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# ANALYSIS OF THE ALTERNATE EXTRUSION AND MULTIAXIAL COMPRESSION PROCESS

# ANALIZA PROCESU NAPRZEMIENNEGO WYCISKANIA I WIELOOSIOWEGO ŚCISKANIA

The paper present the results of numerical simulations of the alternate indirect extrusion and multiaxial compression process, performed using commercial software designed for the thermomechanical analysis of plastic working processes, Forge 2009. The novel method of alternate indirect extrusion and multiaxial compression, proposed by the authors, is characterized by the occurrence of strain states in the material being plastically worked, which are similar to those occurring in the equal channel angular pressing and cyclic extrusion compression processes.

It can be found from preliminary studies carried out that the two alternate operations, i.e. extrusion and multiaxial compression, result in a strain accumulation and the formation of a strain state particularly favourable to grain refinement.

As shown by preliminary numerical studies performed by the authors, a zone of large plastic strains forms at the lateral side of the stamping during extrusion of material, which gradually fades along the stamping axis direction. After the multiaxial compression operation, when the material has been brought again to its original shape, the large strains zone moves and then settles in the form of a torus under the stamp. The subsequent extrusion process results in the formation of a new large strains zone being located at the lateral stamping side, and, at the same time, the displacement of the previously deformed material towards its axis. Repeating the above operations many times should bring about large magnitudes of homogeneous deformation within the entire volume of the material examined. The main problem during carrying out practical tests will be to determine the optimal shapes of dies and stamps, which would assure the intended strain state to be obtained in the material, and would also prevent the buckling and overlaps of the material during multiaxial compression.

*Keywords*: alternate extrusion and multiaxial compression, large plastic strain processes, nano-materials

W artykule przedstawiono wyniki symulacji numerycznych uzyskane za pomocą komercyjnego oprogramowania do termomechanicznej analizy procesów przeróbki plastycznej Forge 2009 procesu naprzemiennego wyciskania przeciwbieżnego i ściskania wieloosiowego. Zaproponowana przez autorów nowa metoda naprzemiennego wyciskania przeciwbieżnego i wieloosiowego ściskania, charakteryzuje się występowaniem w przerabianym plastycznie materiale stanów odkształcenia podobnych do występujących w procesach przepychania przez kanał kątowy i cyklicznego wyciskania ściskającego.

Z wykonanych badań wstępnych można wnioskować, że w wyniku połączenia i powtarzania dwóch naprzemiennych operacji: wyciskania i ściskania wieloosiowego następuje akumulacja odkształcenia i wytworzenie stanu odkształcenia szczególnie sprzyjającego rozdrobnieniu ziarna.

Jak wynika ze wstępnych badań numerycznych, przeprowadzonych przez autorów, podczas wyciskania materiału powstaje strefa dużych odkształceń plastycznych przy powierzchni bocznej wypraski, stopniowo zanikająca w kierunku jej osi. Po operacji wieloosiowego ściskania, gdy materiał zostaje powtórnie doprowadzony do początkowego kształtu, strefa dużych odkształceń ulega przemieszczeniu i lokalizuje się w obszarze w postaci torusa pod stemplem. Kolejny proces wyciskania spowoduje utworzenie nowej strefy dużych odkształceń zlokalizowanej przy powierzchni bocznej wypraski i jednocześnie przemieszczanie uprzednio odkształconego materiału w kierunku jego osi. Wielokrotne powtarzanie opisanych zabiegów powinno w efekcie doprowadzić do uzyskania w całej objętości badanego materiału dużych wartości jednorodnego odkształcenia. Głównym problemem podczas realizacji badań praktycznych będzie określenie optymalnych kształtów matryc i stempli, które zagwarantują uzyskanie zamierzonego stanu odkształcenia w materiale, a ponadto uniemożliwią wyboczenie i zaprasowania materiału podczas wieloosiowego ściskania.

## 1. Introduction

Materials of an ultrafine-grained and nanometric structure exhibit mechanical properties that often surpass those of conventionally obtained materials having phases or grain structures on a micrometric scale. Moreover, the ultrafine microstructure, in the sub-micrometric or nanometric range, results in new and extraordinary physical properties, such as: a decrease in Young's modulus, a reduction in the Debye and Curie temperatures, an increase in the diffusion degree,

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an enhancement of corrosion resistance, and an improvement in magnetic properties. Many studies indicate that by using processes that cause a strain accumulation, materials can be obtained, which combine high strength with high plasticity.

