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NUMERICAL ANALYSIS OF PLANE STRAIN MULTI-DIRECTIONAL UPSETTING OF PRISMATIC SAMPLES

Nemanja Dačević[1, a], Marko Vilotić[1,b], Mladomir Milutinović[1,c], Luka Sevšek[2,d], Ljiljana Stefanović[1,e], Dragiša Vilotić[1,f]
[1]Faculty of Technical Sciences, Novi Sad, Serbia
[2]Faculty of Mechanical Engineering, Ljubljana, Slovenia
[a]dacevic@uns.ac.rs, [b]markovil@uns.ac.rs, [c]mladomil@uns.ac.rs, [d]luka.sevsek@fs.uni-lj.si, [e]ljiljanastefanovic@uns.ac.rs, [f]vilotic@uns.ac.rs

Abstract The plane strain multi-directional upsetting process, a severe plastic deformation (SPD) method, is used for the production of ultra-fine grained metals. Since the value and distribution of accumulated plastic strain and stress directly influence the microstructure, understanding of stress-strain state during the process is of utmost importance. Today, the finite element method (FEM) is one of the most used tools for stress-strain analysis of metal forming processes. In this paper, effective strain and stress distribution, determined by FEM, throughout six upsetting passes is presented. The material of prismatic samples is high-alloyed austenitic steel X2CrNiMo17-12-2, widely used for medical implants. Material characteristics and necessary boundary conditions are experimentally determined. Simulation results are verified comparing force and dimensional measurements from experiment and simulation.

Keywords: Finite element method; plane strain upsetting; severe plastic deformation.

1. INTRODUCTION

In his paper [1] Valiev defined severe plastic deformation (SPD) as metal forming technology used for producing ultra-fine grained (UFG) bulk materials by imposing very high strains without major changes to the sample geometry. UFG materials are defined as materials with an average grain size of less than 1μm [2]. Compared to conventional materials, these materials exhibit superior mechanical characteristics, primarily strength, hardness, and ductility. The improvement of these properties makes it possible to reduce the dimensions and weight of structural and equipment parts. In addition, UFG metals can replace alloyed metals of similar characteristics, reducing the consumption of "rare" metals. Furthermore, the development of micro and nano-components is directly dependent on the availability of suitable materials. For a material to acquire these new properties, the UFG structure must consist of predominantly high-angle grain boundaries and be uniformly distributed throughout the bulk of the material [3].

Valiev also formulated primary conditions that any SPD method should fulfill [4]:

- Even if the considerable refinement of the microstructure already occurs at strains of 1 - 2 [3], the formation of the UFG structure is possible only after exceeding values of 6 - 8. Imposed large strains should not lead to the formation of defects in the material.

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- SPD processes should be carried out at temperatures lower than 0.4 of the melting temperature of the material. Processing at higher temperatures leads to a reduction in accumulated dislocation density and an increase in grain size.
- For SPD processes, a high hydrostatic pressure greater than 1 GPa is desirable as it contributes to the deformability of the material, and therefore allows higher straining.
- Formation of equiaxed ultrafine grains depends on the vorticity of the metal flow which is at the macro level related to the non-monotonous character of the deformation.

If we take a closer look at the given SPD definition and primary conditions, we see that most of the mentioned requirements can be analysed using FEM software. Effective plastic strain and stress are the main results of almost any metal forming process simulation. The distribution of UFG in the sample is directly related to the stress and strain distribution, so to some extent, we can predict the grain refinement after the process by analysing the stress-strain state in the sample. If we include some damage models in the simulation, we can predict the maximum possible strain or the number of stages in repetitive processes. Hydrostatic pressure and material flow are also results that are easy to acquire and analyse. In addition, knowledge of the specific pressure is of great importance for the design of SPD tools due to the high forces in SPD processes. Furthermore, in repetitive methods, such as the one that is the subject of this article, FEA is useful to predict the necessary stroke to achieve the desired dimension after the process.

