STRESS STATE WITHIN WORKPIECES AFTER SEVERE PLASTIC DEFORMATION BY CLOSED DIE

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Abstract

The article presents the results of a study of the stress-strain state of workpieces after severe plastic deformation performed in a closed die. The stress state study was performed by the slip lines method and in the Deform 3D simulation software. The analysis of the stress state shows that the value of the stress components within the workpiece increased after one cycle of deformation by 1.5 - 2.5 times. The prevalence of compressive stresses contributes to metal structure refining via high-cycle alternating strain.

Keywords: Stress state, severe plastic deformation, numerical simulation, FEM

1. INTRODUCTION

One of the perspective trends in metals forming and modern materials science is the production of ultra-fine-grained and/or nanostructured materials with the grain size of about 100 nm or less [1,2]. When conventional coarse-grained materials are transferred to the ultra-fine-grained state, the mechanical characteristics increase and the utility properties, such as electrical conductivity, corrosion resistance, etc., improve too [3-6].

The modern possibilities of application of such materials have been presented by many researchers [7-12]. However, production of such materials in the industrial scale is still an issue to be solved mainly due to the complexity of designing the processes, or the limited size of the final ultra-fine-grained and/or nanostructured products. Nevertheless, some extreme plastic deformation methods, such as ECAP-conform [13,14], and rotary swaging [15], are suitable for industrial production of long products.

The formation of nanostructure depends on the stress-strain state within the workpiece, which depends on the shape of the acting tools (die and punches) and the processing method. In this paper, a newly developed method for producing nanostructured materials by severe plastic deformation (SPD) is investigated, the stress-strain state and the deformation force were the evaluated parameters. As can further be observed, the proposed design of SPD metal processing resembles the known method of "hourglass", which in the case of multicycle alternating deformation ensures the production of nanostructured materials.

2. MATERIALS AND METHODS

The principle of the new device is as follows. The device consists of a closed die with two circular and two central punches. The circular punches are bevelled. At the beginning of processing, the solid cylinder workpiece is located between the circular punches. During deformation, the circular punches move towards each other, thereby displace the workpiece in the area in which the central punches are located and the billet becomes biconvex. When the area between the punches is fully filled with the workpiece material and the upper and lower parts of the workpiece reach the boundaries of the cylindrical voids, the movement of the circular punches ceases. In the second stage of the process, the central punches begin to move towards each other, interacting with the workpiece. In this case, the workpiece affects the inclined sections of the circular punches with pressure and pushes them out. Then the process repeats.

The below presented research carried out by the finite elements method (FEM) using the DEFORM 3D software uses the construction of three-dimensional models having the properties of the real objects. The reliability of results predicted with the use of this software was shown previously e.g. in [16-18]. The process of deformation of the workpiece in a closed die, which implements the SPD in a multi-cycle processing, was divided into two stages. The first stage was the compression by lateral circular punches, the second stage was the involvement of the central punch to press the workpiece. Subsequently, the stages repeat until ultrafine-grained structure is developed.

KOMPAS 3D software was implemented to create the models of the workpiece and the used device. Creating models was carried out taking into account the geometric similarity with the scale factor = 1. Subsequently, the models were imported into the DEFORM 3D software. One of the main parameters that characterize the accuracy of the calculation is the finite element mesh. The models of deformable body were determined by volume distributed tetragonal grid finite elements, the total number of finite elements was selected to be 50 000, which allows the calculation to be performed with sufficient precision. The model of the device was defined as a rigid body. The device and workpiece materials were selected from the software database - tool steel was used for the device, while AISI 1045 construction steel was used for the workpiece. The simulation was carried out taking into account heat exchange (heat transfer) between the workpiece, tooling and the environment under normal conditions (ambient temperature equal to 20 °C). Room temperature was selected for the tool, whereas the temperature of the workpiece was set to be 950 °C in accordance with the suitable forging temperature interval. The friction conditions at the interfaces substantially influence the deformation process and the corresponding load and the stress-strain state in the deformation zone. In this study, the coefficients of friction of 0 and 0.3 were selected based on previous studies [10]. When all the boundary conditions for the simulation are set, the total number of steps is defined. The simulation was considered to be of a single tool stroke, the workpiece dimensions were Ø20x10 mm.

