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# ANALYSIS OF A STRAIN RATE FIELD IN COLD FORMED MATERIAL USING THE VISIOPLASTICITY METHOD

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In this paper the visioplasticity method is used to find the complete velocity and strain rate distributions from the experimental data, using the finite-difference method. The data about values of strain rates in plastic region of the material is very important for calculating stresses and the prediction of product quality. Specimens of copper alloy were extruded with different lubricants and different coefficients of friction and then the strain rate distributions were analysed and compared. Significant differences in velocity and strain rate distributions were obtained in some regions at the exit of the deformed zone.

*Key words:* forward extrusion, copper alloy, visioplasticity, strain rate, lubrication

**Analiza polja brzine deformacije hladno deformiranog materijala rabljenjem vizioplastične metode.** U radu je primjenjena vizioplastična metoda za istraživanje raspodjele brzine i brzine deformacije iz eksperimentalnih podataka pomoću metode konačnih razlika. Rezultati brzine deformacije su vrlo značajni za računanje naprezanja unutar plastičnog područja, kao i za prognozu kvalitete proizvoda. Uzorci bakrene slitine bili su hladno istiskivani različitim mazivima s različitim koeficijentom trenja. U radu su analizirani i uspoređeni raspodjela brzina i brzina deformacije. Utvrđene su značajne razlike u raspodjeli brzine i brzine deformacije u području izlaska iz zone deformiranja.

*Ključne riječi:* istosmjerno istiskivanje, bakrena slitina, vizioplastičnost, brzina deformacije, mazanje

## INTRODUCTION

Cold forming has become one of the most promising manufacturing technologies in the mass production of different components especially in the automotive industry. This is due to its material savings, very high productivity, and increasingly reduced machining, When technology and its parameters started to be understood better, the tools, material, lubricants and machinery became more reliable, and the process stabilised. Metal forming system depends on four major groups of influential parameters [1]:

- input material (physical and mechanical properties, micro- and macro- geometry),
- tools (shape, rigidity, surface quality, wear and load resistance, etc.),
- forming machine (stiffness, kinematics, sensitivity to heat transfers, etc.), and
- forming process with parameters including the impact of lubricants, strain, strain rates, and stress distribution inside a workpiece, heat generation, etc..

Material properties, velocity, stress and strain rate distribution, etc., have to be analysed as precisely as possible in order to reach high quality during the metal forming process and full product functionality. Lubrication is also of great importance in many metal forming processes due to its influence on tool wear, material flow, deformation characteristics and the mechanical properties of the formed parts [2]. Knowing the values of velocity and strain rates in the deforming, or zone of deformation zone of the formed material under different lubrication conditions is very important for calculating stresses, and predicting specimen quality. Although the theory of plasticity provides a sufficient number of independent equations for defining the mechanism of plastic deformation, it is impossible to obtain a complete solution for a general forming problem without simplification and approximations in the deforming mechanism. A number of approximate methods have been developed for the analysis of metal forming problems [3,4].

Different modeling and simulation methods have been used for determination of main parameters in metal forming [5-11], especially in extrusion processes. Among them, the visioplasticity method gives the most realistic solution to various forming problems. Furthermore, this method can be used as a means of examining the approximations of other solutions. The

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visioplasticity method consists of obtaining the velocity field experimentally and calculating the complete velocity, strain rate, strain, and stress fields by considering equilibrium and plasticity equations [12].

In this paper, the velocity and strain rate components distribution in forward extruded specimens of copper alloy were analysed, using the visioplasticity method.

## CALCULATION OF THE STRAIN RATE BY THE VISIOPLASTICITY METHOD

Visioplasticity is a method of obtaining information on material flow by using experimentally determined displacement of velocity fields. This method has gained greater importance over the past decade because of quantitative measurements of nodal point displacement during stepwise deformation, thus describing the material flow pattern.

