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STRAIN DETERMINATION BY THE METHOD OF PHISICAL DISCRETIZATION

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ABSTRACT

The determination of working piece deformation state at bulk metal forming in open dies of axisymetrical pieces has been carried out in this paper. Preparation pieces made in appropriate way have been used in investigations. Preparation pieces are made out of segments, thus they are physically discreeted, so that such a method is said to be the method of physical discretization (MPD). By a suitable mechanical and chemical forming it is possible to obtain a deformed image of a meridial cross-section and determine a deformation state, which has been done. Finally, the results and given directions for further investigations in the sense of improving the method have been analyzed.

1. INTRODUCTION

Bulk metal forming in open dies has been widely applied. The main reason for that is the possibility of obtaining working pieces of very different shapes with good mechanicalcharacteristics. This is achieved due to a favourable stress state within a working piece, during the forming process, especially in the final stage, where stress pressing components are predominant. On the other hand, the development of material and tool forming technology, a possibility of being applied at high temperatures and deformation velocities, are some reasons more for a wide application of bulk metal forming in open dies.

For a successful and economical projection of any technological procedure of bulk metal forming, it is of great importance to know deformation parameters. Accepted basic theoretical assumptions and methods for their determination show evident disagreement in concrete deformation conditions, thus in most cases there is a need for experimental determination of parameters and their modeling.

In the recent time, along with the development of computer equipment, methods of numerical modeling have become more popular and applied in practice, above all the Finite Element Method (FEM). Besides all the possibilities of numerical simulations, there some limitations in their application. These limitations refer, above all, to input data on which the accuracy of simulation results depend. Due to this it is necessary to make an experimental verification of the results obtained and their comparison to the results obtained by other methods.

2. AIM OF THE PAPER

Deformation parameters have been studied to a less degree , especially with axisymmetrical working pieces, due to the characteristics of stress state appearing in the course of deformation process. This refers, above all, to stretching edge stresses, thus an experimental determinationof strain values is made difficult. Investigations have mainly remained on a theoretical level.
The aim of the paper is to determine deformation parameters for the volume of a working piece at bulk metal forming in open dies of axisymmetrical working pieces. Deformation parameters imply all the components of strain tensors. Knowing these parameters is the base for determining all other parameters of a deformation process.
The base for determination of strain tensors components is to know the displacement of the points of a working piece volume. With axisymmetrical working pieces, it is enough to know the displacement of the meridial cross-section points, thus it would be necessery to organize and carry out experimental investigations properly.
Realization of such a goal means a scientific contribution in the field of bulk metal forming in open dies, this meeting strict demands as for product quality, tool durability and utilization of production resources. In this way a contribution to a wider application of this technology is made, also the possibility of applying it, or similar (modified) methodology in other fields of bulk metal forming.

3. STRAIN THEORY BASES

Strain tensor at axisymmetrical deformation state is:

$$T_\varepsilon = \begin{vmatrix} \varepsilon_r & \frac{1}{2}\gamma_{r\theta} & \frac{1}{2}\gamma_{rz} \\ \frac{1}{2}\gamma_{\theta r} & \varepsilon_\theta & \frac{1}{2}\gamma_{\theta z} \\ \frac{1}{2}\gamma_{zr} & \frac{1}{2}\gamma_{z\theta} & \varepsilon_z \end{vmatrix}. \tag{3.1}$$

Strain tensor components in the cylindrical coordinate system are defined as:

$$\left.\begin{array}{ll} \varepsilon_r = \dfrac{\partial u_r}{\partial r} & \gamma_{r\theta} = \dfrac{1}{r}\dfrac{\partial u_r}{\partial \theta} + \dfrac{\partial u_\theta}{\partial r} - \dfrac{u_\theta}{r} \\ \varepsilon_\theta = \dfrac{1}{r}\dfrac{\partial u_\theta}{\partial \theta} + \dfrac{u_r}{r} & \gamma_{\theta z} = \dfrac{\partial u_\theta}{\partial z} + \dfrac{1}{r}\dfrac{\partial u_z}{\partial \theta} \\ \varepsilon_z = \dfrac{\partial u_z}{\partial z} & \gamma_{rz} = \dfrac{\partial u_r}{\partial z} + \dfrac{\partial u_z}{\partial r} \end{array}\right\} \tag{3.2}$$

