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NEW SEVERE PLASTIC DEFORMATION METHOD FOR 316L MEDICAL GRADE STEEL PROCESSING NEW SPD METHOD FOR 316L STEEL PROCESSING

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Abstract: In this paper, a new method for bulk severe plastic deformation (SPD) processing is presented. The method is based on upsetting of prismatic samples in axial direction until it reaches certain height, while the length is increased along the mould length. Since the width of the sample is constant, the plane strain state in the sample is present. After first upsetting, the sample is rotated for 90 degrees and is upset again. Number of upsetting passes depends on material failure and total accumulated plastic strain for the upsetting process is calculated as a sum of strains per upsetting pass. The material chosen for this study is 316L steel, widely used for medical implants. Review on this subject at SCOPUS database showed that severe plastic deformation on 316L steel is scarcely used. Therefore, the results of this research would be promising. After the upsetting at room temperature, material exhibit improved tensile strength and microhardness, while workability is slightly reduced. Improved mechanical properties allow to reduce the dimensions of implants made of the SPD processed materials compared to conventionally produced implants, while keeping the same implant function. Smaller implant dimensions mean faster post operational recovery time for patient and less intrusion in patient's body during surgical operations. Additional advantage of the new die presented in this study is that the die can be also used for workability examination for triaxility stress ratio $\beta \sim -1.73$.
Keywords: severe plastic deformation, plane strain compression die, 316L stainless steel

INTRODUCTION

The research conducted by Hall [1] and Petch [2] in the 1950s, revealed that for the improvement of material properties it is necessary to significantly reduce the crystal grain size of the material. That fact attracted the interest of many scientists and engineers around the world [3]. One of the benefits of this is that the increase of material strength allows reducing the weight of the parts.

Shaping the material by certain metal forming methods, such as cold extrusion, forging, bending and others, slightly change the grain size compared to undeformed billet. However, metal forming processing, such as drawing and rolling, refine the grains in some local zones up to submicron dimensions [4]–[6]. The disadvantage of those methods, from the crystal uniformity standpoint, is that fine grains occupy just a small amount of total volume of the part and refinement process is not possible to control [7].

Processes that can generate fine grains are vapor deposition, fast solidification, high-energy ball milling and severe plastic deformation (SPD) [3], [8]. Severe plastic deformation is a metal forming method in which high values of plastic strain is introduced into the part in high hydrostatic pressure conditions [9]. During SPD processing, three stages of crystal grain changes are present. In the first stage, existing grains are getting elongated, while subgrains are being formed inside the grains, creating low angle grain boundaries. The second stage is characterized by the formation of high-angle boundaries by the division of existing subgrains. Elongated grains in the third stage are becoming refined from the effect of strain localization and shear bands [3]. These stages are not found with conventional metal forming processing that usually exhibits microstructure with elongated grains low-angle boundaries. While the increase of yield and ultimate tensile strength is usually accompanied by the reduction of workability, this may not always be the case for the material processed by SPD [10].

The advantages that processing by SPD offers may be very interesting for the medical industry as well. Implants have been used since early times, but back then one of the major problems was rejection by the human body [11]. This was due to poor biocompatibility and low corrosion resistance. Nowadays many different types of materials (organic and nonorganic) are being successfully used for implants and metal-based biomaterials are usually used for hard tissue substitution or rehabilitation and for total joint substitution. Stainless steel, cobalt alloys, titanium and titanium alloys are the most used metallic materials for medical implants. Biocompatibility, corrosion resistance, material strength, fatigue endurance and impact toughness are the most important implant properties. For example, high values of tensile and fatigue strength of implants made of titanium alloys ensure high durability of implants [12]. To further increase the durability and to prevent or extend revision surgery, implants that exhibit even higher fatigue characteristic are demanded. As an example, 50 MPa increase of fatigue limit, increase the fatigue life of an implant for a number of times. Another example is the application of UFG CP Ti for increased fibroblast growth (major cells that are responsible for the creation of collagen, glycoaminoglycans, and proteoglycans [13]) compared to CG CP Ti. Increased fibroblast growth is linked with shorter recovery time and better integration of implants with the patient body [14]. The use of UFG CP titanium for dental screws helped to reduce the diameter from 3.5 to 2.4 mm, making it possible to be used with the front teeth and on children.

When manufacturing the implants by metal forming technologies [15], [16], workability of the processed metal is of great importance. High workability help to impose high values of strains and create the desired shape of the product and without material failure [17]. The workability can be described as a correlation of limit strain (φ_{elim}) on the average triaxiality factor (β_{avg}). However, despite advances that processing by SPD offers, there are just a few dozen of papers that cover the subject of severe plastic deformation, 316L stainless steel and workability.