Today, there is a wide selection of FEM software specialized for metal forming simulations. For sheet metal forming, there is Stampack, Pam-Stamp, and AutoForm, while for the bulk metal forming simulation Q-Form, Deform, and Simufact.forming are the most popular choices. For the purposes of the research presented in this article, the Q-Form UK 10.2.1 software was used.

2. MULTI-DIRECTIONAL PLANE STRAIN UPSETTING

Because of the many advantages offered by ultrafine-grained metals, much research has been conducted to develop new SPD methods or to modify existing ones. As a result, it is now possible to induce SPD using different processing methods on a variety of metallic materials with different geometries and shapes. In their review paper [5], Bagherpour et al. classify SPD techniques based on the processing method as follows:

- SPD techniques based on equal-channel angular pressing,
- SPD techniques based on torsion under high pressure,
- SPD techniques based on direct/indirect extrusion,
- SPD techniques based on pressing/forging,
- SPD techniques based on rolling,
- Combined SPD techniques.

The common characteristic of all SPD techniques based on pressing is achieving extreme values of strain through repetitive compression using flat or profiled punches on different sides of the specimens. Among all of the methods based on pressing most attention attracted multi-directional forging in open [1] or closed die [6]. Multi-directional forging was first applied for the formation of UFG microstructure in relatively large, bulk billets made of rather brittle metals, because of the

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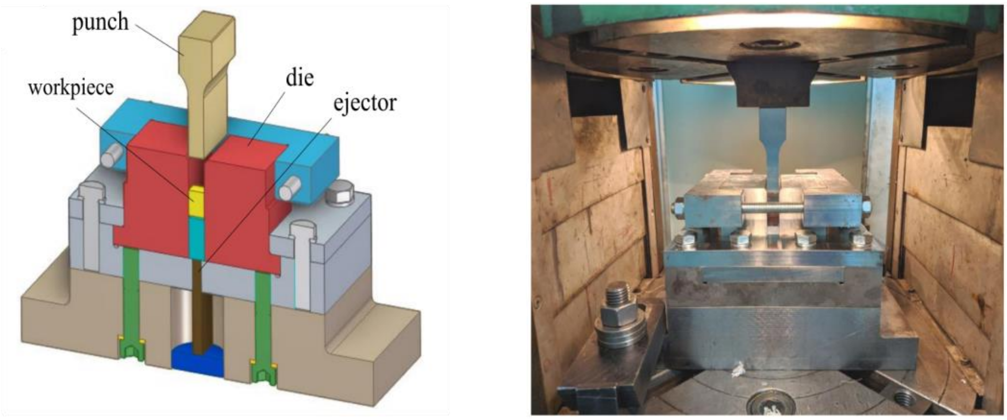
relatively low specific load at the tooling and elevated process temperature. The main disadvantages of this method are the lower strain homogeneity compared to the equal-channel angular pressing and high-pressure torsion, the occurrence of tensile stresses on the free surface, and difficulties in achieving the desired geometric accuracy. When the process is carried out in a closed die, greater hydrostatic stress is applied and geometric accuracy is significantly improved [6]. It is worth noting that the SPD method V-shape die compression [7] was developed in the Department of Mechanical Engineering at the Faculty of Technical Sciences in Novi Sad as part of a larger, decade-long research on SPD methods.

In the plane strain compression method, the prismatic sample is upset in the axial direction with a flat punch for the defined value of stroke. Plane strain compression die (Figure 1) restricts the flow of material in the lateral direction, while the material flows freely along the mould in the longitudinal direction. Since the width of the sample is constant, the state of plane strain is present in the sample. After the first stage, the sample is removed from the dies, rotated for 90 degrees, reinserted into the die and upset again [8]. The dies are mounted on a Sack & Kiesselbach 6.3 MN hydraulic press and the process is carried out at room temperature (Figure 1. b). In order to decrease the friction MoS2 lubrication manufactured by Valvoline, Germany, was used.



(a) *(b)*

Figure 1. Plane strain compression die: (a) a cross-section of the CAD model, (b) a photo of the die attached to the hydraulic press [9].