Ultrafine-grained microstructures can be obtained in thermoplastic working processes with applying severe plastic deformations (SPD) to ordinary materials. The core of the SPD processes is the capability to obtain a very large deformation of material and the rearrangement of strain-induced dislocations, which results in a very strong grain refinement [1, 4, 5].

Among the SPD processes that take advantage of large plastic strain, the most common include:

- Equal Channel Angular Pressing (ECAP),
- High-Pressure Torsion (HPT),
- Multiaxial Forging (MF),
- Cyclic Extrusion Compression (CEC),
- Repetitive Corrugation and Straightening (RCS), and
- Accumulative Roll-Bonding (ARB).

The severe metal deformation processes have a significant impact on the structure and properties of materials. Ultrafine-grained structures and nanostructures can be characterized as being unique owing to their physical and mechanical properties, such as: high low-temperature strength and/or high stress superplasticity and others [2÷9].

During applying high deformations, a strain anisotropy occurs in the material, which causes the anisotropy of mechanical properties. The alternate extrusion and multiaxial compression method proposed by the authors, as illustrated schematically in Fig. 1, is characterized by the occurrence of strain states in the material being plastically worked, which are similar to those occurring in the equal channel angular pressing and cyclic extrusion compression processes.

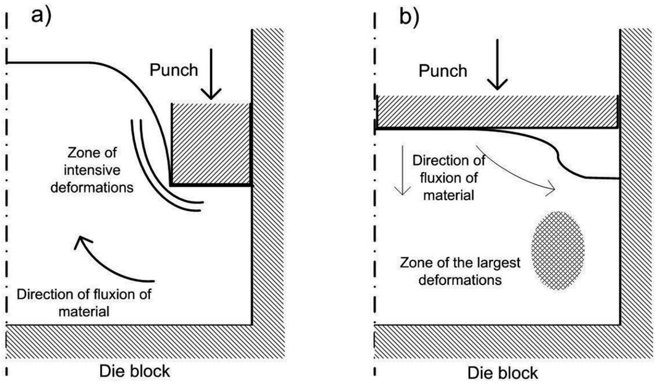

Fig. 1. Schematic of the alternate extrusion and multiaxial compression process; a) extrusion operation; b) compression operation

As shown by the preliminary numerical studies, a zone of large plastic strains forms at the lateral side of the stamping during extrusion of the material, which gradually fades along the stamping axis direction (Fig. 1a). After the multiaxial compression operation, when the material has been brought again to its original shape, the large strains zone moves and then settles in the form of a torus under the stamp (Fig. 1b). The subsequent extrusion process results in the formation of a new large strains zone being located at the lateral stamping side, and, at the same time, the displacement of the previously deformed material towards its axis. Repeating the above operations many times should bring about large magnitudes of homogeneous deformation within the entire volume of the material examined. The main problem will be to determine the optimal shapes of dies and stamps, which will assure the intended strain state to be obtained in the material, and will also prevent the buckling and overlaps of the material during multiaxial compression.

## 2. Numerical modelling

The Forge 2009®software relies on the finite element method and is designed for modelling of plastic working processes. The software enables modelling of plastic working processes in a spatial strain state. A plastically deformed medium is described by the equation based on the Norton-Hoff law:

$$S_{ij} = 2K_0\left(\bar{\varepsilon} + \varepsilon_0\right)^{n_0} \cdot e^{(-\beta_0 * T)} \left(\sqrt{3}\dot{\bar{\varepsilon}}\right)^{m_0-1} \dot{\varepsilon}_{ij}, \tag{1}$$

where: $S_{ij}$ – stress tensor deviator; $\dot{\bar{\varepsilon}}$ - strain rate intensity; $\dot{\varepsilon}_{ij}$ – strain rate tensor; $\bar{\varepsilon}$ – strain intensity, $\varepsilon_0$ – base strain, $T$ – temperature, $K_0, m_0, n_0, \beta_0$ – material constants specific to the plastically worked material.

A general form of this law is as follows:

$$\sigma = 2K\left(\sqrt{3}\dot{\varepsilon}_i\right)^{m-1} \dot{\varepsilon} \tag{2}$$

The coefficient $m$ in Eq. (2) may assume the following values: $m = 1$ corresponds to a Newtonian liquid with a viscosity of $\eta = 2K$, $m = 0$ gives a plastic flow law for a material satisfying Huber-Mises' plasticity criterion with a yield stress of $\sigma_p = \sqrt{3}K$, that is Levy-Mises' rigid-plastic law:

$$\sigma = \frac{2}{3}\frac{\sigma_p}{\dot{\varepsilon}_i}\dot{\varepsilon} \tag{3}$$

