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THE THEORETICAL AND EXPERIMENTAL COMPARATIVE ANALYSIS OF NEW METHOD OF EXTRUSION OF DEEP SLEEVES AND INDIRECT EXTRUSION

TEORETYCZNA I DOŚWIADCZALNA ANALIZA PORÓWNAWCZA NOWYCH SPOSOBÓW WYCISKANIA TULEI GŁĘBOKICH Z WYCISKANIEM PRZECIWBIEŻNYM

The plastic working of materials is the most widespread and prospective method of forming semi-finished and finished products in the machine-building and the metallurgical industries.

One of the basic methods of manufacturing tubes, bars, shapes and machine parts from steel and nonferrous metals by plastic working is the extrusion method. Extruded products are characterized by good mechanical properties, high accuracy, and a clean and smooth surface.

Among all products manufactured in the metallurgical and the machine-building industries, seamless tubes and sleeves make up a major part.

Sleeves can either constitute a semi-finished product intended for further plastic working or machining, or be sold as finished products.

There are several methods of manufacturing sleeves, and the choice of one of them depends on the purpose of the product and its dimensions.

The most widespread method of manufacturing bottomed sleeves is by indirect extrusion. The wide application of this method is chiefly due to the relatively low costs of tools used in extrusion. Sleeves produced by the indirect extrusion method are, however, burdened with some faults, including their wall thickness variability and eccentricity.

The main criterion decisive to the application of the indirect extrusion method in industry is the ratio of the overall height, H_c, of a sleeves to its inner diameter, D_w, (H_{rmc}/D_w). If the ratio of these two dimensions of a sleeve is $H_c/D_w \geqslant 2.5$, then the product is treated as a deep sleeve. The use of the indirect extrusion method in that case is technologically, from the point of view of energy and force process parameters, not recommended.

For the entire duration of the extrusion process, maximal loads act on the extrusion ram, and the variation of the extrusion force is ascending in behaviour.

A method is also used in industry, which involves carrying out preliminary indirect extrusion of a thick-walled sleeve in one tool, followed by the operation of drawing this sleeve through a conical die in another tool to elongate the sleeve and to thin its walls. However, this method involves the use of at least two industrial presses, two sets of tools and the necessity of heating up the stock, which obviously elongates the production cycle of a product unit and increases energy consumption; and, as a consequence, the overall production costs increase.

Other methods of manufacturing deep sleeves or cylinders for the purposes of the machine-building industry are also used in production practice, which consist in joining the sleeve with the bottom by the pressure welding or fusion welding of a semi-finished product produced, e.g., on a press rolling mill. However, the cost of manufacture of 1 running metre of such a semi-finished product is by 30% higher than that of 1 running metre of a corresponding sleeve produced by the extrusion method. Bottomed sleeves are often used either as finished products or semi-finished products intended for the manufacture of hydraulic cylinders designed for operation under the conditions of extreme temperatures and pressures, and it is therefore required that their construction be uniform.

In the presented work, the problem of manufacturing deep bottomed sleeves is solved by applying a method of extrusion in a single technological operation. Two new methods of extruding sleeves are proposed, which are based on known mixed extrusion schemes that allow the elimination of the engineering problems and limitations occurring in the existing processes of manufacturing sleeves.

On the basis of preliminary tests it has been found that, using these new methods, deep bottomed sleeves with a relatively small bottom thickness and a sufficiently uniform wall thickness can be manufactured. Moreover, these methods can be used for making sleeves with a shank (in the case of two-sided extrusion with an opening) of any arbitrary length (depth), thickness

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(diameter) and with any arbitrary cross-sectional shape, without having to adjust the tool during the extrusion process, while using an appropriate tool design, bottomless sleeves can also be manufactured.

It was also demonstrated that, in the single-operation extrusion of sleeves using the new methods, lower magnitudes of forces and pressures on the tools occurred, compared to the most commonly used method of indirect extrusion of sleeves.

It was found that, during extrusion, local heat sources formed in the bulk of metal as a result of its plastic flow, which facilitate metal deformation, resulting in much milder conditions of machine and equipment operation.

Within theoretical studies, computer simulations of the both new extrusion processes were performed using the Forge®2D program. Based on the studies it was shown that lower values of energy and force parameters are needed for the extrusion of sleeves with the new methods, compared to the traditional method of indirect extrusion of sleeves. As a model material in computer simulations of the process, steel C45 was used.

To verify the results of theoretical studies, laboratory tools were designed and made, and a testing stand for extruding sleeves according to the new extrusion schemes, as described in the paper, was built.

In the laboratory tests, the magnitudes of extrusion forces as a function of the extrusion ram path and the metal flow behaviour were determined in both process stages, based on the changes in the shape of the square coordination grid plotted on the longitudinal section of the stock.

With the aim of performing a comparative analysis of the energy and force parameters of the extrusion processes, numerical studies and laboratory tests were also carried out for the processes of indirect extrusion of sleeves, during which the magnitudes of the extrusion force, metal pressures on the extrusion ram, and effective stress were determined. Real sleeves were made under laboratory conditions from a substitute material, which was lead, while determining the magnitude of the extrusion force during extrusion ram displacement.

Keywords: extrusion, single operation of extrusion sleeves

Przeróbka plastyczna materiałów jest najbardziej rozpowszechnioną i rozwojową metodą kształtowania półwyrobów oraz gotowych wyrobów w przemyśle maszynowym i hutniczym.

Jednym z podstawowych sposobów wytwarzania rur, prętów, kształtowników, części maszyn ze stali i metali nieżelaznych drogą przeróbki plastycznej jest metoda wyciskania. Wyroby wyciskane charakteryzują się dobrymi własnościami mechanicznymi, dużą dokładnością oraz czystą i gładką powierzchnią.

Spośród wszystkich wytwarzanych w przemyśle hutniczym i maszynowym wyrobów bardzo istotną część stanowią rury bez szwsu oraz tuleje.

Tuleje mogą stanowić półwyrób do dalszej przeróbki plastycznej lub obróbki skrawaniem, ale mogą być także sprzedawane w postaci gotowych wyrobów.

Istnieje kilka metod wytwarzania tulei, a wybór konkretnej z nich zależy od przeznaczenia wyrobu oraz jego wymiarów.

Najbardziej rozpowszechnionym sposobem wytwarzania tulei z dnem jest przeciwbieżne wyciskanie. Rozpowszechnienie tej metody jest spowodowane przede wszystkim stosunkowo niskimi kosztami narzędzi stosowanych podczas wyciskania. Tuleje otrzymane metodą przeciwbieżnego wyciskania obarczone są jednak wadami, do których należy zaliczyć ich różnościenność i mimośrodowość.

Głównym kryterium decydującym o stosowaniu metody przeciwbieżnego wyciskania w przemyśle jest stosunek całkowitej wysokości tulei H_c do jej średnicy wewnętrznej D_w (H_c/D_w). Jeżeli stosunek tych wymiarów tulei $H_c/D_w \geqslant 2.5$, to wyrób traktuje się jako tuleję głęboką. Zastosowanie wówczas metody przeciwbieżnego wyciskania z punktu widzenia parametrów energetyczno-siłowych procesu nie jest technologicznie zalecane.

Przez cały czas trwania procesu wyciskania na stempel działają maksymalne naciski, a przebieg siły wyciskania ma charakter narastający.

