-tool press. The upper punch is furnished with a flange, whose job is to start the stock extruding sleeve at the next process stage.

Keywords: cylinder extrusion, FEM analysis, bronze extrusion, hot extrusion

1. Introduction

Plastic forming processes such as: extrusion, forging and rolling [3-6] are used in the production of hollow products used for the transmission of various media: gas and liquid. Combining known extrusion processes [7,8], forging [9] and rolling [10] allows you to reduce the plastic resistance of the metal and obtain lower strength parameters [11,12]

The article presents a novel concept for the process of plastic forming of variable longitudinal-section cylindrical products furnished with a connection stub pipe. The concept is the subject of Patent Application P.427426 [12]. Products of this type are currently manufactured using a cut-off fragment of tube or a hollow with a hole in its bottom, to which a pre-drilled hollow is joined by the fillet welding method [12]. Such a construction has at least two welded joints in its structure, whereby it requires considerable labour intensity involved with welding, reaming and finishing machining operations. The purpose of stub-pipe cylinders is to deliver compressed media (such as liquid, air, etc.) to transfer lines connected to the stub pipe. Any joints, such as welds or bolted joints, cause the risk of the construction becoming untight due to the work of the material caused by variations in pressures and temperatures, as well as a result of the cavitation phenomenon. It is therefore desirable for these types of connections to have a solid construction that will eliminate the risk of the aforementioned phenomena.

The proposed method consists in that stock material in the form of a bar placed in a cylindrical container with a slidable sleeve is subjected to the process of upsetting. The upper punch acts up to the moment of pushing the stock material out from the sleeve of an inner diameter being equal to that of the upper punch. Then, by operating the upper punch and the sleeve simultaneously, the previously upset stock material is extruded through the clearance between the cylindrical container and the tool plate. Radial and direct extrusion is used, whereupon the operation of cylinder bottom perforation is done in the tool plate hole with the upper punch. The fundamental difference between the proposed method and the hollow product manufacturing process known from Polish Patent Specification PL 212062 [2] is the possibility of using stock in the form of a bar, offered by the former. A bar may have a much greater length than usual, e.g. exceeding the three times its diameter.

Using stock in the form of normalized bar available in the metal product market as a finished product obviously reduces the process costs. These costs are associated with stock preparation, including casting, rolling, machining, etc. Using a bar as stock results in obtaining a much smaller surface area of contact between the stock and the tool and, as a consequence, a smaller surface of

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stock friction against the tool. This contributes to a reduction of force needed for the plastic forming of the product. The smaller contact surface area and the shorter time of stock contact with the cooler tool results in less intensive heat exchange and stock chilling. This substantially influences the plasticity of the cast material and, as a consequence, the plastic forming force. The proposed method enables also manufacturing cylinders with either a closed or open stub pipe with a regulated length and a varying section. The upper ram is furnished with a flange, whose job is to start the stock extruding sleeve at the next process stage.

Modelling of the plastic forming process was performed in the numerical program Forge 3D®, including thermomechanical computations. Basic process characteristics, such as energy-force parameters and the distributions of temperatures, were determined. A comparative analysis of the proposed methods against other methods of plastic forming of similar products was made.

2. The novel process concept

The proposed method of manufacturing the stub-pipe cylinder [1] is based largely on the author's patent [13,14], in which movable die inserts in the tool container are used. Based on this concept, a series of author's metal product forming processes have been developed. Examples of these processes include:

a) the method of extruding the front-ribbed valve (alloy TiAl6V4) (Fig. 1)

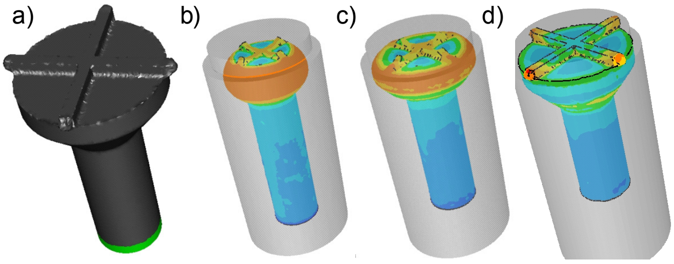

Fig. 1. Numerical modelling of the process of extrusion the cross-ribbed valve – [the author's study]