The conditions of friction between the material and the tools are described by the Coulomb friction model and Treska's friction model, in which respective values of the friction coefficients and the friction factor are taken:

$$\begin{aligned} \tau_j &= \mu \cdot \sigma_n \text{ for } \mu \cdot \sigma_n < \frac{\sigma_0}{\sqrt{3}}, \\ \tau_j &= m\frac{\sigma_0}{\sqrt{3}} \text{ for } \mu \cdot \sigma_n > m\frac{\sigma_0}{\sqrt{3}}, \end{aligned} \tag{4}$$

where: $\tau_j$ – unit friction force vector, $\sigma_0$ – base stress, $\sigma_n$ – normal stress, $\mu$ – friction coefficient, $m$ – friction factor.

The boundary conditions of the heat transfer model are assumed as the combined limiting conditions of the second and third kinds, and are described by the formula:

$$k_x\frac{\partial T_s}{\partial x}l_x + k_y\frac{\partial T_s}{\partial y}l_y + k_z\frac{\partial T_s}{\partial z}l_z + q + \alpha(T_s - T_o) = 0 \tag{5}$$

where: $l_x$,$l_y$ i$l_z$ – directional cosines of the normal to the strip surface, $q$ – heat flow rate on the cooled strip zone, $\alpha$ – heat transfer coefficient, $T_o$ – ambient temperature.

The Forge2009®software enables the determination of the fields of temperature, stresses, strains and strain rates in the analyzed zone of metal being deformed. A substantial advantage that influences the accuracy of obtained computation results is the possibility of inputting the rheological properties of the deformed metal, either in the form of a mathematical function or in a tabularized form, reflecting the actual stress – strain relationships.

## 3. Results of numerical studies

The application of the Forge2009®software using the thermomechanical models incorporated in it requires the definition of boundary conditions which are crucial to the correctness of numerical computation. Therefore, computation results are particularly affected by: the properties of material examined, friction conditions, and the kinetic and thermal parameters describing the plastic working process. The stock and working tool models were made using a CAD type program, and then a finite element grid was plotted on them. When generating the finite element grid, grid elements were locally concentrated in the largest deformation zone, which assured good geometrical consistence of the stock after deformation to be obtained. Because of the symmetry of the process, the theoretical analysis was performed for 1/2 of the stock, which allowed a considerable reduction of the computation time.

Aluminium Al99 acc. to the DIN standard was used as stock material for the studies; the properties of the material to be deformed were taken from the material database of the Forge2009®program. The initial stock height was equal to 100 mm, while the diameter of the deformed disk equalled 100 mm. The following initial conditions were assumed for both stages of numerical studies: friction coefficient $\mu$ = 0.1, and friction factor $m$ = 0.2; coefficient of heat exchange between the deformed metal and the tool, $\alpha$ – 1000 [W/Km$^2$]; coefficient of heat exchange between the deformed metal and the air, $\alpha_p$ – 10 [W/Km$^2$]; initial stock temperature, tool temperature and ambient temperature = 20°C.

The influence of piston shape on good quality material obtaining in multiaxial compression process was analyzed. Fig. 2 shows the deformation distribution during extrusion operation and then multiaxial compression for diameter reduction equalled 15%.

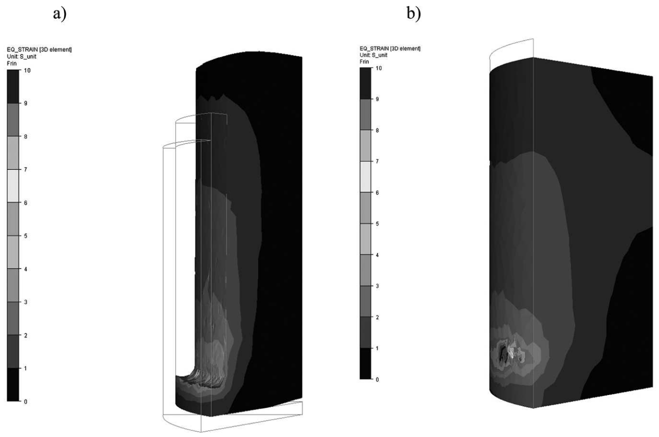

Fig. 2. 15% reduction of the diameter; a) deformation distribution in extrusion process; b) deformation distribution in multiaxial compression process

On the base of the deformation distribution presented an Fig. 2 can be stated that the biggest deformation occurs near the bottom edge of the punch. Moreover in the next operation of multiaxial and the deformation accumulation, the probability is that the mould inserts and defects inside of the material will appear. Increasing of the punch rounding radius is necessary. Fig. 2 shows the deformation distribution obtained in extrusion operation and following operation of multiaxial compression for 30% reduction of the diameter and increased rounding radius of the punch.