W przemyśle stosuje się często również metodę polegającą na przeprowadzeniu w jednym narzędziu wstępnego przeciwbieżnego wyciskania tulei grubościennej, a następnie w drugim narzędziu tuleja ta jest poddawana operacji przeciągania przez stożkową matrycę, w celu wydłużenia tulei i pocienienia jej ścianek. Metoda ta wymaga jednak zastosowania, co najmniej dwóch pras przemysłowych, dwóch zestawów narzędzi oraz konieczności dogrzewania wsadu, co w oczywisty sposób wydłuża cykl produkcyjny pojedynczego wyrobu, zwiększa się zużycie energii i wzrastają ogólne koszty produkcji.

W praktyce produkcyjnej stosuje się również inne sposoby wytwarzania głębokich tulei lub cylindrów na potrzeby przemysłu maszynowego, polegające na łączeniu tulei z denkiem metodą spawania lub zgrzewania do półwyrobu, otrzymanego np. w prasowalcarce. Jednak koszt wytworzenia 1 metra bieżącego takiego pólwyrobu to około 30% wyższy od kosztu 1 metra bieżącego tulei otrzymanej metodą wyciskania. Tuleje z dnem wykorzystuje się często jako wyroby gotowe lub półwyroby do wytwarzania cylindrów hydraulicznych, przeznaczonych do pracy w ekstremalnych temperaturach oraz ciśnieniach i wymaga się, aby ich konstrukcja była jednolita.

W prezentowanej pracy rozwiązano problem wytwarzania tulei głębokich z dnem metodą wyciskania w jednym zabiegu technologicznym. Zaproponowano dwa nowe sposoby wyciskania tulei, bazującej na znanych schematach wyciskania mieszanego, które pozwalają wyeliminować problemy i ograniczenia technologiczne występujące w dotychczasowych procesach wytwarzania tulei.

Na podstawie badań wstępnych stwierdzono, że stosując te nowe sposoby, można wytwarzać głębokie tuleje z dnem, o stosunkowo małej grubości dna i dostatecznie równomiernej grubości ścianek. Ponadto metody te mogą być stosowane do wykonania tulei z trzonem (w przypadku dwustronnego wyciskania z otworem) o dowolnej długości (głębokości), grubości (średnicy) i dowolnym kształcie przekroju poprzecznego bez konieczności regulacji narzędzia podczas wyciskania, a stosując odpowiednią konstrukcję narzędzi można również wytwarzać tuleje bez dna.

Wykazano także, że podczas jednooperacyjnego wyciskania tulei za pomocą nowych sposobów występują mniejsze wartości sił i nacisków na narzędzia, w porównaniu z najczęściej stosowanym sposobem przeciwbieżnego wyciskania tulei.

Stwierdzono, że podczas wyciskania w wyniku plastycznego płynięcia metalu w jego objętości powstają lokalne źródła ciepła, które ułatwiają odkształcanie metalu, co skutkuje znacznie łagodniejszymi warunkami pracy narzędzi i maszyn.

Podczas badań teoretycznych wykonano symulacje komputerowe obydwu nowych procesów wyciskania za pomocą programu Forge®2D. Na podstawie badań wykazano, że do wyciskania tulei nowymi sposobami wymagane są niższe wartości parametrów energetyczno-siłowych niż podczas tradycyjnej metody przeciwbieżnego wyciskania tulei. Jako materiału modelowego podczas komputerowych symulacji procesu użyto stali C45.

W celu weryfikacji wyników badań teoretycznych, zaprojektowano i wykonano narzędzia laboratoryjne oraz zbudowano stanowisko badawcze do wyciskania tulei zgodnie z nowymi, opisanymi w pracy schematami wyciskania.

W trakcie badań laboratoryjnych wyznaczono wartości sił wyciskania w funkcji drogi stempla oraz charakter płynięcia metalu w obydwu stadiach procesów na podstawie zmian kształtu kwadratowej siatki koordynacyjnej naniesionej na przekroju wzdłużnym wsadu.

W celu wykonania analizy porównanwczej parametrów energetyczno-siłowych procesów wyciskania wykonano również badania numeryczne i laboratoryjne dla procesu przeciwbieżnego wyciskania tulei, podczas których określono wartości siły wyciskania, nacisków metalu na stempel oraz intensywności naprężenia. Wykonano w warunkach laboratoryjnych rzeczywiste tuleje na materiale zastępczym, jakim był ołów, jednocześnie wyznaczając wartości siły wyciskania podczas przemieszczania się stempla.

1. Introduction

The extrusion process can be effectively utilized for the production of parts to be used in the machine building, automotive, aircraft, metallurgical, and other industries.

The main advantages of the extrusion process include: its high versatility (extrusion methods can be applied to the plastic working of practically any grades of steel and nonferrous metals, and even cast iron), good mechanical properties of metal worked, high dimensional accuracy of workpieces, slight material losses (a small amount of waste), and high productivity.

However, the extraction processes share a common, basic drawback, which is the high magnitude of extrusion force and unit metal pressures on the working tools during the deformation of the stock. This involves directly a shorter tool life, a relatively large energy consumption and, in the overall balance, higher manufacturing costs.

In the study of extrusion processes, similarly as in other plastic working fields, there is a trend towards developing methods to reduce the energy-force parameters of the process. The most commonly used methods consists in the reduction of friction forces through the change of the tool shape, or the application of appropriate lubricants. There are also methods that allow the reduction of the energy-force parameters by changing the metal deformation scheme during the process, as demonstrated in works, e.g. [1,2].

In industrial practice, the most commonly used method of producing deep sleeves is by indirect extrusion. The main criterion decisive to the application of this method of extrusion is the ratio of the overall height, H_c, of a sleeve to its inner diameter, D_w, (H_c/D_w). If the ratio between these dimensions of a sleeve is $H_c/D_w \geqslant 2.5$, then the use of the indirect extrusion method is not recommended technologically from the point of view of energy-force process parameters. To avoid the excessive wear of damage of the tools, inter-operation technological treatments are performed, which most often include soft annealing or heating up the stock. This will result, however, in an increased energy consumption, a decrease in production process efficiency, and an increase in overall production costs. Therefore, two new alternative methods of extruding sleeves have been developed, and the obtained values of energy-force parameters are compared with those of the traditional method of indirect extrusion.

2. The new processes of extruding deep sleeves

A product or semi-finished product is referred to as a deep sleeve, when the ratio of the overall height, H_c, of the sleeve to its inner diameter, D_w, is greater than 2.5 ($H_c/D_w \geqslant 2.5$).

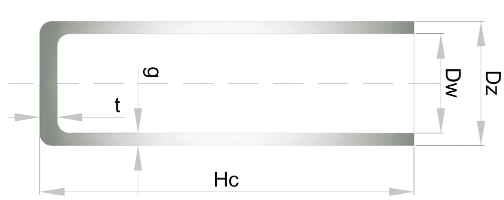

Fig. 1. A bottomed deep sleeve

where: H_c – overall height of the sleeve, D_z – outer diameter of the sleeve, D_w – inner diameter of the sleeve, g – wall thickness of the sleeve, t – bottom thickness of the sleeve.

Figures 2 & 3 show schematic diagrams of the new methods of extruding bottomed deep sleeves [4].