At axisymmetrical stress state there is no displacement in tangential direction and the changes in the rest two displacements in that direction are equal to zero [1]:

$$u_\theta = 0, \quad \frac{\partial u_r}{\partial \theta} = 0, \quad \frac{\partial u_z}{\partial \theta} = 0, \tag{3.3}$$

thus the strain tensor components are:

$$\left.\begin{aligned} \varepsilon_r &= \frac{\partial u_r}{\partial r} & \gamma_{r\theta} &= 0 \\ \varepsilon_\theta &= \frac{u_r}{r} & \gamma_{\theta z} &= 0 \\ \varepsilon_z &= \frac{\partial u_z}{\partial z} & \gamma_{rz} &= \frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r} \end{aligned}\right\}, \tag{3.4}$$

The value defined as:

$$\varepsilon_e = \frac{2}{\sqrt{3}}\sqrt{I_2(T_\varepsilon)} = \frac{\sqrt{2}}{3}\sqrt{(\varepsilon_r - \varepsilon_\theta)^2 + (\varepsilon_\theta - \varepsilon_z)^2 + (\varepsilon_r - \varepsilon_z)^2 + \frac{3}{2}\gamma_{rz}^2}\ , \tag{3.5}$$

where $I_2(T_\varepsilon)$ is second invariant of strain tensor (3.1) [2], is effective strain or strain intensity, quantitatively defined the degree of the shape change of the observed piece of a body and is expressed in dependence on strain components.

4. EXPERIMENTAL INVESTIGATIONS

4.1. Experimental definition

As the process of bulk metal forming is one of the most complex processes of deformation, within which there is a great variety in view of the used materials and shapes, investigations have been narrowed to a family of stepped axisymmetrical pieces (Fig.4.1.) [3].

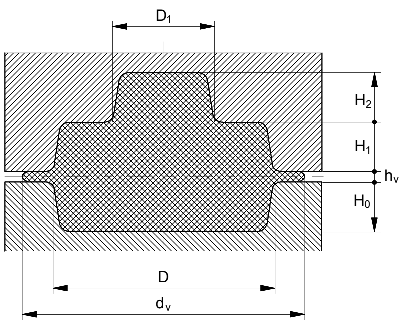


Fig.4.1. A working piece and dies

There have been adopted two levels of height from the upper side and one level of height from the low side of the die plane (Fig.4.1.). These are the following zones of a meridial cross-section of a working piece:

- low die zone (H_0=10 [mm]),
- ring zone (h_v=1 [mm]),
- first level upper die zone (H_1=10 [mm]) and
- second level upper die zone (H_2=10 [mm]).

Investigations are carried out on a real material in laboratory conditions and are adjusted in the way to be as much similar to real (production) conditions being present in direct industrial environment. The following investigation conditions are adopted:

- As investigated material there has been used an aluminum alloy AlMgSi0,5, which is very often used in processes of bulk metal forming, before all in extrusion processes and bulk metal forming in open dies.
- Investigation is carried out at temperatures of hot forming of the mentioned alloy, namely at t=440 [°C].
- Deformation is realized by constantan deformation velocity: v=2 [mm/s].
- Process is carried out by graphite grease lubrication, being applied in production conditions.
- There have been adopted other geometrical parameter of a working piece (Fig.4.1.):
    - Diameter of the upper die second level zone: D_1=40 [mm]
    - Basic die diameter: D=40 [mm];
    - Ring diameter: d_v=50 [mm];

4.2. Experimental equipment

Investigation place is formed in the Laboratory of the Faculty of Mechanical Engineering in Podgorica (Fig.4.2.).

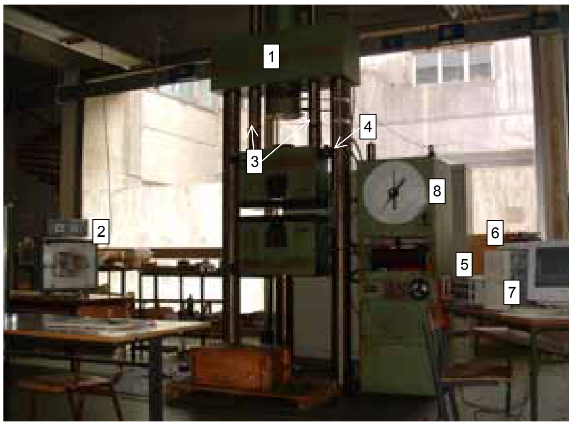


Fig.4.2. A photo of investigation place: 1 - hydraulic press, 2 - laboratory furnace, 3 - resistant force sensor, 4 - inductive displacement sensor, 5 - measuring bridge, 6 - transmission unit, 7 - computer with A/D card, 8 - measuring and regulating press device

As a deformation machine there has been used a machine for static investigation with hydraulic drive, type R100, of Russian production, maximum force 1 [MN] and working table moving velocity v=2 [mm/s]. The press is equipped with digital measuring equipment linked to an information measurement system.