Prismatic samples were made of high-alloy, low-carbon steel X2CrNiMo17-12-2. The main characteristics of this steel are austenite microstructure, high strain hardening and high corrosion resistance. The results of tensile tests [9] have shown that this steel has excellent mechanical properties: relatively low yield strength, high strength, high elongation at fracture and extremely high uniform deformation. The uniform elongation and the low value of the ratio between the yield strength and the strength of the material indicate a very pronounced tendency of the steel to strengthen during cold forming. The dimensions of the samples before upsetting were 20x20x13.5 mm. Figure 2 shows a prismatic sample after each of the six stages.

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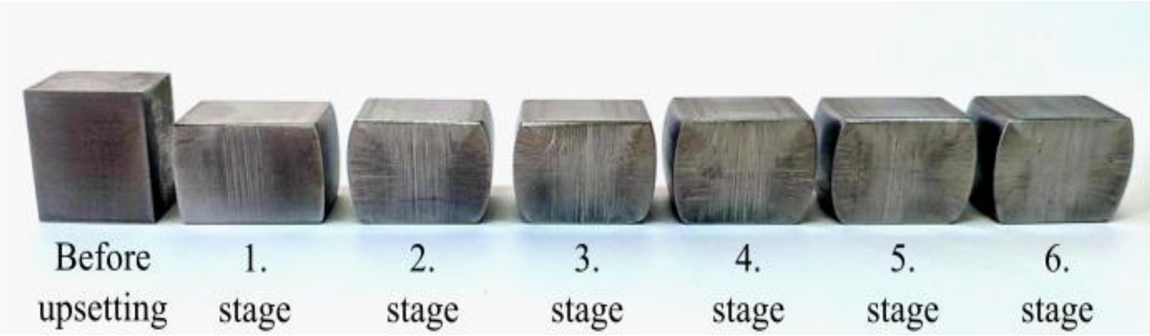

Figure 2. Prismatic sample after each of the six upsetting stages [9].

In the FEM analysis setup, dies were modelled as rigid. The material of the sample was modelled as plastic with a modulus of elasticity of 200GPa and a Poisson's ratio of 0.27. The stress-strain curve was determined experimentally by upsetting Rastagaev specimens [9]. The Coulomb friction coefficient was used to describe the contact conditions. A value of 0.075 was determined by the ring compression test [9]. Based on preliminary simulations, it was concluded that a coefficient of friction of 0.1 on the contact surface between the upper tool and the sample better describes the actual conditions. A friction coefficient of 0.075 was used for all other contact surfaces. The finite element mesh was defined by the maximum dimension of an element of 1 mm. For the type of FEM element, tetrahedral ones were chosen. In table 1 dimension and force measurements from the simulation and experiment are compared.

Table 1. Force and dimension measurements from experiment and simulation.

Stage number:	Longitudinal dimension of the sample (mm):		Height of the sample (mm):	Effective strain:	Force (kN):	
	Experiment:	Simulation:			Experiment:	Simulation:
0	20.06	20	20.03	/	/	/
1	24.71	25.02	15.5	0.29	359	366
2	24.46	24.89	16.05	0.5	488	495
3	24.64	25.40	15.84	0.5	558	587
4	24.39	24.32	16.1	0.49	588	632
5	24.44	24.24	16.08	0.48	588	604
6	24.35	24.12	16.13	0.48	598	634

If we compare the data from the previous table, we see a good correlation between the experimental and simulation results. This verifies the simulation setup is verified and further analysis is possible.

Figure 3 shows the effective strain distribution in longitudinal and cross-section. The distribution is not completely uniform over either the longitudinal or the lateral cross-section, but a certain gradient can be seen. The maximum strain occurs in the centre of the sample and along the diagonals with values between 3.6 and 4.4. The average effective strain over the entire volume of the sample is 2.66, while the accumulated effective strain calculated from the experiment is 2.74.