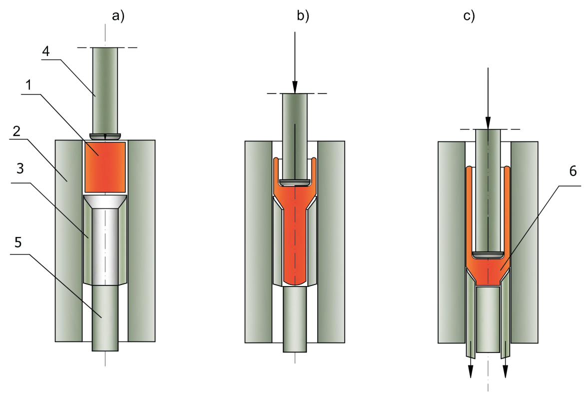

Fig. 2. Complex extrusion

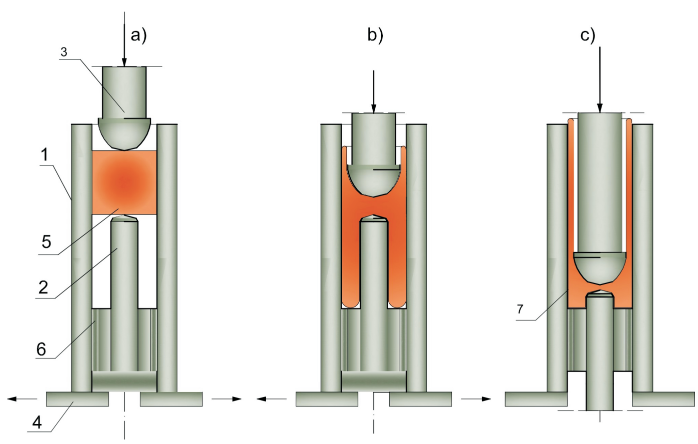

Fig. 3. Double-side complex extrusion

The diagram of the complex extrusion of a sleeve in the container with a movable ring is shown in Fig. 2. The idea of the process is that the preform (1) in the shape of a cylinder is placed in the container (2) on the tapered part of the ring (3), which, in the first phase, is a fixed tool (Fig. 2a). As a result of the ram (4) pressing with force P on the metal of the preform (1), the metal flows in two directions: into the gap between the walls of the container (2) and the ram (4) and into the opening of the ring (3). Thus, a sleeve with a stem is formed. After reaching the preset distance “t” between the ram (4) and the ring (3) (Fig. 2b), both the ram and the ring start mowing down at an equal speed, while not changing the distance “t” until the completion of the extrusion process (Fig. 2c). Then the sleeve (6) is removed from the container by the pusher (5). [1]

The method of double-side complex extrusion (Fig. 3) consists in that the preform in the form of a cylinder is placed in the contained (1) on the lower ram (2) (Fig. 3a). As a result of the upper ram (3) pressing on metal, the metal flows into the space between the ram (3) and the mandrel (2) and the container (1), whereby a semi-finished product in the form of a variable-walled sleeve is formed with a partition between the tools (Fig. 3b). After reaching the preset distance between the rams, which is, at the same time, the bottom thickness of the sleeve, and releasing the blocking (4), the mandrel (2) and the ram (3) start moving down at an equal speed, while not changing the distance between one another. The metal flows then toward the container walls (1) as a result of being pressed out from the partition (5) and is, at the same time, sized by the ram and extruded upwards (Fig. 3c). [2]

When the mandrel (2) has been slipped into the guide (6), the extrusion process is finished, and the ready sleeve is removed from the container by the mandrel (2) sliding up.

3. Numerical modelling of processes in the Forge® 2D program

From the point of view of metal flow kinematics, the processes are composed of two basic stages:

– Stage I makes use of the known scheme of simultaneous indirect extrusion and coextrusion (also referred to as mixed or combined extrusion), as a result of which a semi-finished products, called a stemmed sleeve or double-side sleeve, is obtained. The deformed metal flows plastically in two directions, with part of the volume of the deformed preform flowing toward the lower tool, while the rest of the metal flows in the direction opposite to the ram movement direction, to form part of the sleeve proper already at this stage.

– Stage II is characterized by a specific deformation scheme, whereby the sleeve is formed from the material of the stem or the thick-walled sleeve formed at Stage I of the process. At Stage II of the process, the ring or the lower ram moves down together with the ram to gradually release the metal from the lower zone of the container. Then, as a result of the ram acting on the metal, the metal starts flowing toward the container wall. Next, the sizing of the wall thickness and the gradual extrusion of the sleeve to the required height take place. The thickness of the sleeve bottom can be adjusted by setting the distance of the ram from the movable ring or the lower ram.

The Forge®2D program used [3] provides no possibility of modelling processes in such a manner that during the motion of one tool, the other tool be started at any arbitrary point of the process. Therefore, the *multistep* function was used during simulations, that enables data (results) from the last computational step of Stage I to be transferred to the first computational step of Stage II, owing to it was possible to take into account the initial process conditions during further computation.

Figures 4a & 4b show assembly diagrams for the computer simulations of processes in a plane state of strain.

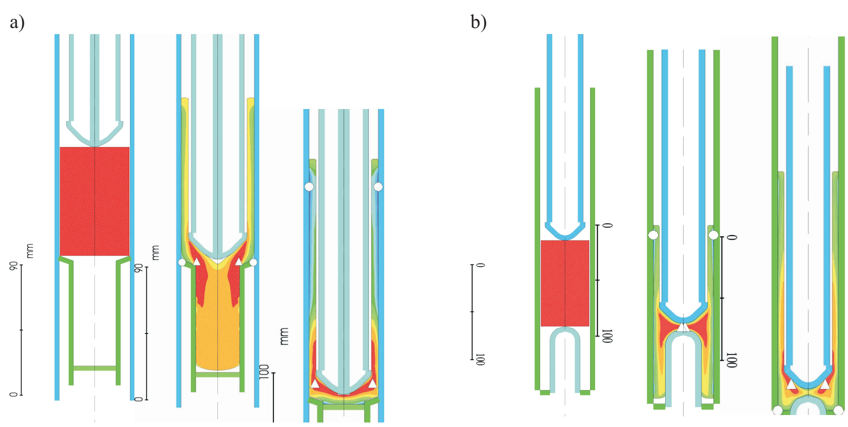

Fig. 4. A schematic diagram of extrusion process simulation using the Forge®2D program a) complex extrusion, b) double-side complex extrusion

4. Theoretical analysis of process of complex extrusion of a sleeve - the determination of extrusion force

Figure 5 shows diagrams of extrusion force variation as a function of the ram path.