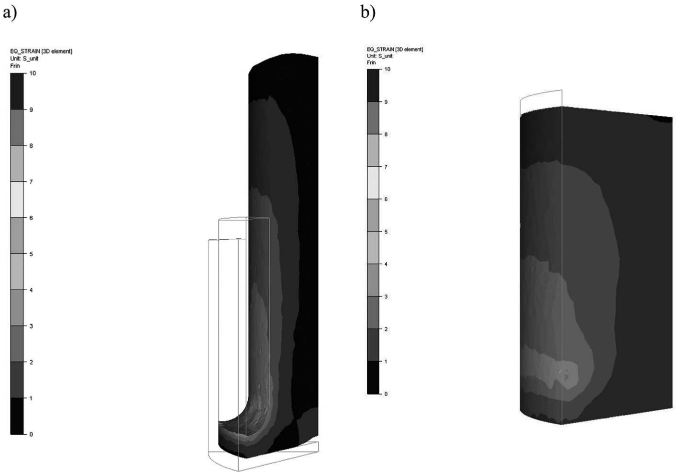

Fig. 3.

Deformation distribution for extrusion process and multiaxial compression shown in Fig. 3 confirm that the application of larger rounding radius of the punch caused lower values of deformation obtaining near the bottom edge of the punch. Simultaneously the application of increased diameter reduction caused bigger deformation in whole volume of the material. Fig. 4 presented the deformation distribution obtained during extrusion operation and following operation of multiaxial compression for 40% reduction of the diameter.

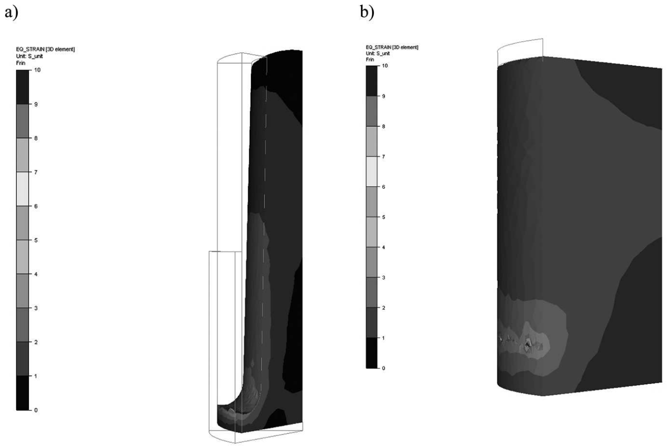

Fig. 4. 40% reduction of the diameter; a) deformation distribution in extrusion process; b) deformation distribution in multiaxial compression process

On the base of deformation distributions shown in Fig. 4 can be stated that the increase of the diameter reduction up to 40% despite using larger rounding and inclination of the punch can result In mould inserts and internal defects in deformed material.

## 4. Summary

The paper present the results of numerical simulations of the alternate indirect extrusion and multiaxial compression process, carried out using Forge 2009, commercial software designed for the thermomechanical analysis of plastic working processes. The novel method of alternate indirect extrusion and multiaxial compression, proposed by the authors, is characterized by the occurrence of strain states in the material being plastically worked, which are similar to those occurring in the processes of equal channel angular pressing and cyclic extrusion compression processes.

From the preliminary studies carried out it is found that the combination of the two alternate operations, i.e. extrusion and multiaxial compression, result in strain accumulation and the formation of a strain state particularly favourable to grain refinement.

The paper has also presented selected results concerning the distribution of strains and stresses in the process of alternate extrusion and multiaxial compression. Examples of die and ram shape modifications are also given and their influence on the strain distribution, as well as on the likelihood of occurrence of material lapping, are discussed. The presented results of the studies confirm the assertion that by the appropriate modification of the die and ram shapes it is possible to obtain material of homogeneous properties within its entire volume.

The example modifications of the punch shape and its influence on the deformation distribution and also on probability of mould inserts occurrence in the material were presented. Obtained results confirm that during the extrusion process should be applied, the diameter reduction not higher than 30% together with rounding the bottom edge of the punch. The selection of the prager shape of the punch significantly decreases the probability of the appearance the mould inserts and internal defects in deformed material during multiaxial compression process. The obtaining of the material without internal defects will allow to multiple repeating of alternate extrusion process and multiaxial compression and will make possible deformation accumulation that influence in microstructure refining.

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