The material flow can be determined by comparing un-deformed and deformed grids. Mostly, square grids composed of line nets are used on longitudinally cut sections when bulk forming. The grid can be inscribed on the specimen by mechanical means of etching, by photographic methods or pressing. The grid lines must be thin and sharp and the grid mesh should not split off, which would make the measurements difficult.

For steady-state flow problems in which the flow field does not vary with respect to time, it is possible to introduce a flow function $\theta$ by measuring the coordinates of the points located along the grid lines after steady-state conditions are reached. In steady-state axi-symmetric extrusion, the velocity field can be expressed by the flow function $\theta$ *(r, z),* as follows [12]:

$$v_z = \frac{1}{r} \cdot \frac{\partial \theta}{\partial r} \quad ; \quad v_r = -\frac{1}{r} \cdot \frac{\partial \theta}{\partial z} \tag{1}$$

where $v_z$ and $v_r$ are the velocity components in axial and radial directions.

When the velocity components $v_z$ and $v_r$ are known at all points in the deformation zone, the strain rate components can be obtained according to [12]:

$$\dot{\varepsilon}_r = \frac{\partial v_r}{\partial r} \quad ; \quad \dot{\varepsilon}_\vartheta = \frac{v_r}{r} \quad ; \quad \dot{\varepsilon}_z = \frac{\partial v_z}{\partial z} \tag{2}$$

$$\dot{\varepsilon}_r = \frac{1}{2} \cdot \left( \frac{\partial v_r}{\partial z} + \frac{\partial v_z}{\partial r} \right)$$

The effective strain rate is then calculated from its definition:

$$\dot{\varepsilon}_e = \sqrt{\frac{2}{3} \dot{e}_r^2 + \dot{e}_\vartheta^2 + \dot{e}_z^2 + +\dot{e}_{rz}^2} \tag{3}$$

The total effective strain can be evaluated by numerical integration of effective strain rate along the flow lines with respect to time:

$$\varepsilon_e = \int_o^{t_1} \dot{\varepsilon}_e \cdot \mathrm{d}t \tag{4}$$

where $t_1$ is the time required for a point to be displaced along a flow line. Strain rate components can also be written as follows [12]:

$$\begin{aligned} \dot{\varepsilon}_r &= \lambda \cdot (\sigma_r - \sigma_m) \\ \dot{\varepsilon}_z &= \lambda \cdot (\sigma_z - \sigma_m) \\ \dot{\varepsilon}_\vartheta &= \lambda \cdot (\sigma_\vartheta - \sigma_m) \\ \dot{\varepsilon}_{rz} &= \lambda \cdot \tau_{rz} \end{aligned} \tag{5}$$

where:

$$\sigma_m = \frac{\sigma_r + \sigma_\vartheta + \sigma_z}{3} \tag{6}$$

$\lambda = \frac{3 \cdot \varepsilon_e}{2 \cdot \sigma_f}$, coefficient of proportionality. (7)

The stress fields can be calculated easily from the calculated strain rate fields, using the integral equation in visioplasticity.

## EXPERIMENTAL WORK

Rods of special copper alloy CuCrZr were used during the experimental investigation. The initial dimensions of the specimens were Φ22 × 32 mm.

1 mm square grids were ascribed to the meridian plane of one-half of a split specimen. This specimen was extruded through a conical die having a $22{,}5^0$ half-cone angle and a 73 % reduction in area. Three different lubricants were used with different coefficients of friction ($\mu$= 0,05, 0,11 and 0,16). The major difficulty was that extremely high pressures were involved during the cold extrusion process and forming speeds were relatively low. Thus, liquid lubricants have to be used very attentively with thin, but equally accumulated, lubricant film [13,14]. Coefficients of friction for all lubricants were determined in the ring tests [12,15,16].

Forward extrusion was carried out at a punch speed of 12 mm/s and the extrusion process was stopped when a sufficient length of specimen was extruding, to ensure the establishment of a steady-state motion. The deformed grid of the specimen after forward extrusion is shown in Figure 1.