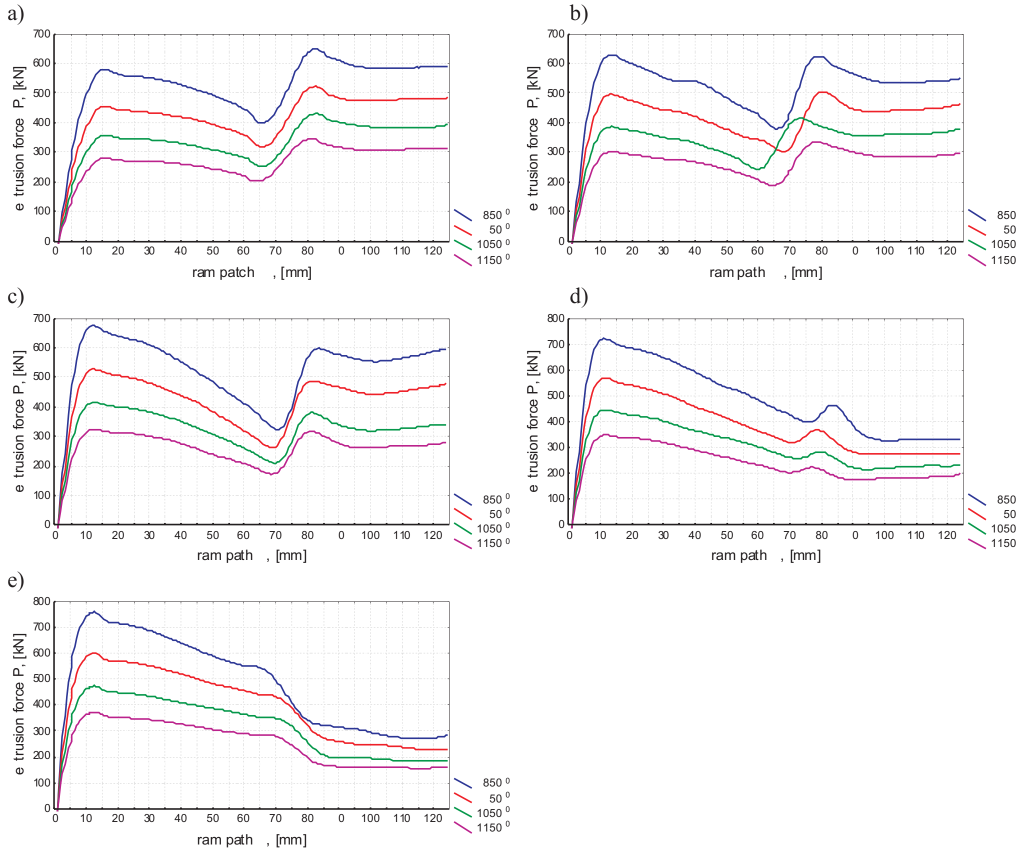

Fig. 5. Variation of the magnitude of force P in the process of extrusion for: v=25 mm/s, T_0=850, 950, 1050, 1150 °C a) ε=0.25, b) ε=0.35, c) ε=0.50, d) ε=0.60, e) ε=0.80

During studies, the mean value of the extrusion force was also determined. This value takes into account the force recorded along the entire ram path. The mean extrusion force makes it possible to determine the energy consumption of the process and to establish the optimal conditions of process parameters, such as the deformation value, process rate or initial temperature.

Figure 6 shows, for two example temperature variants, the distribution of mean extrusion force values for the variable process parameters examined.

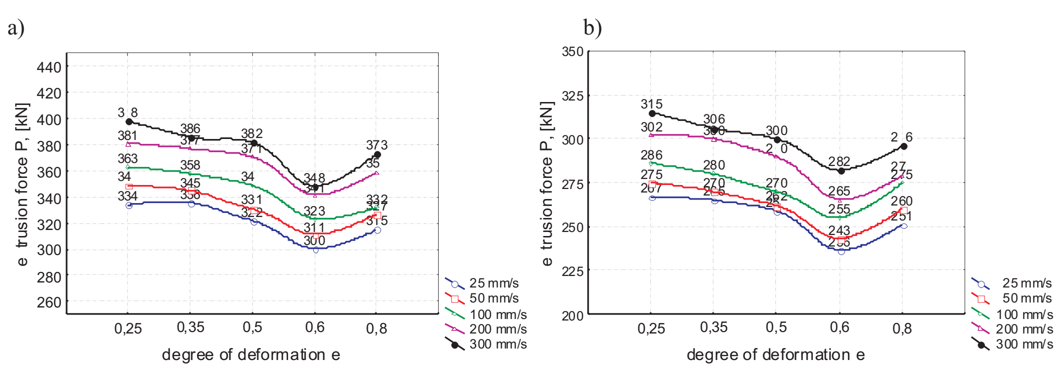

Fig. 6. The effect of ram advance velocity v, stock temperature T_0, and strain ε on the magnitude of the mean extrusion force $P_{śr}$ for a) T_0=1050°C, b) T_0=1150°C

In theoretical studies, five variants of strain preset in the process were used. The change in the strain value resulted from the use of rings of different diameters. At Stage I of the process, the force increases with increasing strain, whereas at Stage II of the process an opposite phenomenon occurs, namely the magnitudes of the extrusion force decreased when preset strain variants were increased (Fig. 5).

The analysis of the temperature distribution in the sleeve cross-section indicates that the heat sources at Stage I of the process form in the zone, where the metal flows into the ring channel. At Stage II of the process, when the ring moves down, the greatest plastic strains occur in this region, and the highest temperatures form. It is known that the greater strain magnitude at Stage I of the process, the larger local heat sources and elevated temperature zones are. The deformation resistance of metal decreases, and then the least extrusion force magnitudes occur for the highest strain magnitudes.

Figure 6 shows an example temperature distribution at Stages I and II of the process for complex extrusion. a) b)

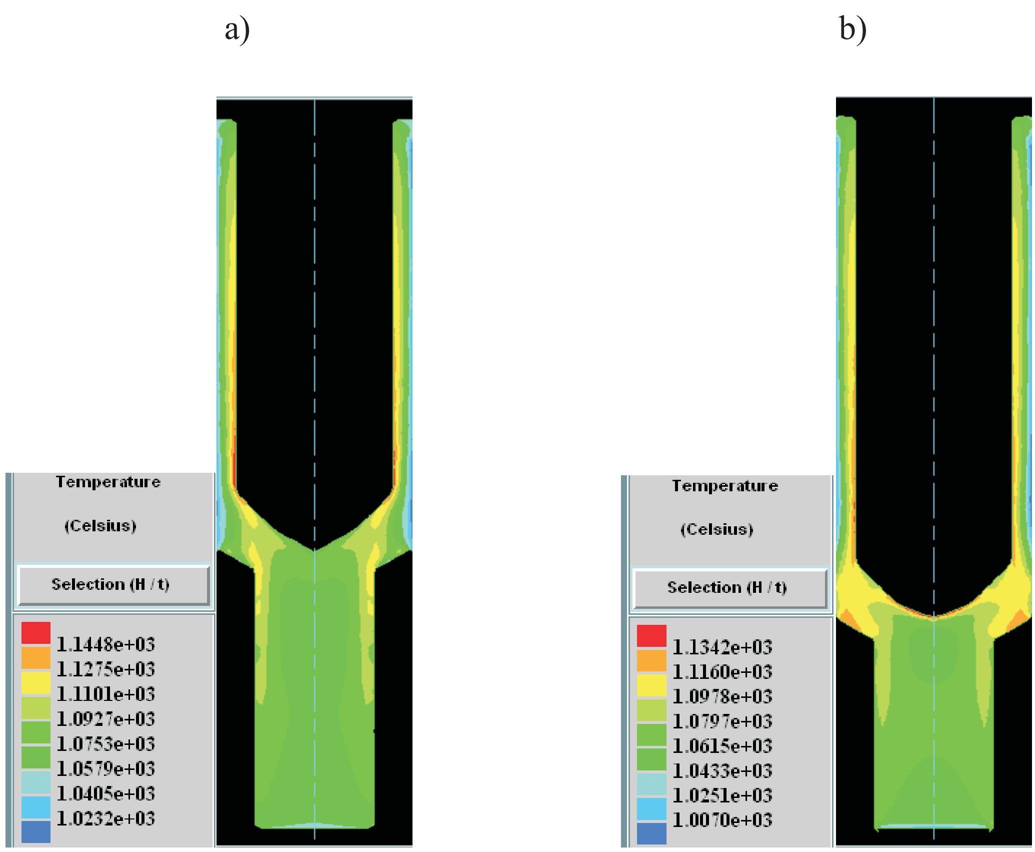

Fig. 7. Distribution of metal temperature at particular stages of the sleeve extrusion process forT_0=1050°C, complex extrusion of a sleeve: a) Stage I, b) Stage II