4.3. Tools for deformation in open dies

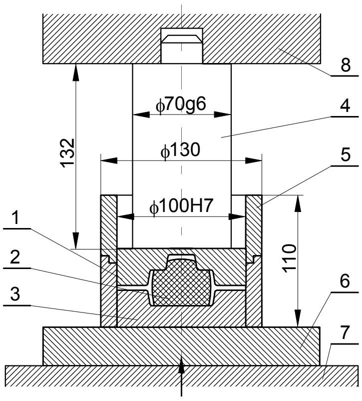


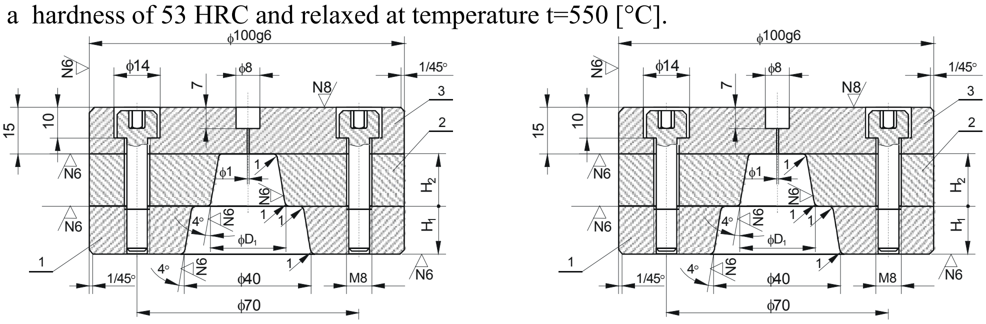
Fig.4.3. Fit of tool for deformation in open dies: 1 - upper die, 2 - lower die, 3 - working piece, 4 - punch, 5 - tube guide, 6 - flat plate, 7 - lower press table, 8 - hydraulic cylinder

Fit of tools for deformation in open dies is given on Fig.4.3.

With tool for deformation in open dies, upper (1) and lower (2) dies are located in the tube guide (5) providing their coaxiality during the process, and with hot working they also have the role of completing a chamber to maintain constant temperature. The guides are made of two parts, in order to be heated together with dies and preparation pieces. The pressing process is performed by making the upper press table move (7) upwards, under force of hydraulic piston.

4.4. Segment dies

So-colled segment dies (Fig.4.4.) have been used for bulk metal forming in open die. These dies are made by combination of segments-plates. The plates with bolts are fixed to the basic plate (3), thus forming a rigid structure representing a die - either upper or lower one, with adopted dimensions. Forging slopes are made at an angle α=4° in reference to the axis, and transitional radii are r=1 [mm] [4,5].
Die material is tool steel for work at hot state marked Č.4751 (Utop 2), heat treated by quenching to a hardness of 53 HRC and relaxed at temperature t=550 [°C].



a) b)

Fig.4.4. Segment dies for work in hot state: a) upper die; b) lower die

4.5. Experimental material and its preparation

Experimental material is an aluminum alloy AlMgSi0,5 of a chemical composition given in Table 4.1. The material is in the shape of hot extruded rods, of diameter ϕd=ϕ45 [mm].

Table 4.1. Chemical composition of the materials used in experimental investigation

Material	Fe%	Si%	Ti%	Cu%	Zn%	V%	Cr%	Mn%	Mg%	Ni%	Impurities
AlMgSi0,5	0.207	0.477	0.01	0.09	0.068	0.004	0.01	0.1	0.493	0.02	-

4.6. Segment preparation pieces

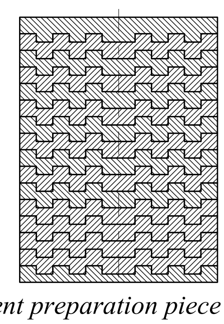


Fig.4.5. Segment preparation piece made of groove plates

Preparation pieces are made of segments in the form of groove plates (Fig.4.5).
With such preparation pieces, the grooves of plates in meridial cross-section practically form a mesh of finite elements, whose elements are determined with four nodes and three lines, so it is possible to determine a displacement of node points both in radial and axial directions.