The investigation was performed by compressing the cylindrical workpiece with an outer circular punch before the workpiece enters the cylindrical area between the upper and lower punches. When moving the upper and lower punches, the circular punches are simultaneously pushed out by the material of the workpiece. The constant external pressure on the circular punch was 150 kN. The 0 friction coefficient was considered for the purpose of revealing the main regularities of the deformation process. In the following figures, the form of the workpiece after crimping with external circular punches (the first stage) is represented in the left part of the figure, while in the right part of the figure the workpiece after the introduction of the central punches (the second stage) is presented.

3. RESULTS AND DISCUSSION

The results of the simulation allow evaluation of the stress-strain state as well as shape change of the workpiece during the deformation process and also provide data to be compared to the real experiment (**Figure 1**). As the distribution of the hydrostatic pressure shows, during deformation the compressive stresses prevail for the entire section of the workpiece. At the same time, as a result of compression by the circular punches, localization of stresses in the peripheral part of the workpiece can be observed - the compressive stresses exceed 500 MPa, however, gradual decrease in stresses up to nearly 200 MPa occurs in the central part of the workpiece and 0 was predicted at the free surfaces. After the 2nd stage of deformation, the hydrostatic stress is reduced to - 500 MPa for the entire section of the billet. At the same time, the effective stress rises from 180 MPa in the central area of the workpiece to 500 MPa in the peripheral areas. This tendency is observed for both, the first stage and the second stage of deformation, however, in the second stage of deformation, the regions having stress effective values of 500 MPa and more become prevalent.

Due to the development of intensive shear on the contact surfaces, the effective strain takes relatively high values - 0.5 to 0.75, in the zones of interaction with the bevelled sections of the circular punches [19]. On the other hand, the free areas and the regions between the circular punches feature the effective strain value of 0.25. By the effect of central punches, the central area of the workpiece is subjected to intensive deformation and the effective strain value in this area reaches 1.25. In the zones of direct contact between the workpiece and the central punch, the effective strain reaches the value of 2.

The force acting on the external circular punches gradually increases during deformation and reaches to 150 kN by the end of the first stage. This development is typical for SPD processes featuring gradual filling of the die [20,21]. During the second stage, the constant force of 150 kN is applied to the external punch, while a gradually increasing force is applied to the central punches from the beginning of the second stage. This force finally increases up to 500 kN at the end of the second stage.