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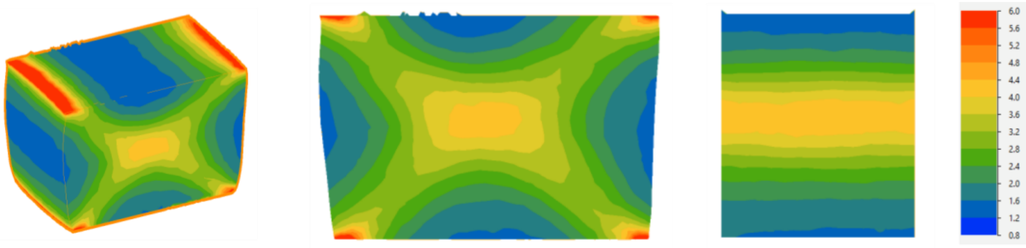


(a) (b) (c)

Figure 3. Effective strain distribution (a) in the sample, in his (b) longitudinal and (c) lateral cross-section.

The mean, hydrostatic stress has only negative values in the sample, which means that a state of compressive stress is present. The average value of the mean stress was 997 MPa, the maximum was close to 1400 MPa, while the minimum was around 700 MPa.

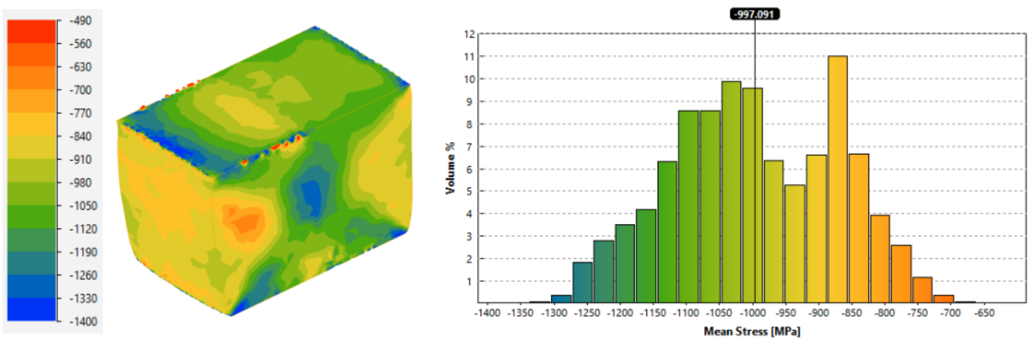
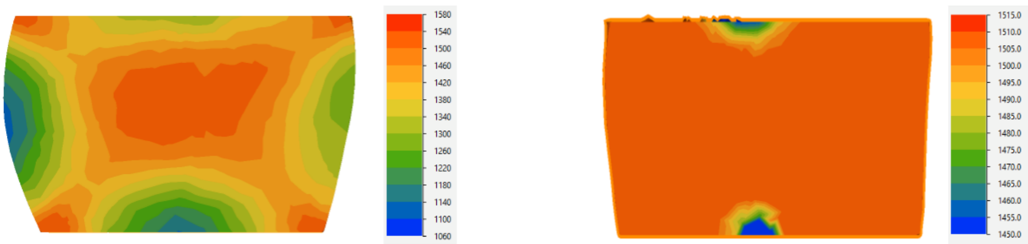


Figure 5. Mean stress distribution and statistics.

Figure 4. shows the effective stress distribution after third and sixth upsetting pass. As we can see, the central zone with maximum effective stress from the third phase expanded across almost the entire cross-section after the sixth stage.



(a) (b)

Figure 4. Effective stress distribution after (a) the third and (b) the sixth stage

3. CONCLUSIONS

Following conclusions can be drawn from the previous findings.

1. The simulation setup was verified by comparing the force and dimensions of the sample from the experiment and the simulation

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2. The simulation predicts the longitudinal dimension quite well, which is important, given that it represents the height of the sample in the next stage.
3. The average value of the effective strain was 2.66. To satisfy the Valiev condition, at least 7 additional phases must be performed.
4. The average value of the mean stress was 997 MPa, which means that in the next stage Valiev condition will be fulfilled.
5. After the sixth stage, the maximum effective stress was achieved over the entire cross-section of the sample.

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