The analysis of the state of stress has also shown based on the effective stress distribution (Fig. 8) that at Stage I of the process the deformation resistance of the material under the ram increases when the strain magnitude is increased, which results in an increase in the values of effective stress and extrusion force. At Stage II of the process, an opposite phenomenon occurs, namely the stress magnitude decreases as the strain magnitude is increased. The cause of this, aside from the temperature effects, is the action of the ram to increasingly smaller diameter of the metal stem formed in the ring channel.

Also the statistical juxtaposition of effective stress values with the variable parameters examined made in the form of a surface diagram shows that, at Stage I of the process, with increasing strain magnitude the effective stress increases, whereas at Stage II it decreases (Fig. 9).

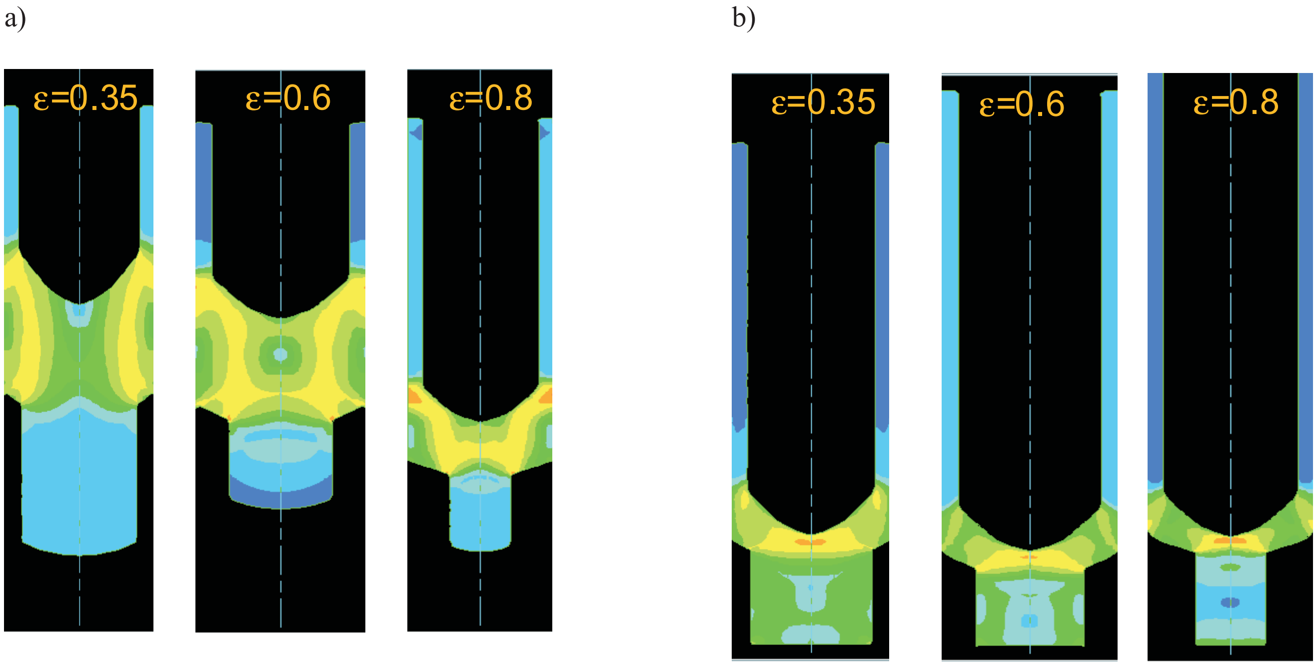

Fig. 8. Effective stress distribution. a) Stage I of the process, b) Stage II of the process

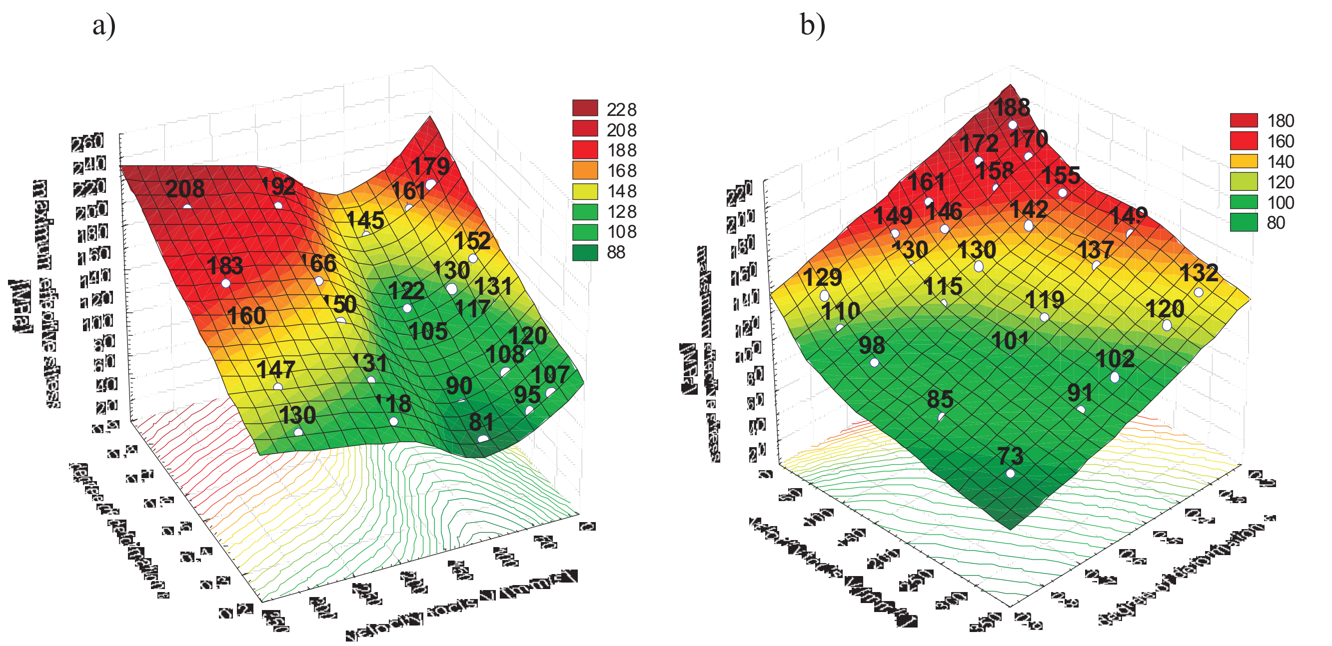

Fig. 9. The effect of ram advance velocity v and strain ε on the magnitudes of effective stress for T_0=1050°C. a) Stage I of the complex extrusion process, b) Stage II of the complex extrusion process

5. Theoretical analysis of process of double-side complex extrusion of a sleeve - the determination of extrusion force

Figure 10 shows diagrams of extrusion force variation as a function of the ram path.