Introducing the pre-upsetting of the bar portion beyond the movable die insert, followed by the extrusion of the remaining stock portion, to the deformation method (a) yielded very satisfactory results. Most of all, this reduced the plastic forming force, compared to the classic method, as demonstrated in Fig. 2.

b) forging of toothed gears (AlMgSi) (Fig. 3)

A common feature of processes (Fig. 2 and Fig. 3) is the use of stock in the form of a bar and, as a consequence, a relatively small force needed for the plastic forming of products (Fig. 2 and Fig. 4).

Therefore, a concept arose to use such deformation schemes in the proposed novel method of extruding cylinders.

For carrying out the proposed process, a schematic tool was used (Fig. 5). The tool has cylindrical container 1, which houses upper punch 2 with slidable sleeve 3 and lock 4. Slidable sleeve 4 constitutes a tool whereby the upsetting process is conducted, the stability of the upset stock material is maintained, and the extrusion process is carried out. Tool plate 5 provided with a hole is used for the radial and direct extrusion of the stock and the perforation of the bottom. While ejector 6 serves to initially

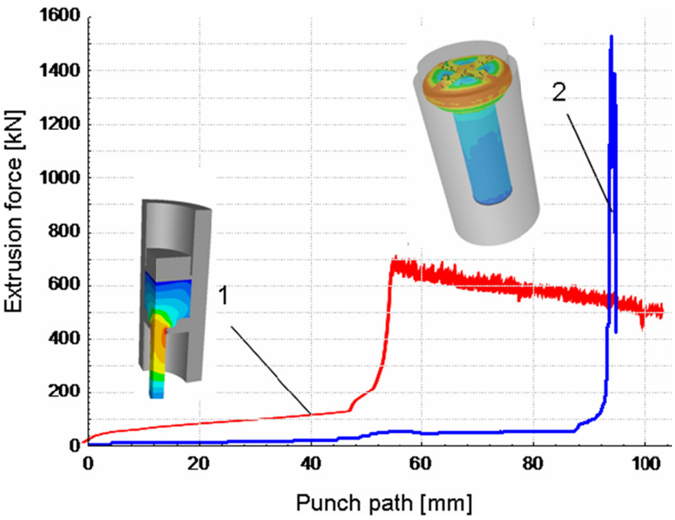

Fig. 2. Dependence of pressure force on the punch path: 1. the direct extrusion process; 2. forging in the slidable die

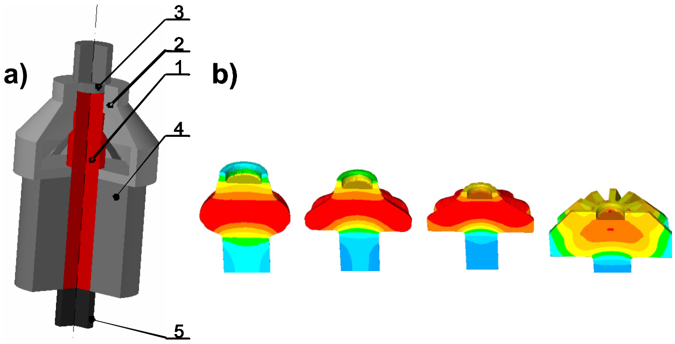

Fig. 3. Toothed gear forging modelling process; a) tool concept; b) numerical modelling – [the author's study]. 1. stock material (ϕ 20 mm bar), 2, die, 3, punch, 4, slidable insert, 5 ejector