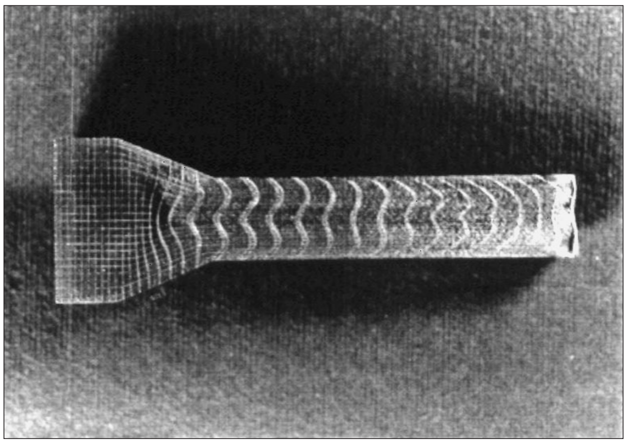

**Figure 1.** Deformed grid on the cold extruded specimen

## RESULTS AND DISCUSSION

The position of every node in the deformed grid after forward extrusion (Figure 1) was measured using an optical microscope. These values were put in a special computer program for visioplasticity, developed in the Laboratory for Material Forming at the Faculty of Mechanical Engineering, University of Maribor [17], as well as every node of the initial grid, distance between initial grid nodes, flow curve of the material to be formed and the punch speed. By measuring the difference between initial grid nodes and nodes on the deformed grid it was possible to calculate the velocities of every point in the r- and z- directions. The strain rates can be obtained from the equations (2) to (7). The results of the distributions of strain rate components in the deforming region of the specimens are presented in Figures 2 to 6.

In Figure 2 the axial component $v_a$ of the velocity is shown for three different coefficients of friction, as used in the cold forward extrusion process. The axial component is increasing with the strain and reaches the highest value on the exit zone ($v_a$= 4 mm/s).

By using lubricants with higher coefficients of friction ($\mu$ = 0,11 and 0,16) for extrusion process, the axial velocity values differ slightly at the exit zone where the axial velocity increases by 6 to 10 % compared to those values where a lubricant with a lower coefficient of friction was used ($\mu$ = 0,05).

The largest radial velocity $v_r$ (Figure 3) was reached along the outer side of the cone at the exit zone. In this area the largest value increased by about 20 % (from –1,0 to –1,2 mm/s) when using the lubricant with coefficient of friction $\mu$ = 0,16.

Generally, the distributions of axial velocity (and radial velocity, too) in specimens extruded under different lubrication conditions are very similar in the major area of the specimens, except in a small area at the end of the deforming zone. Figure 4 shows the contours of strain rate in the radial direction ($\dot{\varepsilon}_r$).

The largest value is obtained at the end of the deforming zone, while the smallest value is observed near the entrance.

There is no significant difference in the contours when the lubricant with coefficient of friction 0,16 was used except on the cone line, where the strain rate for coefficient of friction 0,16 is 0,18 $s^{-1}$ compared to $\dot{\varepsilon}_r$= 0,15 $s^{-1}$ for $\mu$ = 0,05. This represents an increase of 20 % which is significant, especially because of the greater strain rate's influence on stress distribution in cold formed material**.**

The influence of different lubricants on strain rate was noticeable on the cone line and at the exit of the deformation zone where the values for axial strain rate were a little higher when lubricants with coefficients of friction 0,11 and 0,16 were used for the extrusion process.