4.7. Manufacturing segment preparation pieces out of groove plates

In the course of development of segment preparation pieces out of groove plates, there were empirically obtained nominal values of the dimensions of the plate grooves. The dimension of the plate grooves with tolerance in manufacturing and quality of the formed surface are given in Fig.4.6.

Hot extruded rods of alloy AlMgSi0,5 of diameter $\phi d=\phi 45$ [mm] are reduced by axial working on the lathe to a needed plate diameters. Such rods are cut by a knife for cutting on pre-measurement with additional parts $\delta=0.5$ [mm] for forming a finite measure, namely a height of h=5.5 [mm]. For manufacturing grooves there is formed a cutting tool whose photo is given in Fig.4.7.

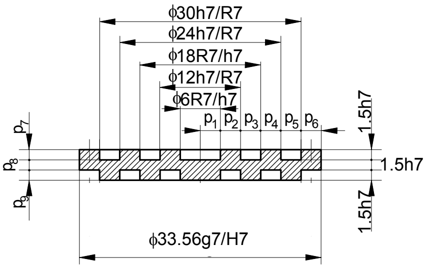


Fig.4.6. Characteristic plate dimensions

Fig.4.7. Tool for manufacturing groove plates

The same tool is used for making grooves on both sides of the plate, but the other side it is displaced for the value of nominal with of a groove 3 [mm] in radial direction. Working passage of the tool is in axial direction. These have been made special plate holders providing a maximum repetition of operation and production of plates with prescribed tolerances.

To obtain a segment working pece out of groove plates it is necessery to make an initial and final plate, having one flat side (Fig.4.8.). The final plate is left with the aditional part for making a formed segment preparation piece to a final measure.

After being made, plates are put into corresponding matrixes (Fig.4.9.). In the matrixes they are loaded by hydrostatical pressure being connected into one whole. Thus obtained preparation pieces are stable and behave as if being compact during manipulation, heating, deformation and subsequent forming by cutting.

For the adopted die dimensions, a needed number of plates is given in the Table 4.2.

a)

b)

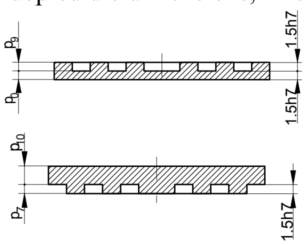
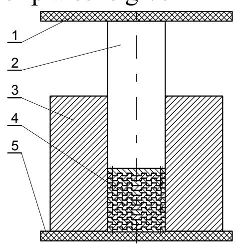


Fig.4.8. Final groove plates:
a) initial and i b) final



1 - pusher (hydraulic cyllidar)
2 - punch
3 - matrix
4 - groove plates
5 - basic plate

Fig.4.9. Connecting plates in matrix:

Table 4.2. Dimensions and numbers of segment preparation pieces

d_0 [mm]	h_0 [mm]	No. of groove plates	Whole No. of the pieces of groove plates
33.56	33.94	10.74	11

4.8. Preparation of a working piece for determination of deformation state

After deforming a preparation piece in t state at temperature t=440 [°C] and cooling, by forming on the milling machine, one half was drawn off to the symmetry axis. A flat surface of a meridial plane is finely polished and corroded by 30% water solution on NaOH in the duration of approximately 15 [min]. After that it is possible clearly to notice by an eye a deformed image of a cross-section. To be able to determine deformation state, it is necessary to determine numerical value of the deformed mesh. This has been done in a way to put the cross-section of a working piece onto computer scanner, where, at suitable adjusting of scanning parameters (light, sharpness, color), there has been obtained a good digitalized image of the cross-section in meridial plane with deformed mesh (Fig.4.10.).
To determine accurate values of initial characteristic geometrical parameters of groove plates within finished segment preparation pieces, there have been made meridial cross-sections and they were identically worked as working pieces after the deformation process (Fig.4.11.).