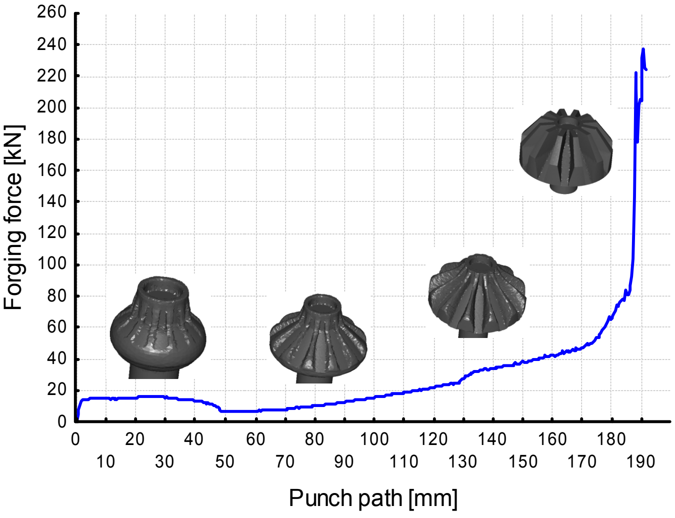

Fig. 4. Dependence of forging force on the punch path

lock the stock, and after completion of the process, to push the product out and to remove the resulted waste.

The proposed novel method of extruding the stub-pipe cylinder (Fig. 5) consists in that stock material in the form of a bar placed in cylindrical contained 1 with a slidable sleeve 3 is initially subjected to the process of upsetting. The stock is pressed on by upper punch 2 until the stock material is completely pushed out from slidable sleeve 3. The sleeve has an inner diameter equal to the diameter of the upper punch. Then, lock 4 is released and, by acting with upper punch 2 and slidable sleeve 3 simultaneously, the previously upset stock material is extruded. The extrusion takes place through the clearance between cylindrical container 1 and tool plate 5. This is radial and direct extrusion. Next, ejector 6 is retracted down, after which the operation of cylinder bottom perforation is performed in tool plate hole 5 with the upper punch.

Figure 5 a illustrates the initial state of the process, figure 5b illustrates the process of upsetting perform from of a bar, figure 5c,d, illustrates process of direct, indirect and radial extrusion.

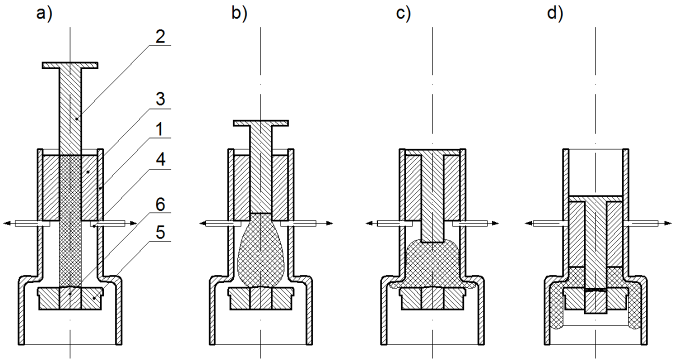

Fig. 5. Schematic diagram of the stub-pipe cylinder extrusion process [see a description in the text.]. 1. cylindrical container, 2. upper punch, 3. slidable sleeve, 4. lock, 5. plate, 6. ejector

The purpose of this study is to propose a method for manufacturing the stub-pipe cylinder (e.g. for pressure connections, cross-section reductions), which will enable the reduction to a minimum or elimination of machining. The manufacture will be possible by the plastic forming of a variable longitudinal-section product in a single technological operation. Moreover, no need for using separate tools will occur, and the main advantage will be the reduction of the force parameters of the entire process.

The concept assumes that the stock will be normalized bars commonly available in the metal product market. This will substantially reduce the cost of stock preparation, and the only operation will be cutting the stock into appropriate lengths and finishing machining.

3. Assumptions and numerical computations

Numerical modelling of the process 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 aluminium bronze in grade CuAl10Ni5Fe4 (BA1054). The main characteristic of bronze in grade BA1054 high strength and ductility, both at ambient temperature and at elevated temperatures, as well as good abrasion and corrosion resistance (e.g. to 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 numerical studies, ϕ20 mm × 120 mm cylindrical bar was used.

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 [15,16], which can be expressed with the equation below:

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

where: S_{ij} – stress tensor deviator, [16], $\dot{\varepsilon}$ – 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 ($0 < m < 1$).

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 – 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. Because of considerable plastic deformations occurring both in the examined process and the comparative process(Fig. 8 and Fig. 9), the Treska friction model with the value m = 0.8 was adopted to computation. The initial process temperature was T_0 = 700°C, tool temperature was 250°C, and the speed of tool travel for the examined processes was V = 25 mm/s.