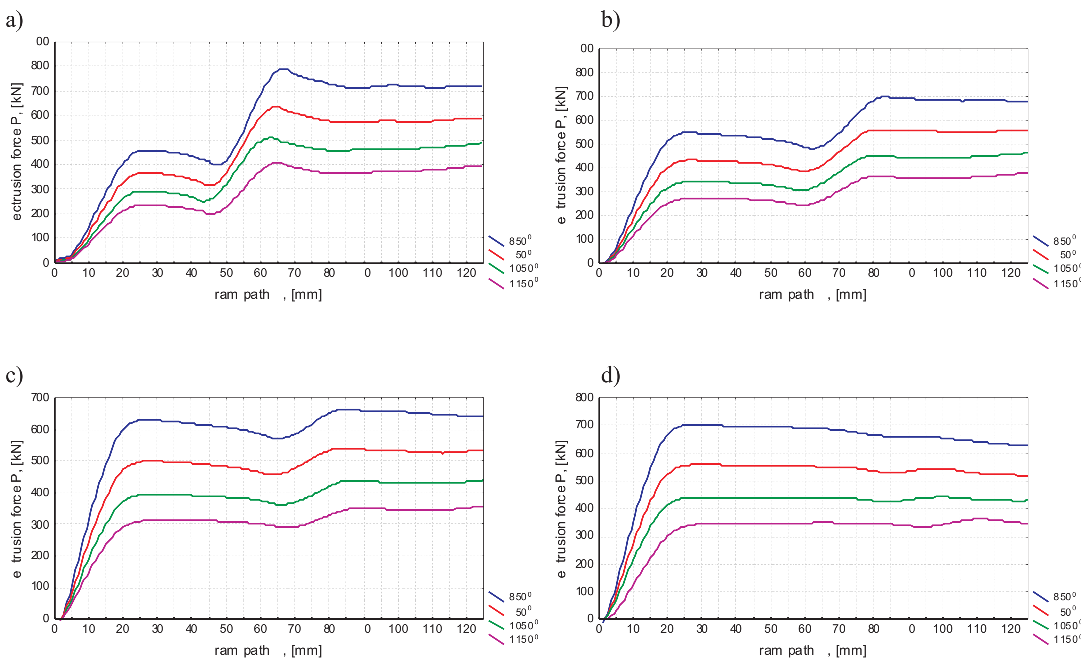

Fig. 10. Variation of the magnitude of extrusion force *P* in the process of extrusion for: v=25 mm/s, T_0=850, 950, 1050 and 1150 °C; a) D_g/D_d=2; b) D_g/D_d=1.6; c) D_g/D_d=1.33; d) D_g/D_d=1.14

In the examined process of two-side complex extrusion of a sleeve, the variation in the magnitude of strain during Stage I of extrusion was defined by the ratio of upper ram diameter to lower ram diameter.

The following variants of upper-to-lower ram diameter ratio were applied in the examination: D_g/D_d=40/20, 40/25, 40/30, 40/35;

where: D_g – upper ram diameter, D_d – lower ram diameter.

In Stage I of the process, with increasing lower ram diameter values, the extrusion forces increase. This is caused by increasing strain and friction surface between metal and the lower ram surface. For the ram diameter ratio D_g/D_d=2, the space between the lower ram and the container is the greatest, and the friction surface between metal and the lower ram is the least, hence the force at Stage I for the strain variant under consideration has the lowest magnitude.

The force distribution shown in Fig. 10 indicate that during transition from Stage I to Stage II of the process with the greatest ram diameter difference, the greatest extrusion force increment occurs. With decreasing ram diameter difference, the force increment between the process stages decreases, and at the least ram diameter difference, D_g/D_d=1.14, no force increment is noted.

Such differences in extrusion force magnitudes at particular process stages can be explained by the fact that the extrusion forces increase during transition from Stage I to Stage II as a result of simultaneous sizing and extruding by the upper ram of the metal from the volume of the sleeve wall formed by the lower ram at Stage I of the process. The wall of the sleeve has the greatest thickness when the greatest ram diameter difference is used, therefore the highest extrusion force magnitudes at Stage II of the process were noted for this case.

Figure 11 shows, for two temperature variants, the relationships of mean extrusion force values for the process parameters examined.

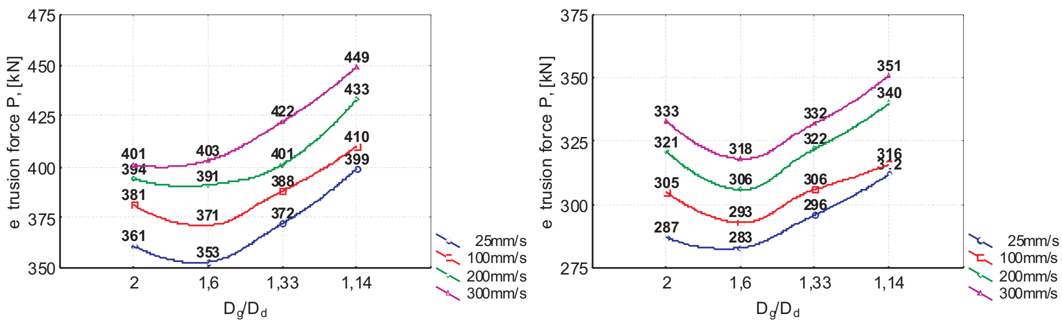

Fig. 11. The effect of ram advance velocity v, stock temperature T_0, and the ram diameter ratio D_g/D_d on the mean extrusion force value; a) T_0=1050$^{|circ}$C, b) T_0=1150°C

In engineering processes, the consumption of energy needed for the production of unit product is very important from the point of view of the economics of those processes. Understanding energy consumption in a given process is crucial to the determination of the competitiveness of that process against other engineering processes.

The mean extrusion force values shown in Fig. 11 has been determined using a statistical program [6] from the set of data obtained during the determination of the variation of force magnitude in the extrusion process.

For D_g/D_d=1.14, the difference between the maximum forces from Stages I and II is the least, which suggests that the mean force of the entire process will be the greatest. For D_g/D_d=1.33 and D_g/D_d=1.6, respectively, the mean extrusion force decreases, while at the greatest diameter ratio of D_g/D_d=2 the mean force value increases. The cause of this is the dramatic force increment during transition from Stage I to Stage II of the process for D_g/D_d=2 and attaining by the force the highest value from among all strain variants examined (Fig. 10a).