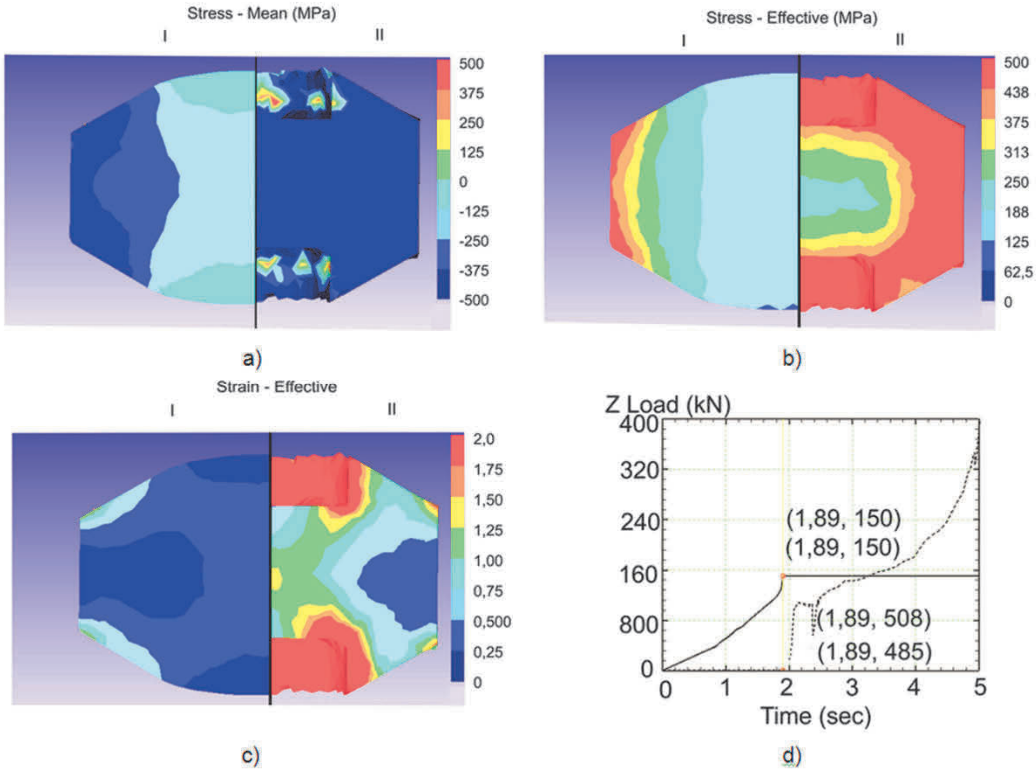


Figure 1 The stress-strain state within the workpiece and load graph for deformation in a closed die (a-mean stress, b-effective stress, c-effective strain, d-load graph)

In the case of industrial implementation of the presented process, the coefficient of friction will be significantly different from 0. However, the results can be used to provide the approximation of the results also for other deformation conditions. By this reason, computer simulation for a coefficient of friction of 0.3 was also realized.

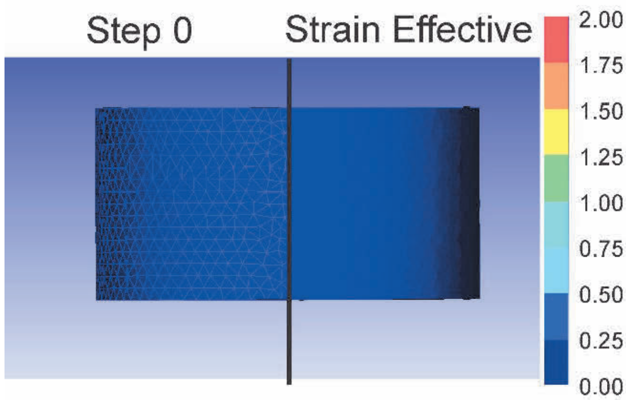
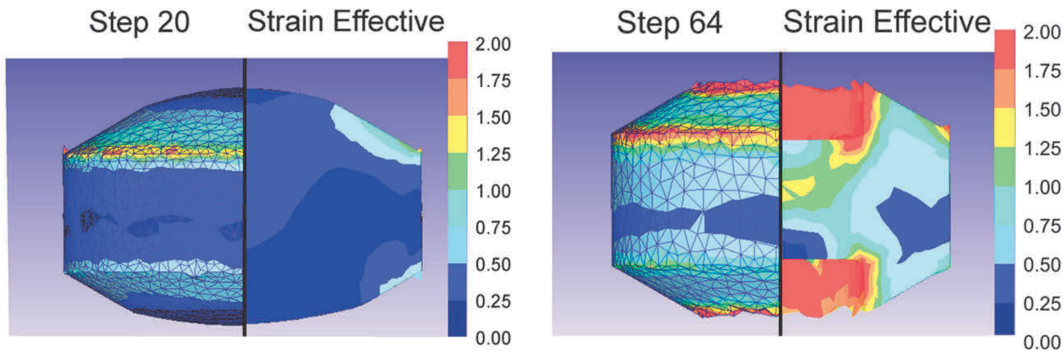


Figure 2 The model of workpiece before deformation

The workpiece in the initial moment at the beginning of deformation is shown in **Figure 2**. Given by the symmetry of the workpiece, the figures are represented as a combination of the image of workpiece section (right) and its full appearance (left). For the convenience of evaluating the stress-strain state during the deformation process, only workpiece without the details of the tooling is shown. In addition, the workpiece is shown with the finite element mesh.