Figure 6 illustrates the numerical modelling of the stub-pipe cylinder manufacturing process on the example of temperature distribution.

When used in the form of a ϕ20 mm-diameter prismatic bar, the stock is subjected to partial upsetting at the first stage of the process. At the same time, the upper part of the stock is pushed out from the tool. Because the stock part being upset has no contact with the cooler tool, it will not cool down fast (Fig. 6a,b). The stock portion being pushed out from the sleeve, on the other hand, is subjected to friction against the sleeve surface, whereby it also loses less heat from its surface. Practically during the whole

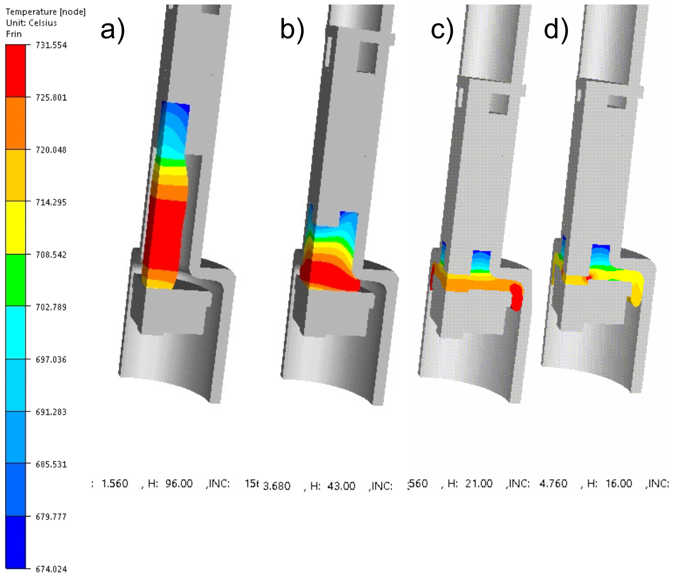

Fig. 6. The distribution of temperature during the stub-pipe cylinder extrusion process: a) upsetting the stock beyond the sleeve, b) direct and side extrusion, c) forcing through the die, d) stub-pipe punching

extrusion process, the temperature of the middle stock portion does not go down below the initial temperature. An advantage of the plastic forming scheme is a low deformation resistance of the stock material because of the high temperature and local heat sources in the plastic deformation zones. This is also due to a much smaller surface of friction between the stock and the tools.

The low deformation resistance of the metal is associated with relatively low energy and force parameters. This can be seen on the example of the distributions of the pressures of the deformed metal on the tools in correlation with the graph of extrusion force as a function of the punch path (Fig. 7).

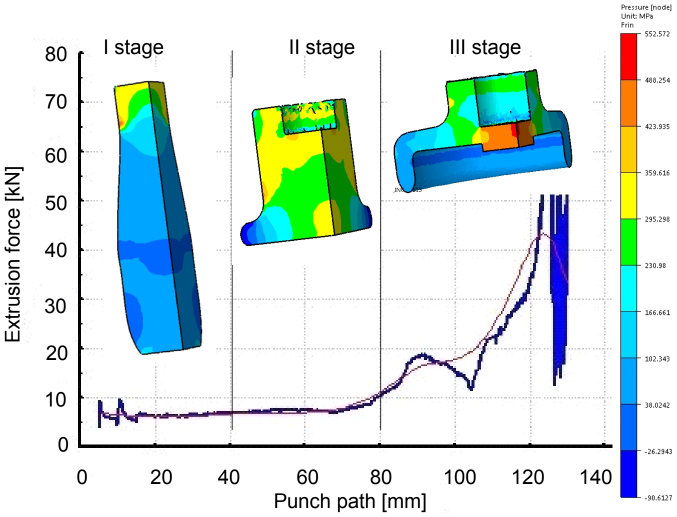

Fig. 7. The distribution of metal pressures on the tools in correlation with extrusion force as a function of the3 punch path

The magnitude of extrusion force, shown in the graph, is related to the 1/4 of the stock volume. Computation was done for the 1/4 of the stock because of the axial symmetry of the process. The maximum extrusion force for the whole stock was, therefore, four times the computed value, i.e. 168 kN. As can be seen from the presented pressure distribution, the pressures and the smallest at Stage I. At Stage II, the metal exerts pressure already on the container walls, the die and the ejector. At the end of Stage II, the force increases. At Stage III, the stub-pipe and the cylinder are formed. The metal exerts the greatest pressure on the punch that perforates the bottom. The extrusion force at this stage also rapidly increases.