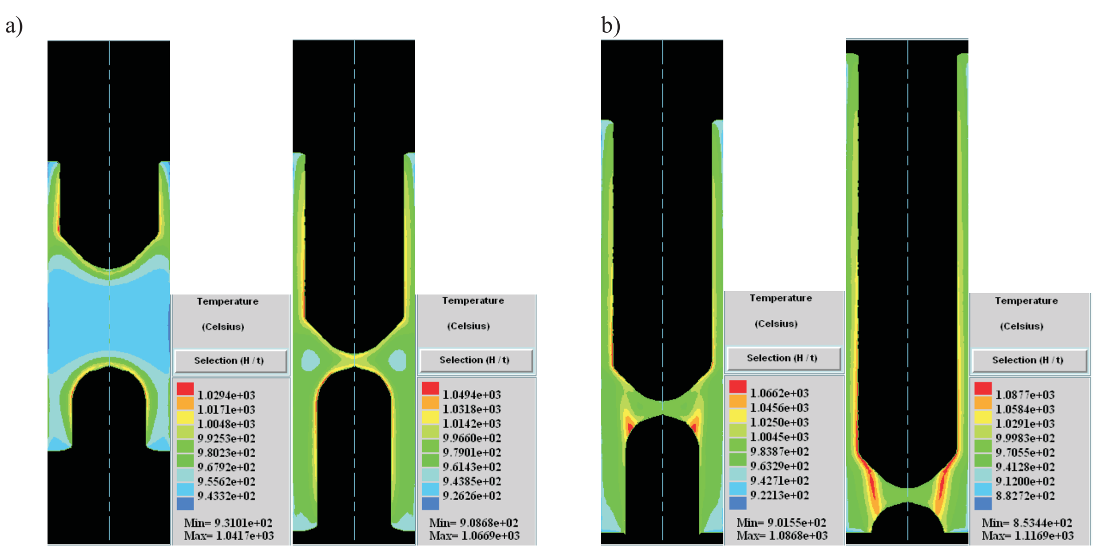

Fig. 12. Distributions of temperature at particular stages in the process of double-side extrusion of a sleeve for: T_0=950°C, v=100 mm/s, D_g/D_d=1.6; a) Stage I, b) Stage II

Similarly as for the complex extrusion method, the analysis of the distribution of temperature in the cross-section of the sleeve indicates that the largest heat sources at Stage I of the process form in the zone, where the metal flows into the space between the container and the lower ram (Fig.12a). At Stage II of the process (Fig.12b), when the lower ram moves down, this is the region, where the greatest plastic strains occurs and the highest temperatures form, the deformation resistance of the metal decreases, and in that case, for the variants of the greatest strain magnitudes, the least extrusion force magnitudes occur.

6. Experimental analysis of process of complex extrusion of a sleeve – the determination of extrusion force

A schematic diagram and a description of the operation of the laboratory tool for the physical partial verification of numerical computations are provided in work [5]. The model material used for the theoretical studies was lead. During examinations, sleeves were extruded and the relationship of force versus ram path was recorded (Fig. 13).

In laboratory tests, strain magnitudes and working tool shapes similar to those used during numerical examinations were employed.

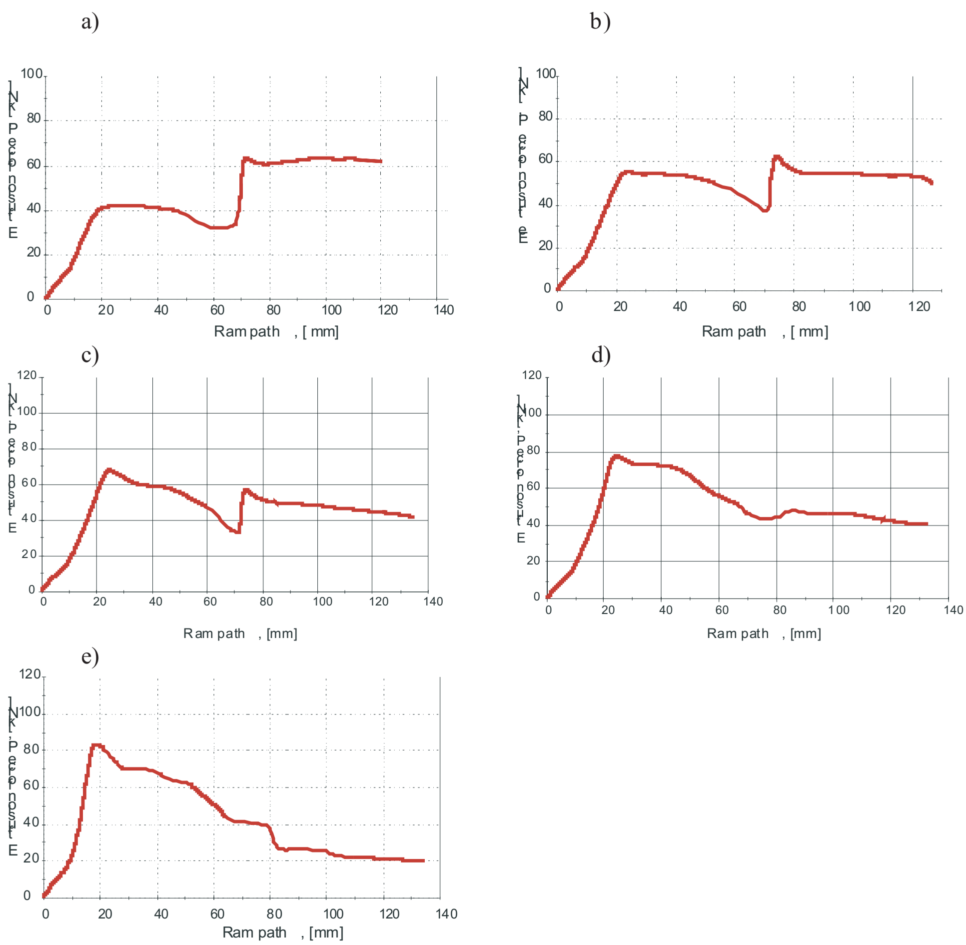

Fig. 13. Diagrams of the relationship of extrusion force P[kN] versus ram path s [mm], experimental test results; a) ε=0.25, b) ε=0.35, c) ε=0.5, d) ε=0.6, e) ε=0.8

When comparing the data shown in the diagrams (Fig. 5) and (Fig. 13) it can be noticed that the shapes of the curves are very similar for all variants of the preset strain. This is indicative of the similarity of flow behaviour during extrusion of the model material for the numerical studies and lead for the experimental tests.

Also, the analysis of deformations of the coordination grid plotted on the longitudinal section of the preform after comparison with the distribution of effective strain as determined from the numerical computation confirmed the similarity in the deformation of the model materials (Fig. 14). In the zones, where the greatest magnitudes of effective strain occurred during numerical examination, areas of the greatest plastic strains were also observed in experimental tests.

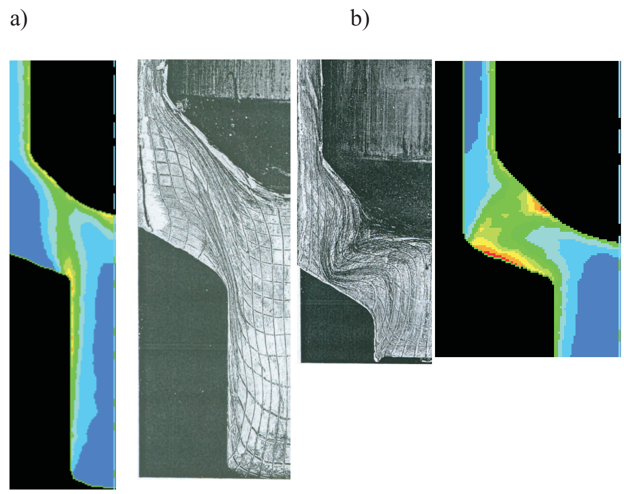

Fig. 14. Comparison of the distribution of effective strain and coordination grid deformation during the complex extrusion of a sleeve: a) Stage I, b) Stage II

7. Experimental analysis of process of double-side complex extrusion of a sleeve – the determination of extrusion force

The laboratory tests consisted in extruding a sleeve in a laboratory tool. The design of the tool enabled the extrusion process to be carried out in a manner similar to the computer simulations. First, the relationships of force versus ram path were determined, which are shown in (Fig. 15).