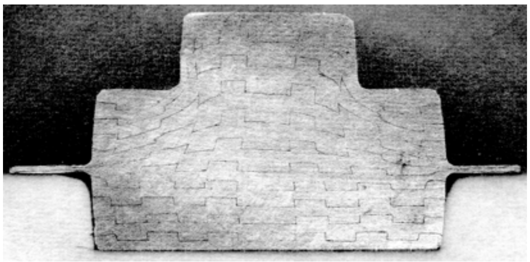


Fig.4.10. Digitalized cross-section of working piece

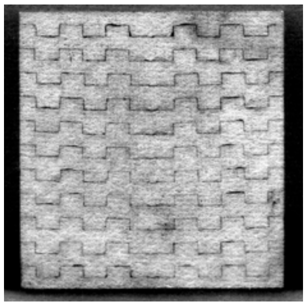


Fig.4.11. Digitalized cross-section of preparation piece

5. STRAIN DETERMINATION

The basis for determining deformation parameters in each point of the working piece volume is to know point displacement. Determination of volume point displacement was done differently by many authors, depending on the deformation process, stress state and other possibilities [6,7,8]. In the investigations given in this paper, segment preparation pieces of groove plates have been used for displacement determination. Thus, a preparation piece is phisically discreeted, and this method is called the Method of Phisical Discretization (MPD).
Measurements of a deformed mesh of digitalyzed image of a working piece cross-section is done on computer in Microsoft Excel - a standard programme Microsoft Office packet. First, arbitrary straight lines are made, whose points lead to overlapping with the lines of the deformed mesh, at an increase of 400%, which is enough for overlapping to be done with great accuracy. Coordinate system is adopted in a way that ordinate coincides with axis, whereas apscisa does it with the lower side of the working piece.
The determinations of the deformed mesh lines were done separately. The lines were previously vertical to the axis of a working piece, especially the line of previously parallel axis of a working piece, namely deformed radial and axial mesh lines (Fig.5.12. and Fig.5.13.).
All the lines in axial and radial directions, to treat them easier later on, are with the same number of points. It was necessary to take a sufficient number of points to be able to approximate in a qualitative way even twistings with small radius. This means that in the zones of small radii are

put points close enought to obtain a broken line which, when in calculation interpolated by cube interpolation, it does not go out of the thikness of a deformed mesh line at the cited magnifying. In this way there has been obtained an optimum number of points of the deformed mesh lines, and for radial lines it is j_r=41, whereas for axial ones i_z=20.

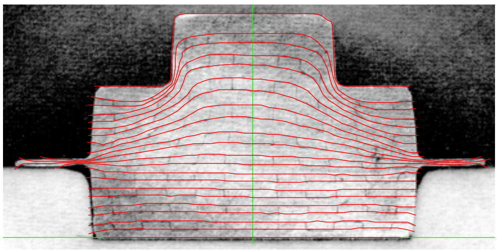


Fig.5.12. Radial lines of deformed mesh

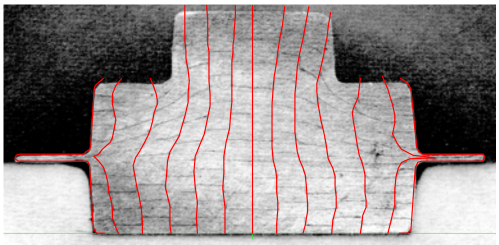


Fig.5.13. Axial lines of deformed mesh

Numerical values of the points of deformed lines represent a part of input data for determining deformation state. Data processing is made by computers, by means of a program made in MATLAB (v.7.0). Program generated deformed mesh is given in Fig.5.14.

First, intersection points of radial and axial deformed mesh lines are determined and they represent intersection points whose displacements in radial and axial direction may be determined. Other points are obtained by cube interpolation.

Non-deformed mesh is generated on the basis of the known values of geometrical parameters of groove plates (Fig.4.6.). obtained, for greater accuracy, measuring on non-deformed mesh of a preparation pieces (Fig.4.11.). Program generated non-deformed mesh is given in Fig.5.15., whereas the values of plate parameters of the segment a preparation piece in Table 5.1.