To demonstrate that the proposed stub-pipe cylinder extrusion process is advantageous from the point of view of force parameters, computations were performed for three alternative stub-pipe cylinder extrusion methods, namely:

- direct extrusion,
- indirect extrusion with forcing through,
- double-side extrusion.

Direct extrusion of the stub-pipe cylinder

Figure 8 shows a schematic diagram of the computer model of the stub-pipe cylinder direct extrusion simulation tools. Stock 1 in container 2 is extruded by punch 3 through die 4.

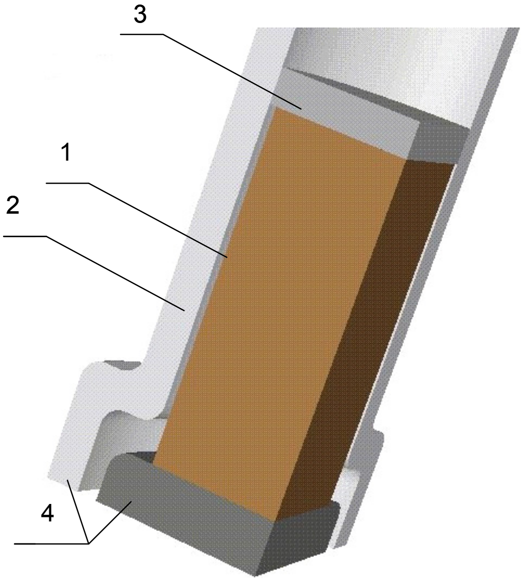

Fig. 8. Schematic diagram of the model of the direct extrusion process tools. 1. stock, 2. container, 3. punch, 4. die

Figure 9 illustrates the computer simulation of the stub-pipe cylinder extrusion process along with the distribution of the temperature of the deformed stock in cross-section.

The obtained temperature distribution shows that, at the initial stage, the stock was substantially overcooled. The reason for this is the fact that the stock contacts the much cooler tool with all its surface and, with the absence of plastic deformations, the metal relatively readily gives up heat to the tools. In addition, to produce the stub-pipe, it is necessary to perform a forging shank perforation or drilling operation.

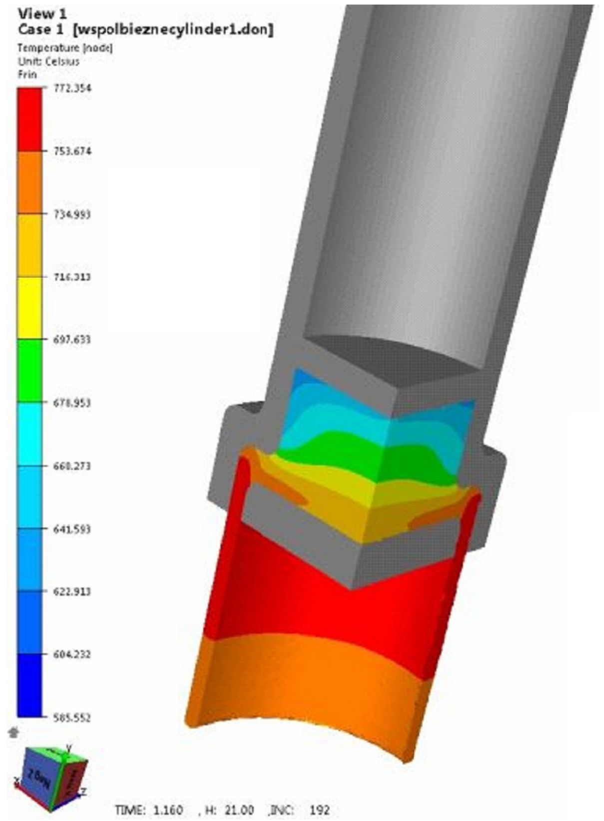

Fig. 9. The distribution of temperature during the stub-pipe cylinder direct extrusion process

Indirect extrusion of the stub-pipe cylinder

Figure 10 shows the CAD model of the tool for carrying out computer simulation of the stub-pipe cylinder indirect extrusion process.

