The strain state under severe plastic deformation by dual-angular equal-channel extrusion

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Keywords

Severe plastic deformation, dual-angular equal-channel extrusion, grid strain analysis method

1. Introduction

A grid laid onto a specimen is one of the most popular methods of investigating the kinematics and the dynamics of plastic flows, giving detailed information about strain zones and transitional areas, as well irregularity of the stress-strain state into the body volume. At first the method consists in laying a grid onto the surface of a specimen and studying the kinematics of the flow according to the results obtained from the deformation of its elements. It is believed that the method gave only a qualitative picture for the stress state, but subsequently such means of processing experimental data have been developed that have led to the possibility of calculating the strain state around the deformable volume.

The geometrical dependence of transforming an ordinary cube with an inscribed globe into a parallelepiped with an inscribed ellipsoid is taken into account at formulae entry for deformations reading. In solving the plane problems the initial elements are a square and a circle, which after deformation are converted into a parallelogram and an ellipse, respectively, Fig. 1.

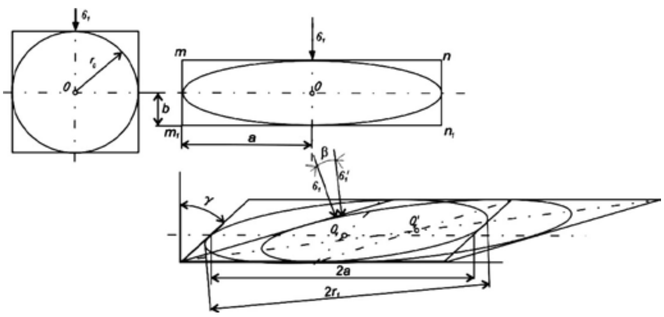

Figure 1. Elements of a grid before and after deformation.

In this case the two major deformations of the circle deformed into the ellipse can be described by means of following expressions taking into consideration the change of the ellipse axes:

$$\varepsilon_1 = \ln\frac{r1}{r0};\ \varepsilon_2 = \ln\frac{r2}{r0};\ \varepsilon_3 = \mathrm{tg}\gamma. \tag{1}$$

It is necessary in determining the effective strains the angle γ to be defined, which can also be expressed by r_1, r_2. The relationships derived through semi-major axis and semi-minor one of the ellipse inscribed into the parallelogram can be described by the following expressions:

$$r_1 = \pm\sqrt{\frac{1}{2}\left[a_2+\left(\frac{b}{sin\gamma}\right)^2\right]+\frac{1}{2}\sqrt{[a^3+(\frac{b}{sin\gamma})^2]^2-4a^2b^2}} \tag{2}$$

$$r_2 = \pm\sqrt{\frac{1}{2}\left[a_2+\left(\frac{b}{sin\gamma}\right)^2\right]+\frac{1}{2}\sqrt{[a^2+(\frac{b}{sin\gamma})^2]^2-4a^2b^2}} \tag{3}$$

where *a, b* are dimensions of the parallelogram after deforming, Fig. 1.

At the grid method the angle α that characterizes the direction change of major and minor axis of the ellipse with respect to the deformation direction is determined. The angle α can be defined by means of the following expression according to the literature data:

$$\tan\alpha = -\tan\gamma(\frac{r_2^2}{r_1^2}-1)+\frac{1}{2}\sqrt{\tan^2\gamma(\frac{r_2^2}{r_1^2}-1)-4\frac{r_2^2}{r_1^2}} \tag{4}$$

The determined directions of the major and minor axis of the ellipse give data for the situation of the axes of the main deformations and the main normal stresses in the plane of the grid.

2. Methodology of experiment

In this paper the experiments are carried out by using the grid analysis method in order to investigate the strain distribution in the volume of simple shear deformation through a die.

The physical modeling is performed by using the grid analysis method with the elementary cell dimensions 1.85×1.85 mm laid to a plane passing through the axis of symmetry of the lead preform, which is extruded. The preform with dimensions 10.6×10.6×55 mm is divided into two halves along its length.

To achieve the highest possible accuracy the tool is initially hardened then manufactured on DMG Lasertec 40 machine, shown in Fig. 2. This machine is laser milling machine as the process is also known as laser ablation.

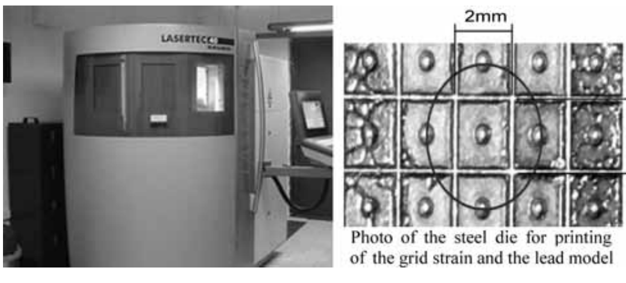

Figure 2. Overview of DMG Lasertec 40 machine.