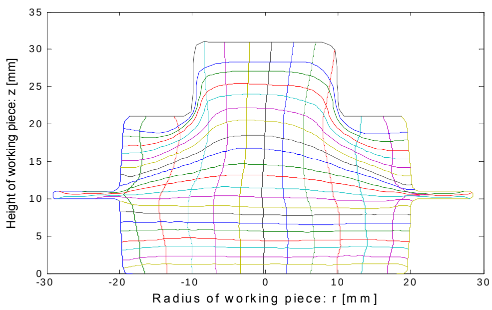


Fig.5.14. Deformed mesh

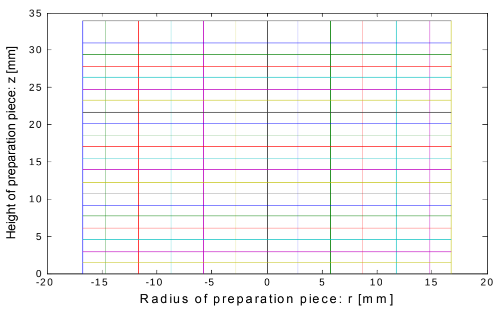


Fig.5.15. Non-deformed mesh

Table 5.1. Geometrical parameters of groove plates

d_0 [mm]	p_0 [mm]	p_1 [mm]	p_2 [mm]	p_3 [mm]	p_4 [mm]	p_5 [mm]	p_6 [mm]	p_7 [mm]	p_8 [mm]	p_9 [mm]
33.56	1.49	2.81	2.96	2.96	2.97	3.04	2.00	1.45	1.66	1.45

Based on the known values of coordinates of intersecting points of radial and axial lines of a non-deformed and deformed mesh, a displacement of points in radial and axial direction is determined. At this, displacement are:

$$\left.\begin{array}{l} u_r = r_{p1} - r_{p0} \\ u_z = z_{p1} - z_{p0} \end{array}\right\} \qquad (5.1)$$

The values of displacement in other points are approximated by cube interpolation, so to obtain an uninterrupted function of displacement of the meridial plane points of a working piece in dependence of radius and height. Thus it is possible to determine partial derivatives of displacement according to radius and height, through which one comes to relative strains (3.4). An exception is strain edge component which is determined in a simple way as a quotient of radial point displacement and its radius. Effective strain is determined by expression (3.5).
For practical reasons, due to feature of activity, it is suitable to use the components of logarithm strains. The values of logarithm strains are obtained on the basis of the known connection with relative strains [9]:

$$\varphi=\ln(1+\varepsilon). \tag{5.2}$$

The values of the components of logarithm strains and effective logarithm strain are given in Fig.5.16. till Fig.5.20.