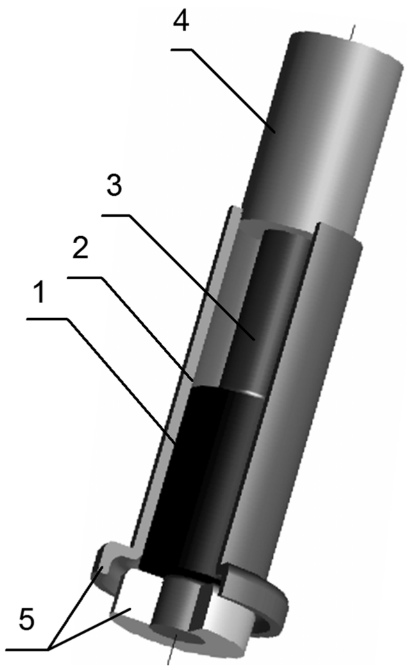

Fig. 10. Schematic diagram of the CAD models of the tool for computer simulation of the process. 1. stock, 2 contained, 3. punch, 4. tools, 5. die

At Stage I, stock 1 placed in contained 2 is indirectly extruded by punch 3. The, at Stage II, tool 4 forces the hollow semi-finished product through die 5.

Figure 11 shows the distribution of temperature in the process of stub-pipe cylinder indirect extrusion and forcing-through.

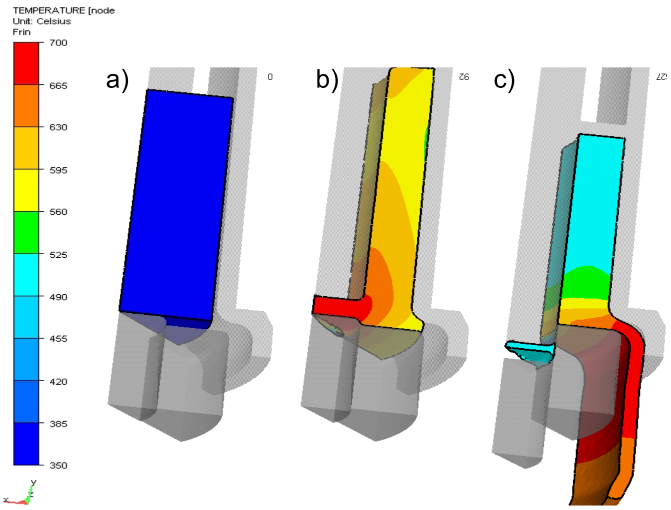

Fig. 11. Distribution of temperature during the process of stub-pipe cylinder indirect extrusion and forcing through; a) initial state, b) indirect extrusion, c) forcing through and perforation

As a result of plastic deformations, during indirect extrusion at the first stage of the process, the stock temperature stays slightly below the initial temperature. This is why during forcing the semi-finished product through the die the stock plastic forming temperature exceeds the initial temperature on the entire cylinder cross-section. It is this feature that essentially distinguishes this process from the direct extrusion process.

Double-side stub-pipe cylinder extrusion and forcing through

The process of double-side extrusion of the stub-pipe cylinder is based on the author's patented method of extrusion of bottomed and bottomless hollows. The purpose of applying this deformation scheme was to substantially reduce the force parameters of cylindrical product extrusion. Therefore it was used for a comparative analysis to compare it with the new stub-pipe cylinder extrusion method proposed in this study.

Figure 12 shows a schematic diagram of the computer model of the tools for stub-pipe cylinder double-side extrusion simulation.

Figure 13 shows the distribution of temperature in computer modelling of the process of stub-pipe cylinder double-side extrusion.