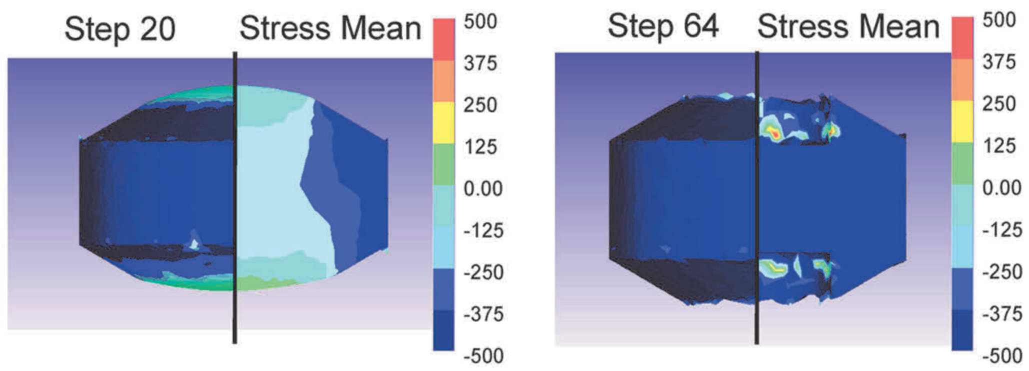
At the moment when the workpiece fills the area between the punches fully and reaches the boundary of the cylindrical hollow with the upper and lower parts of the blank, the effective strain takes the values of ~ 0.75-1.0 on the inclined sections of the circular punches and ~ 0.25-0.5 in the central area (**Figure 3**). In the second stage of the process, the central punches begin to move towards each other and start to affect the workpiece. In this stage, the workpiece affects the inclined sections of the circular punches with pressure and pushes them out. The back pressure on the circular punches is 150 kN. As a result, the strain in the workpiece accumulates and reaches ~ 0.5-0.75 in the peripheral sections and in the central area between the two punches acquires the values from 1 to 1.5. In the areas of workpiece being in contact with the central punches, the effective strain reaches the value of 2.0. Then, the cycle is repeated.



a) b)

Figure 3 The strain state of the workpiece during deformation (a-end of 1st stage, b- end of 2nd stage) in a closed die

The stress state of all-round (hydrostatic) compression promotes by such favourable distribution of the effective strain (**Figure 4**) [22]. At the first stage of deformation (during the movement of circular punches), the workpiece area located between the circular punch sections is subjected to compressive stresses exceeding 500 MPa. In the central zones, the workpiece material is displaced towards the central punches. By this reason, the stresses reach to 0 MPa in the upper and lower sections of the workpiece. In the second stage of deformation, as a result of the implementation of the central punches and back pressure on the circular punches, the entire workpiece is subjected to the action of all-round compression with stresses exceeding 500 MPa.



a) b)

Figure 4 The hydrostatic pressure during deformation (a-end of 1st stage, b- end of 2nd stage) in a closed die

Such a stress state favourably eliminates any formation of microcracks and micropores, supports healing of internal defects, provides intensive refining of structural components and enables achieving the maximum possible ductility of the workpiece [23-25]. Thus, the absence of metal losses in the process of deformation in a closed die enables the process to be repeated in order to accumulate strain and achieve the required level of metal characteristics.

4. CONCLUSION

The new method of severe plastic deformation (SPD) in a closed die had been developed and investigated; a computer simulation was used to investigate the stress-strain state after SPD in a closed die. In the main deformation zone, the compressive stresses prevail during deformation. The effective strain in the individual workpiece sections reaches the maximum value of 2 at the end of the second stage of deformation. The repetition of the first and second stages of deformation will ensure the production of high quality workpieces with a high degree of structural refinement.

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