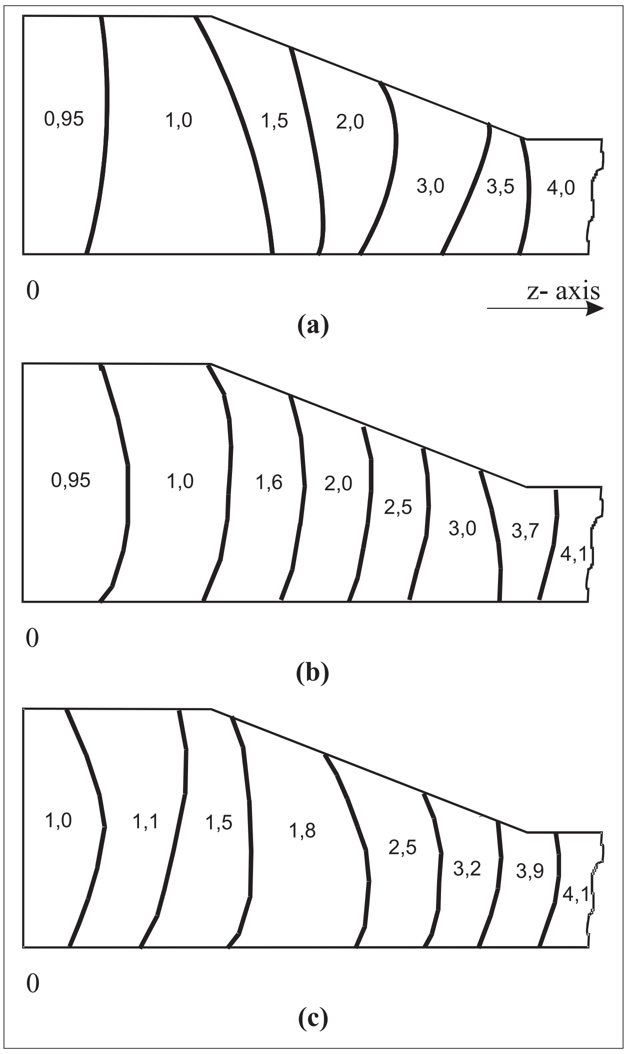

**Figure 2.** The contours of axial velocity $v_a$ / mm/s ($v_{punch}$ =12 mm/s, $R_{area}$= 73 %) for: (a) $\mu$ = 0,05, (b) $\mu$ = 0,11, (c) $\mu$ = 0,16

Distributions of the shear strain rate in extruded specimens are presented in Figure 6. The largest shear strain rate ($\dot{\varepsilon}_{rz}$) was obtained at the outer side of the deforming zones The differences in the strain rate values in the deforming zones of the specimens, extruded by three different lubricants coefficients of friction, was from 0 % (at the entering points) to nearly 15 % at the exit of the deformation zone. By using the lubricant with a lower coefficient of friction for the forward extrusion process, lower radial, axial and shear strain rate values were reached over the whole extruded specimen, especially at the end of the deforming zone.

## CONCLUSIONS

Velocity and strain rate distribution in a workpiece during the deformation process determine the stress state and achievable deformation limits. An advanced plasticity theory can be used to determine the velocity and strain rate values in the deformation zone from the local strains obtained from material movement. Visioplasticity is such a method, which is very useful in providing a detailed dis-