Double-side extrusion causes an increase in temperature in the zone between the punches. These are the largest plastic deformations. Thanks to this, at the second stage of the process (Fig. 13c), the stock that is subjected to side extrusion is at a temperature much higher than the initial temperature. This

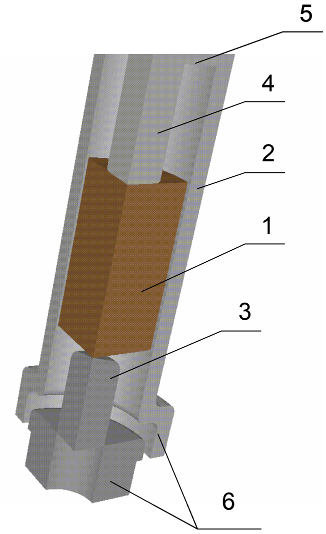

Fig. 12. Schematic diagram of the model of the tools for the double-side extrusion process. 1. perform, 2. container, 3. lower die, 4. upper die, 5. plate, 6 shaping tool

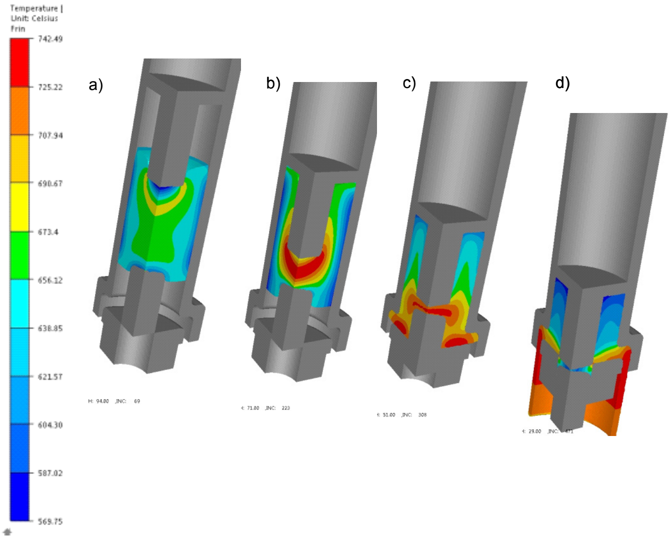

Fig. 13. Temperature distribution in the double-side extrusion and forcing-through process. a), b) hollow double-side extrusion., c) side extrusion, d) forcing-through and punching

allows much smaller forces needed for stock plastic forming to be obtained.

Figure 14 shows force and energy parameters for four stub-pipe cylinder extrusion processes. In Figure 14a, the graph of extrusion force as a function of the punch path is shown for the novel patented extrusion method proposed in the study. Figures 14b-d show the graph of extrusion force as a function of the punch path for direct extrusion, double-side extrusion and indirect extrusion, respectively.

The results presented for all extrusion methods relate to the 1/4 of the deformed stock volume. This way of computation was adopted because of the axial symmetry of the process.