The laboratory for metal forming at Faculty of Technical Sciences, University of Novi Sad is conducting the research on severe plastic deformation and workability as well. In the laboratory, the V-shape dies were developed that can be successfully used as an SPD method [18] and for workability determination [19]. The new dies presented in this paper, "Plane strain compression dies", can be used to initiate severe plastic deformation in processed metal, but can be also used for the determination of the workability for average triaxiality factor β_{avg} value about $-\sqrt{3}$. In this paper, the detailed information about the dies is presented.

MATERIALS AND METHODS

The cross section of the plane strain compression die is presented in Figure 1. SPD processing is carried out as following: prismatic sample (3) is upset in the axial direction by a punch (1) until it reaches a certain height, while the length is increased along mould (2) length. Since the width of the sample is constant, plane strain state in the sample is present. After first upsetting, the sample is removed from the dies, rotated for 90 degrees, reinserted between into the die and upset again.

A number of upsetting passes depend on material failure. When the sample is pressed by the punch, the height is reduced, the length is increased and material flow in axial direction occurs. In order to reduce the friction between the sample and the mould and to facilitate the material flow during upsetting, stearine is inserted in between. High values of strain can be imposed into the sample by repeating these compression passes. The working parts of the die are made of X210Cr12 steels, while the rest of the parts are made of 42CrMo4.

The dies are mounted on hydraulic press Sack & Kiesselbach 6.3 MN and the upsetting is conducted at room temperature, with punch speed of 1 mm/s (Figure 2). CAD and finite element method (FEM) were used to optimize die geometry.

Prismatic samples (20 x 20 x 14 mm) were made of 316L stainless steel. In order to retain the stearine between the sample and the mould, a small amount of the material (0.2 mm) was removed from the sample (Figure 3). During upsetting, low friction also makes strain distribution in sample more uniform.

One of the tests that can be used to determine the workability of processed material is upsetting of cylindrical samples by flat plates. The cylindrical samples are machined from upset prismatic samples. The dimensions of the cylindrical samples are presented in Figure 4a.

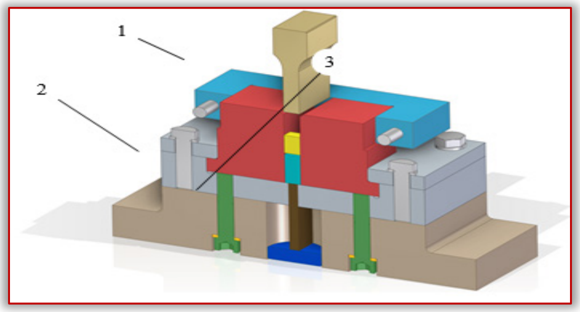

Figure 1. Section of the die CAD model; 1 - punch, 2 - mould, 3 - sample

Figure 2. Plane strain compression die mounted on hydraulic press

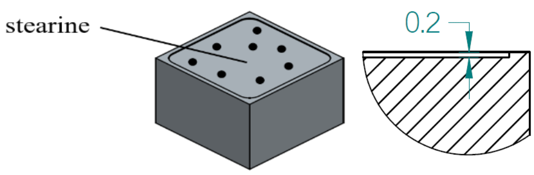

Figure 3. A CAD model of the sample and pocket height

During the workability test, the friction is present on contact surfaces and material cracking occurs at free surface in the equatorial area. Because of that, the calculation of stress components is relatively easy since $\sigma_r = 0$ which means that plane stress condition is present [19, 20].

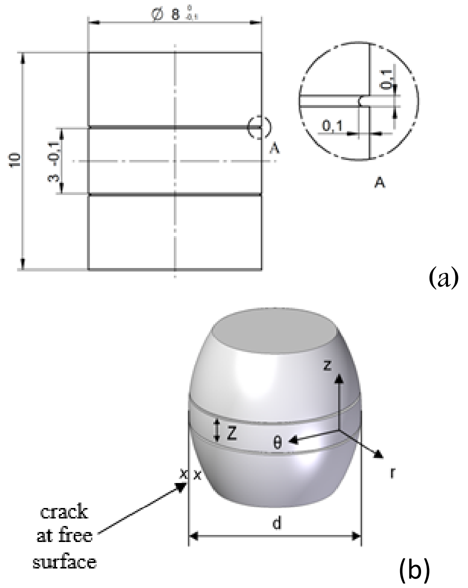

Figure 4. Cylinder dimensions (a) and crack at free surface (b)

In order to calculate the stress-strain state at the site of material crack during cylinder upsetting, the change of cylinder diameter (*d*) in the equatorial zone and the change of the height of zone (*Z*) where the crack is about to initiate, is measured for each upsetting pass (Figure 4b). Logarithmic strains in tangential, radial and axial directions can be calculated by Eq.(1), while an effective strain is calculated by Eq.(2). Letter *i* refers to the current, while *i-1* refers to the previous upsetting pass.