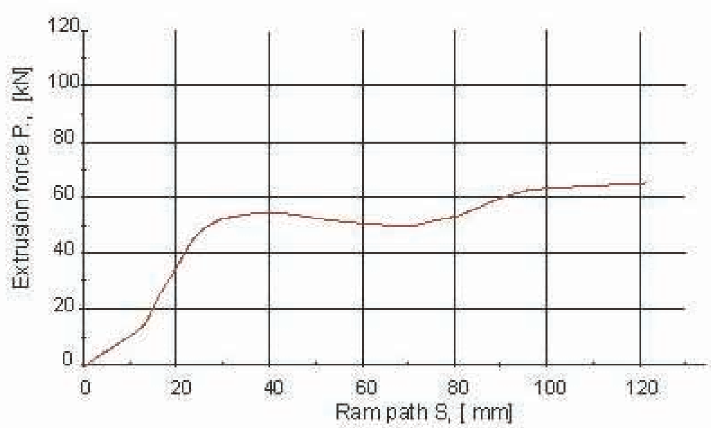

Fig. 15. A diagram of the relationship of extrusion force P[kN] versus ram path s [mm], for: D_g/D_d=133; laboratory tests – model material: lead.

Within the laboratory tests, an extrusion trial for one strain variant was carried out, because the numerical studies had shown that the ram diameter ratio of D_g/D_d=1.33 turned out to be the optimal in respect of the occurrence of the least extrusion forces out of all strain magnitude variants examined. Comparing the diagram shown in Fig. 15 with the diagram in Fig. 10c, a similarity in shape between the curves of the relationship of force versus ram path can be noticed. This similarity shows that the flow of the model material in the extrusion process (steel C45) and that of lead are very similar.

Comparison of the results of numerical effective strain studies and the results of experimental tests consisting in the analysis of grid deformation also showed a similarity in the flow behaviour of the model materials. In locations, where numerical studies showed the greatest effective strain magnitudes, the coordination grid plotted in the section of the lead preform would undergo the greatest deformations. Comparison of numerical examination results and experimental tests results is provided in Fig.16.

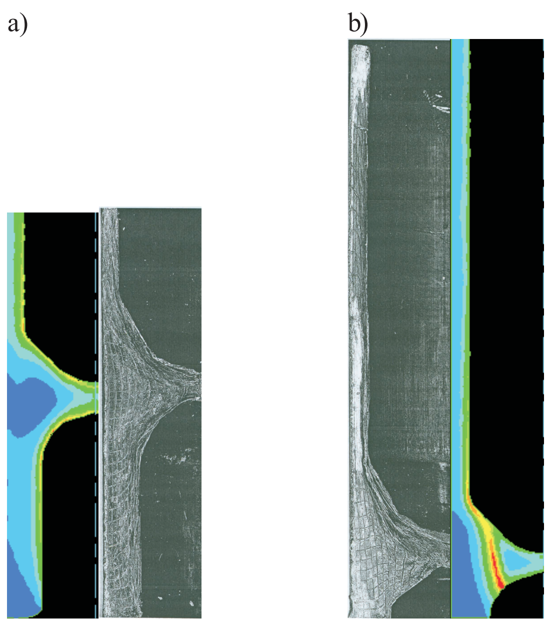

Fig. 16. Comparison of the distribution of effective strain and coordination grid deformation during the double complex extrusion of a sleeve: a) Stage I, b) Stage II

8. Indirect extrusion – the determination of extrusion force

The proposal of the newly developed extrusion methods was intended to present alternative ways of producing deep sleeves, especially for the indirect extrusion method. Within the theoretical studies, computer simulations of the indirect extrusion process were performed using temperature and velocity conditions similar to those applied in the computer simulations of the new extrusion processes.

Also, within the laboratory studies, sleeves were made by the indirect extrusion method using the tool designed for examination of the new extrusion methods. Both in the laboratory studies and in the laboratory tests, the energy and force parameters of the indirect extrusion process were determined in the form of diagrams of the relationship of extrusion force as a function of ram path (Figs. 17a, b). Tests were carried out to compare the extrusion force magnitudes occurring in the extrusion processes under examination.

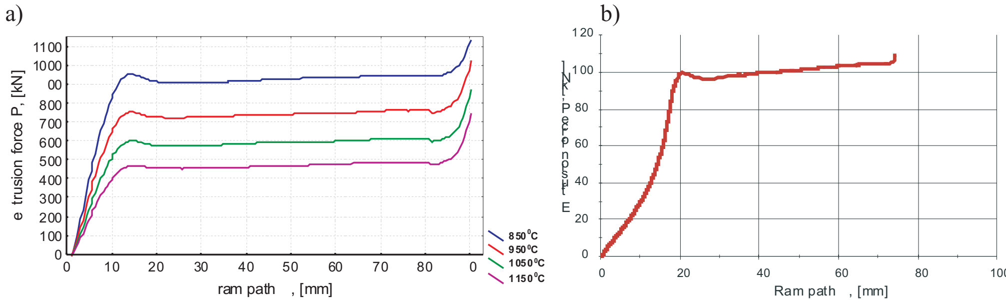

Fig. 17. Diagrams of the relationship of the variation of extrusion force P[kN] versus ram path s [mm] – indirect extrusion; a) theoretical computations – steel 45, b) laboratory tests – lead

9. Summary and conclusions

Two new methods of producing deep sleeves have been presented in the present article, which are effective in terms of reducing the energy & force parameters of extrusion processes and making actual sleeves of preset shapes and dimensions.

During extrusion, the magnitudes of forces in particular phases of the process are always variable and depend on the strains applied in extrusion.

The optimal values of the energy & force parameters were obtained for:

- complex extrusion of a sleeve in a container with a movable ring – (theoretical computation and physical modelling), when a strain of ε=0.6 was applied;
- complex double-side extrusion a sleeve – (theoretical computation and physical modelling), when the ram diameter ratio was D_g/D_d=40/30=1.33.

The overall maximum extrusion forces in both processes examined are smaller that the forces occurring with the traditional method of making sleeves by the indirect extrusion method.

The reduction in force magnitudes in relation to the indirect extrusion of sleeves was:

- for the complex extrusion of a sleeve in the container with a movable ring:
  - according to the theoretical computation: 38%
  - according to the physical modelling: 40%;
- for the complex double-side extrusion:
  - according to the theoretical computation: 29%,
  - according to the physical modelling: 34

During indirect extrusion, at the very end of the process, when the bottom of the sleeve is formed, a significant increase in the extrusion force occurs in the diagram (Figs. 17a,b). Such a dramatic increase in the force shortens the life of the tools and puts them at risk of being damaged. In the proposed new extrusion methods, owing to the application of a second movable tool, the phenomenon of force increase during the final forming of the sleeve bottom has been eliminated (Figs. 5a÷e, 13a÷e, 10a÷d, 15).

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