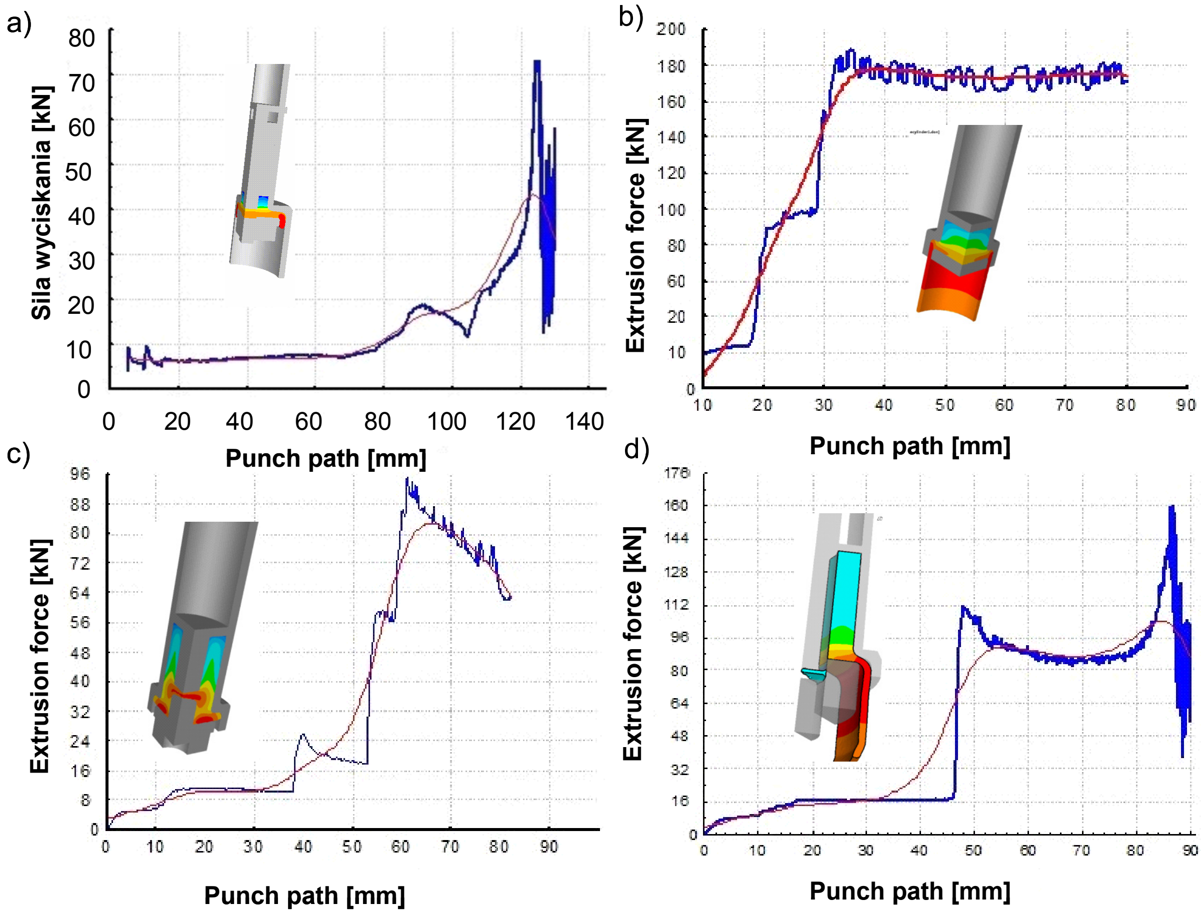

Fig. 14. Diagrams of extrusion force as a function of the punch path. a) new extrusion method, b), c), d) alternative methods

For the method illustrated in Fig. 14a, the maximum force was 168 kN, while for the other methods it was, respectively: (Fig. 14b) – 720 kN, (Fig. 14c) – 328 kN and (Fig. 14d) – 400 kN.

The analysis of the computation results obtained through numerical modelling shows that the method of stub-pipe cylinder extrusion according to the new concept (Fig. 5) [ ] has the lowest energy and force parameters. The cause is the intensification of plastic deformations and the combination of the upsetting, indirect extrusion, side extrusion and forcing-through schemes. The formation of many localized temperature increases, especially during upsetting of the stock caused a drop in metal plastic flow resistance. As a consequence, this caused a decrease in force parameters, compared to the presented alternative extrusion methods. An important aspect are also much smaller surfaces of stock-tool contact. In that case, friction forces and heat exchange are much lower, compared to the other methods.

4. Conclusions

Using stock in the form of normalized bar commonly available as a finished product in the metal product market clearly reduces the costs involved with stock preparation for plastic working, including casting, rolling, machining, etc. The proposed deformation scheme makes it possible to obtain a much smaller surface of stock contact with the tool. This results in a smaller surface of stock friction against the tools. This contributes to a reduction of force needed for the plastic forming of the product. The smaller contact surface area and the shorter time of stock contact with the cooler tool results primarily in less intensive heat exchange and stock cooling down. This substantially influences the resistance to material plastic forming and, as a consequence, the extrusion force. The proposed method enables also manufacturing cylinders with either a closed or open stub-pipe with a regulated length and a varying section.

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