Laser milling is a new technology suitable for machining a wide range of materials like metals, glass, ceramics and plastics by removing material in a layer-by-layer [Vasco et al., 2005;

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Pham et al., 2004]. This technology involves heating the material and subsequent melt and material removal, Fig. 3.

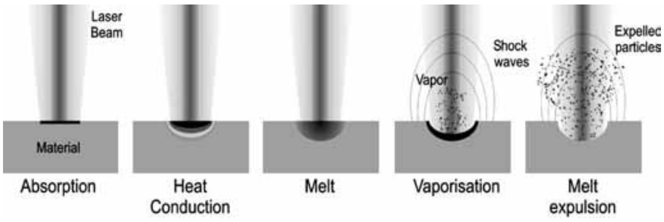

Figure. 3 The interaction between the laser and the material during a laser milling operation [Bartolo et al., 2006].

At the beginning test series is carried out on the hardened work-piece at different parameters in order to achieve the best surface quality and accuracy. The chosen parameters for producing the grid structure are: the layer thickness 1 μm, the track displacement 8 μm, the scanner speed 300 mm/s and the frequency 30 kHz. This low power technology guarantees low thermally affected layer thickness, the best surface quality and accuracy.

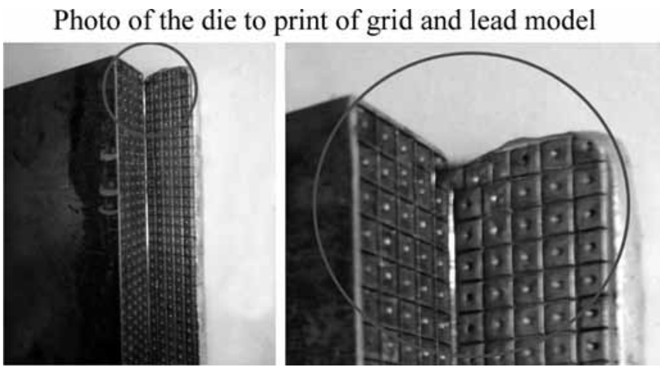

Photo 1. Laser-treated surface of the steel die with a positive impression of the grid.

The deformations into the geometric center of each one cell from the grid can be determined by the change of the geometrical dimensions of that cell. The two diagonals of the cell and the rotation angle of the grid at the vertices of the rhomboid are measured.

The deformations which have to be determined are the two major linear strains along the axes of the two diagonals d13 and d24. They are calculated as the true (logarithmic) strains according to the relations:

- true (logarithmic) strain of diagonals d_{13} - $\varepsilon_{13} = \ln (d_{13} / d_0)$;

- true (logarithmic) strain of diagonals d_{24} – $\varepsilon_{24} = \ln (d_{24} / d_0)$;

where d_0 is the initial size of the diagonals of the cell before deformation.

The linear strain along the third axis, which is perpendicular to the plane with the laid grid, is determined by means of the law of constancy of volume, i.e.:

$$\varepsilon_{13\text{-}24} = - (\varepsilon_{13} + \varepsilon_{24}).$$

The angular strains of the grid are defined as the average value of the tangent of the outer angles at the top of the obtained rhomboid.

The deviator of the strain defines the change of the form of elementary volume, while the spherical tensor defines only its relative volume change. The quadratic invariant of this deviator plays an important role in the theory of plasticity, as defined effective angular strains. The effective strain actually gives a numerical expression of the strains deviator and can be used as a numerical parameter in determining the irregularity of the strains in the volume of the deformed body.

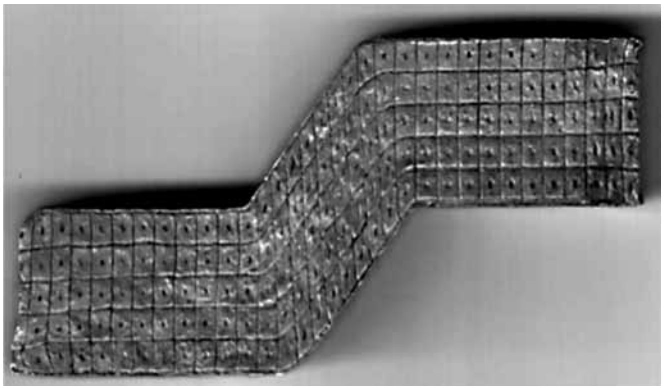

Photo 2. The deformed lead specimen with plotted grid strain.

The distribution and the irregularity of strains are determined within four sections of deformation space of the tool for dual-angular extrusion by four rows from elementary cells:

- An initially unstained part (the input channel immediately to the counter punch) with partial penetration into the deformation zone of the first cross-channel;
- A first angular deformation zone of the first cross-channel between input and output ones;
- An area between deformation zones of cross-angles between input and output channels;
- A second angular deformation zone of the second cross-channel with penetration in the zone of the output channel.