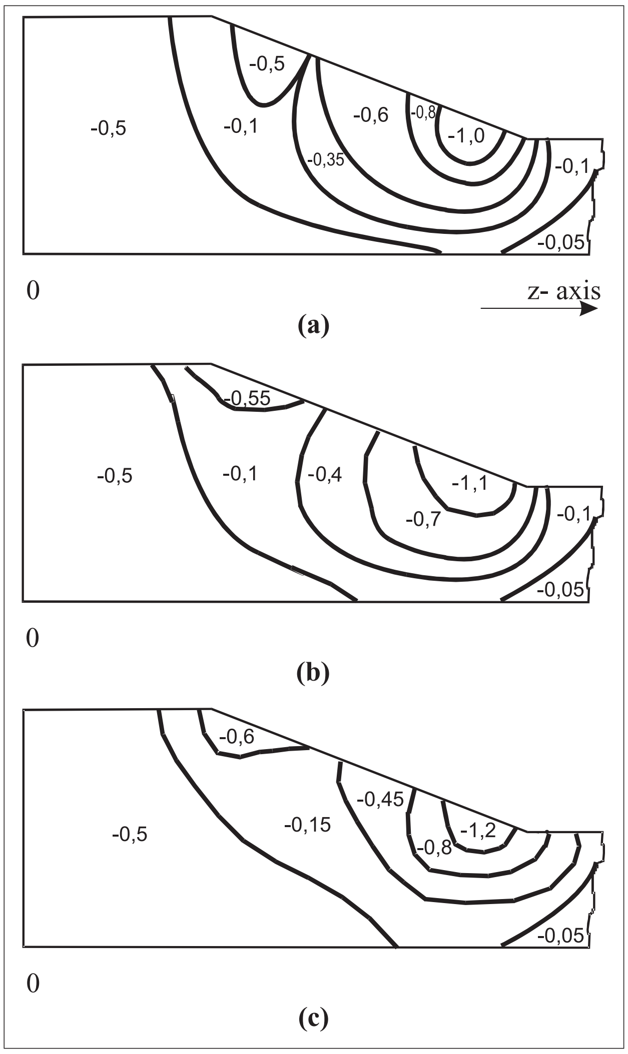

**Figure 3.** The contours of radial velocity $v_r$ / mm/s ($v_{punch}$ =12 mm/s, $R_{area}$= 73 %) for: (a) $\mu = 0{,}05$, (b) $\mu = 0{,}11$, (c) $\mu = 0{,}16$

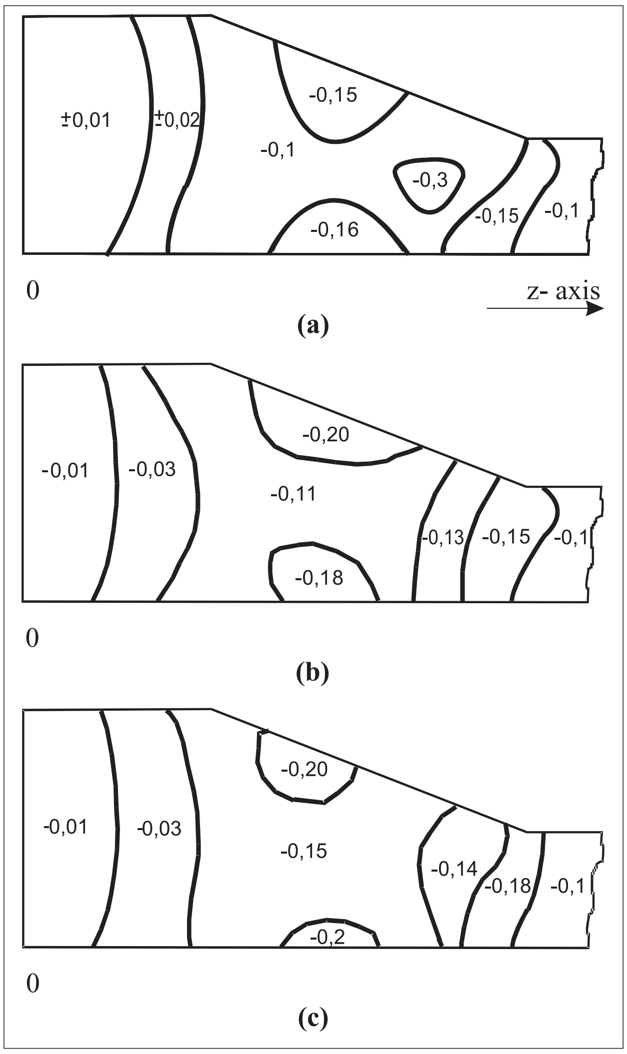

**Figure 4.** The contours of radial strain rate $\dot{\varepsilon}_r$ / $s^{-1}$ ($v_{punch}$ = 12 mm/s, $R_{area}$ = 73 %) for: (a) $\mu = 0{,}05$, (b) $\mu = 0{,}11$, (c) $\mu = 0{,}16$

tribution analysis of the major field variables, such as effective strain, strain rates and stress in any section within the plastically deformed region.