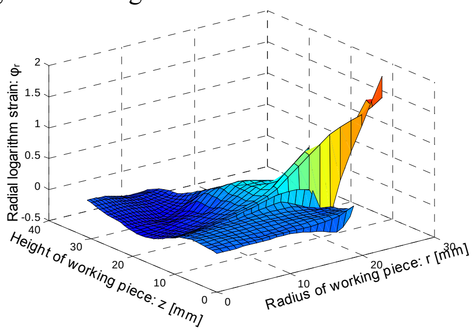


Fig.5.16. Radial logarithm strain: φ_r

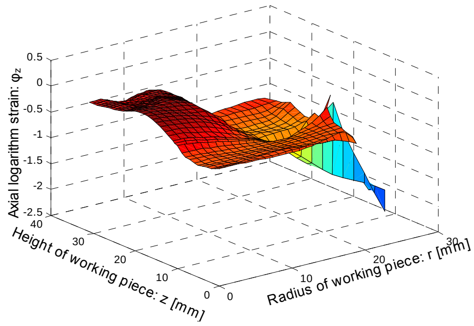


Fig.5.17. Axial logarithm strain: φ_z

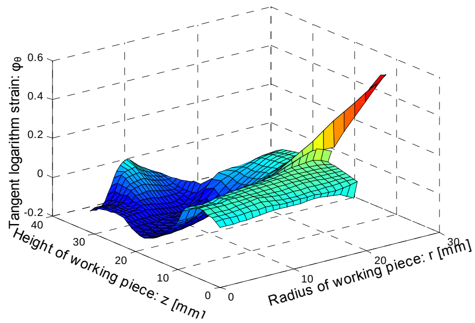


Fig.5.18. Tangent logarithm strain: φ_θ

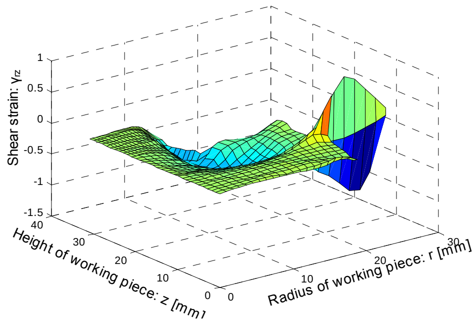


Fig.5.19. Shear strain: γ_{rz}

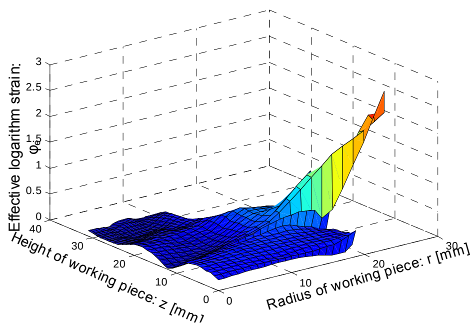


Fig.5.20. Effective logarithm strain: φ_e

6. CONCLUDING CONSIDERATION

At bulk metal forming in open dies of axisymmetrical working pieces, it is very difficult to determine a deformed state of meridial cross-section. To this purpose, there has been given a method of phisical discretization (MPD) in this paper, starting from corresponding discretization of a preparation piece. The discretization gives the possibility to obtain a deformed mesh after deformation. By a suitable echanical and chemical forming, their representing a condition for determining deformation state.

By analyzing the obtained parameters of deformation state of a working piece, it may be noted that two zones of values appear:

- zone corresponding to inner part of the die - die zone, and
- ring zone.

Normal components of logarithm deformation degree and effective logarithm strain have a similar character of changes in absolute values and of the same value order. Maximum values are at the end of the ring. Axial component differs for having negative values in its greatest part.

Shear strain component has extreme values in the middle of the ring, maximum on the lower, and minimum on the upper side.

MPD is not finite and further investigation should be directed towards its improvement:

- The improving of method refers, above all, decreasing dimensions of plate grooves for making segment preparation pieces.
- By discretization of the deformation process in open dies and determination of deformed parameters in phases, the accuracy of the results obtained is increased.
- Due to non-homogenity of the process and strain anizothropy, by statistical processing according to one of the famous distribution, one would come to the values of parameters with greatest probability.
- An applied methodology of determining deformation state, along with some corrections and adaptation, may be applied even to non-axisymmetrical forged pieces.
- Also, the MPD may be used in other processes of bulk metal forming, e.g. at upsetting, extrudion of the same or opposite direction pieces and rolling.
- The method of phisical discretization is possible to be applied to solving practical industrial problems, when speaking of a family of pieces of the same of similar shape with variation of geometrical parameters.

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ODREĐIVANJE DEFORMACIJA METODOM FIZIČKE DISKRETIZACIJE

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REZIME

U radu je izvršeno određivanje deformacionog stanja obradka kod zapreminskog deformisanja u otvorenim kalupima osnosimetričnih djelova. Za ostvarivanje postavljenog cilja istraživanja razvijeni su odgovarajući pripremci. Nakon niza pokušaja, koji su bili manje ili više uspješni, došlo se do toga da se ripremci izrađuju od segmenata u obliku žljebastih pločica. Žljebovi plošica praktično predstavljaju konačne elemente i fizičkom smislu. Dakle, pripremci su fizički su diskretizovani, pa je ovakav metod nazvan metodom fizičke diskretizacije (MFD). Pogodnom mehaničko hemijskom obradom nakon procesa deformisanja, moguće je dobiti deformisanu sliku meridijalnog presjeka. Najprije se obradom rezanjem odstranjuje jedna polovina obradka do ose simetrije, odnosno do meridijalnog presjeka. Zatim se površina fino polira i hemijski nagriza vodenim rastvorom NaOH, nakon čega deformisane konture žljebastih pločica postaju vidljive golim okom. Dobijeni presjek se skenira i dobija njegova digitalna verzija pogodna za dalju računarsku obradu.

Osnovu za odreživanje deformacionog stanja čine pomjeranja tačaka meridijalnog presjeka. Pomjeranja tačaka se određuju na osnovu poznate geometrije žljebastih plošica prije deformisanja i izmjerenih koordinata tačaka sa digitalizovane slike meridijalnog presjeka nakon deformisanja. Mjerenja se vrše tako što se postavljaju linije sa dovoljnim brojem tačaka. Na kraju je napravljena analiza rezultata i date smjernice daljih istraživanja i usavršavanja metoda.