The deformation of the lead specimen in these four sections from the deformation space of the tool will be discussed below.

3. Distribution of the strains in initially unstrained part with partial penetration into the deformation zone of the first cross-channel

The distribution of logarithmic linear strains and angular one of the grid in rows cells from No. 5 to No. 9 along the length and in the cross-section of the deformed specimen are given in Tables below.

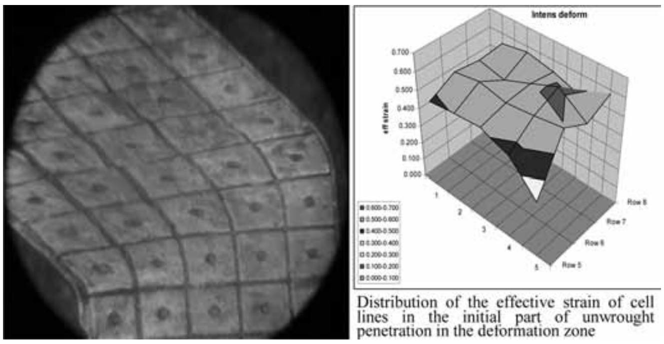

Photo 3. The deformed grid in the initial part of unwrought partial penetration in the first deformation zone.

The effective strain in the cells of the first cross-channel between input and output ones is relatively high – up to

0.55–0.56 and after the row No. 5 it is uniformly distributed. Elevated values of the effective strain above 0.62 are related with the uncorrected deformation of a single cell.

4. Distribution of effective strains in the deformation zone between input and output channels

The deformed grid and the effective strain of rows cells from No. 9 to No. 12 along the length and in the cross-section of the deformed lead specimen are given in Tables below.

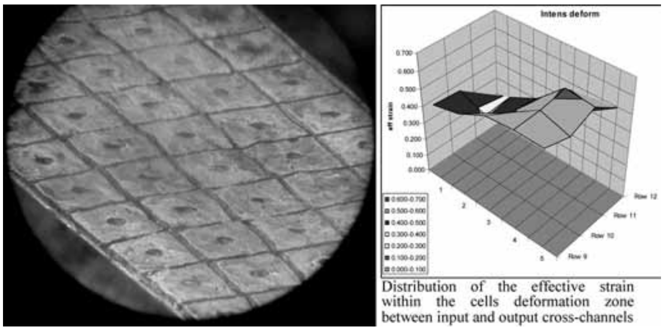

Photo 4. The deformed grid within the deformation zone of the cross-angles between input and output channels.

The effective strain in cells within the deformation zone between input and output channel is relatively high – up to 0.55–0.58, but it is uniformly distributed in the cross-section. Elevated values of the effective stress above 0.61 are around the external curvature of the channel, until after at the inner radius of curvature they decreased within 0.26–0.27. After the inner radius there are very low levels, i.e. from 0.08 to 0.09 in row No. 12, which indicate penetration into the deformation zone of the second angle, and thereafter "ironing" the cells of the grid in the reverse direction.

5. Distribution of strains between deformation zones of cross-angles of input and output channels

The distribution of logarithmic linear strains and angular one of the grid in rows cells from No. 9 to No. 12 along the length and in the cross-section of the deformed specimen are given in Tables below.

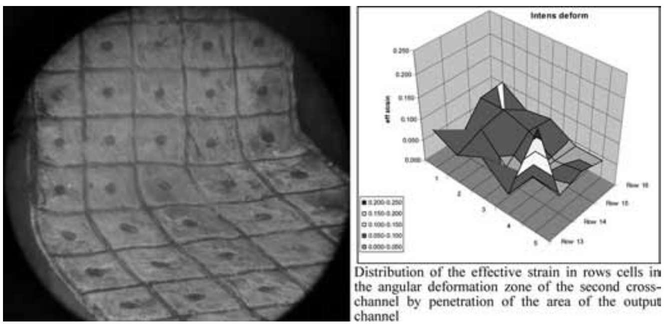

Photo 5.The deformed grid in the angular deformation zone of the second cross-channel and the exit area of the output channel.

The effective strain in the angular deformation zone of the second cross-channel is relatively high and uniformly distributed in the cross-section. Elevated values above 0.23 around the outside curvature are for cells, which are not finally „ironed". Values of about 0.10 near the inner radius of curvature of the channel are related to the residual deformations of the grid, which will remain and after the end of extrusion.

6. Comparison of the irregularity of strains at dies obtained by 3D computer simulation and its verification using grid method

The computer simulation of the dual-angular equal-channel extrusion is done by the CAD/CAE software Quantor Form 2D/3D. The two zones of the severe plastic deformation (simple shear zones) are clearly delineated – they are at both angular changes of the channel. This corresponds with the theoretical formulation for the carried out consecutively deformation of the cross-section of the preform, which is typically at the severe plastic deformation by the equal-channel angular extrusion.