$$\varphi_{\theta i} = \ln\left(\frac{d_i}{d_{i-1}}\right), \quad \varphi_{zi} = \ln\left(\frac{Z_i}{Z_{i-1}}\right), \quad \varphi_{ri} = -\left(\varphi_{\theta i} + \varphi_{zi}\right) \quad (1)$$

$$\varphi_e = \frac{\sqrt{2}}{3} \cdot \sqrt{\left(\varphi_r - \varphi_\theta\right)^2 + \left(\varphi_\theta - \varphi_z\right)^2 + \left(\varphi_z - \varphi_r\right)^2} \quad (2)$$

After that, the history of deformation in the tangential and axial direction is plotted and strain component ratio α is calculated by Eq.(3):

$$\alpha = \frac{d\varphi_\theta}{d\varphi_z} \quad (3)$$

Strain ratio is used to calculate stress in the tangential and axial direction (Eq.(4)) and to calculate triaxiality factor β as well (Eq. (5)).

$$\sigma_\theta = \sigma_z \cdot \left(\frac{1+2\cdot\alpha}{2+\alpha}\right), \quad \sigma_z = -K\left[1 - \frac{1+2\cdot\alpha}{2+\alpha} + \left(\frac{1+2\cdot\alpha}{2+\alpha}\right)^2\right]^{-\frac{1}{2}} \quad (4)$$

$$\beta = \frac{\sigma_\theta + \sigma_z}{K} \quad (5)$$

The average value of triaxiality factor β_{avg} is essential for the construction of the workability diagram, where the dependence of β_{avg} on φ_{el} is presented. The average value can be calculated by Eq.(6).

$$\beta_{avg} = \frac{1}{\varphi_{e\lim}} \int_0^{\varphi_{e\lim}} \beta\left(\varphi_e\right) \cdot d\varphi_e \quad (6)$$

RESULTS AND DISCUSSION

The distribution of effective strain at the longitudinal cross-section of the sample in plane strain upsetting conditions obtained by FEM is presented in Figure 5. Three different locations at cross-section were chosen: center, near free surface and half-distance between the center and free surface. Upsetting was conducted in five passes, with a total punch stroke of 43.9 mm. The stroke for the first pass was 4 mm, while the strokes for the rest of the passes were 10 mm.

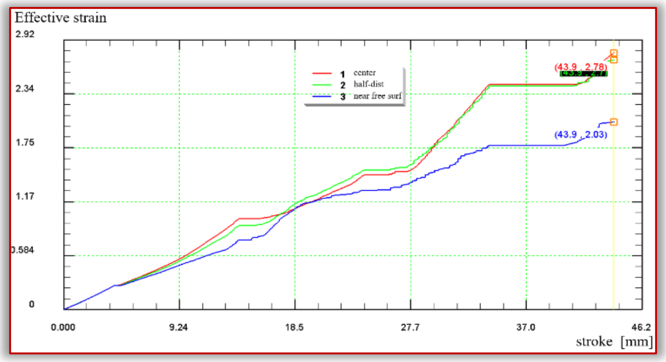

Figure 5. Effective strain distribution at sample cross-section in three different locations

Few conclusions can be drawn from FEM results. Firstly, it can be observed that the effective strain uniformity is very good – the difference between the center (2.78) and free surface (2.03) is not so pronounced. Secondly, the difference between strain value at the center and a half distance from the center (2.7) is almost insignificant and this may be due to the consecutive rotation of the sample between the passes. Finally, these values of effective strain and the change of strain path can lead to severe plastic deformation and grain refinement.

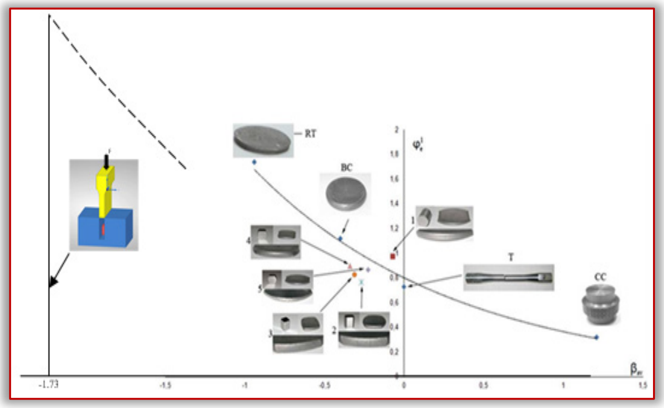

Figure 6. The position of Plane strain compression process in workability diagram [20]

This die can also be used for workability determination in stress conditions near $-\sqrt{3}$ (Figure 6).

Obtained workability is valuable for metal forming processing under these stress conditions.

CONCLUSION

- Upsetting by Plane strain compression dies can be successfully used as an SPD method
- Effective strain uniformity is very good – center (2.78), half distance (2.7) and near the free surface (2.03)
- The dies can be also used to determine workability for β_{avg} = -1.73

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