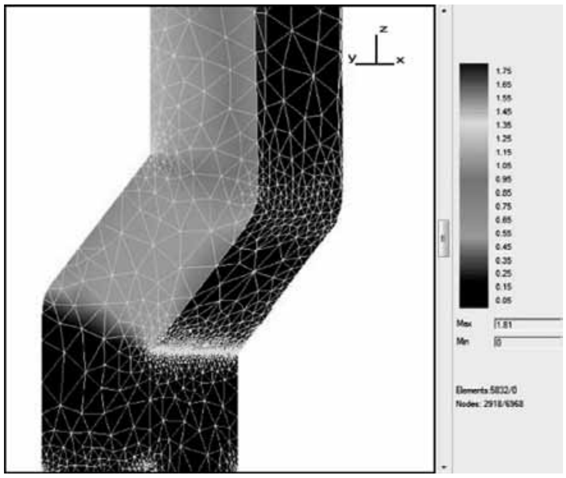

Photo 6. Distribution of the effective strain in the deformation space of the die-matrix by 3D computer simulation with the software Quantor Form 2D/3D.

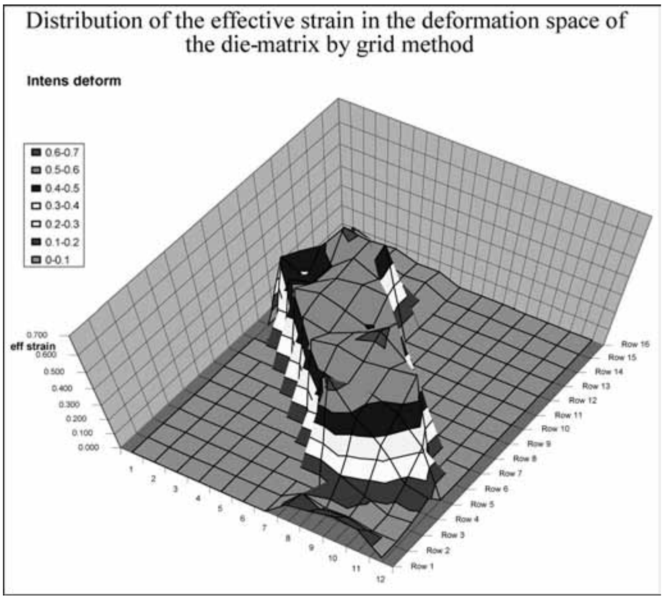

Photo 7. Distribution of the effective strain in the deformation space of the die-matrix by grid method.

It is found at the computer simulation that the effective strain after first cross-channel is about 0.55 (from 0.45 to 0.55) in the cross-section of the preform. It is uniformly distributed, and higher values are around the outside curvature of the channel. The effective strain increases up to 1.05 after the second cross-channel, as the distribution in the cross-section becomes almost uniform from 0.95 to 1.15.

The distribution of the effective strains obtained by the computer simulation is verified by physical modeling the process using the grid method. The effective strain in the cells after the first cross-channel between the input and output channel determined by the grid method is from 0.55 to 0.56. There is observed the "ironing" the grid and return to the initial size of the cells. This means that the estimated value of the effective strain in the cells after the second cross-channel is twice larger – till 1.10–1.15.

The comparison between the results for the effective strain as achieved values and distribution in the cross-section of the deformed specimen obtained by both the methods, i.e. the computer simulation and physical modeling, are in good agreement. This allows quantitative determining the accumulated effective strains for each subsequent pass of the dual-angular equal-channel extrusion or other methods for the severe plastic deformation.

7. Conclusion

1. The results from physical modeling the lead alloy specimen subjected to the severe plastic deformation by dual equal-channel angular extrusion are shown. The distribution of deformation zones and irregularity of strains, as well their localization in the areas of the cross-channels, under the severe plastic deformation by the dual-angular equal-channel extrusion are established by using the grid analysis method.

2. The verification of the results obtained by the computer simulation with CAD/CAE software Quantor Form 2D/3D is performed by means of the grid strain analysis method. The effective strain as achieved values and the distribution in the cross-section of the deformed specimen obtained by both the method, i.e. the computer simulation and physical modeling, are in good agreement.

3. A real approach to determining the accumulated and distributed effective strains in the volume of deformed body for each pass of the dual angular equal-channel extrusion or other methods for the severe plastic deformation is suggested.

Acknowledgement

The research is related to the project No BG051PO001-3.3.06-0046 "Development support of PhD students, postdoctoral researchers and young scientists in the field of virtual engineering and industrial technologies". The project is implemented with the financial support of the Operational Programme Human Resources Development, co-financed by the European Union through the European Social Fund.

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