The material flow is mainly influenced by the strain distribution, strain hardening effects, the geometry of the tooling and the friction conditions between workpiece and tool. Knowing the distributions of strain rates in the plastic region of the material and choosing the right lubricant, its proper application and its influence on wear, forming force, temperature, material and geometric properties is very important for predicting specimen quality, and can also promote production efficiency.

This article analysed the influence of different lubricants with different coefficients of friction, on the axial and radial velocity components and strain rate values in the forward extruded copper alloy CuCrZr. Velocity fields and strain rates were determined using visioplasticity method.

The experiments have shown that the coefficient of friction's influence on the velocity components and strain rate distributions in extruded specimens is small in most measured regions of the deformed zone. Significant differences in velocity and strain rate distributions were obtained in some regions at the exit of the deformed zone. In these regions, higher values of velocity and strain rate components could be expected when using a lubricant with a higher coefficient of friction. This finding is important, especially because of the strain rate's influence on stress distributions in the cold formed material and the quality of the formed specimen.

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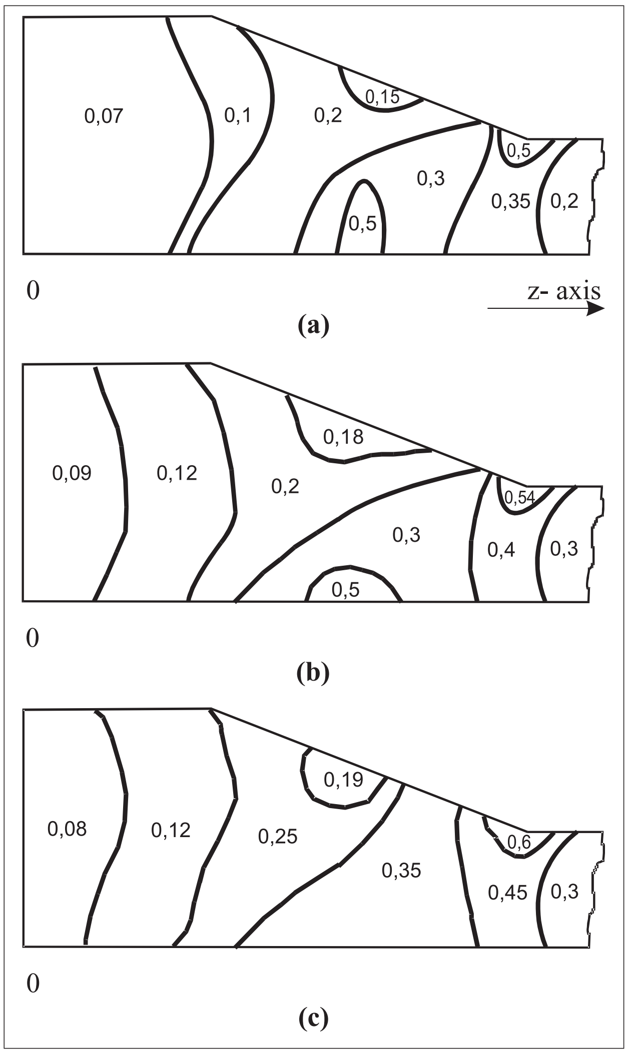

**Figure 5.** The contours of axial strain rate $\dot{\varepsilon}_z / s^{-1}$ ($v_{punch}$ = 12 mm/s, $R_{area}$= 73 %) for: (a) $\mu$ = 0,05, (b) $\mu$ = 0,11, (c) $\mu$ = 0,16

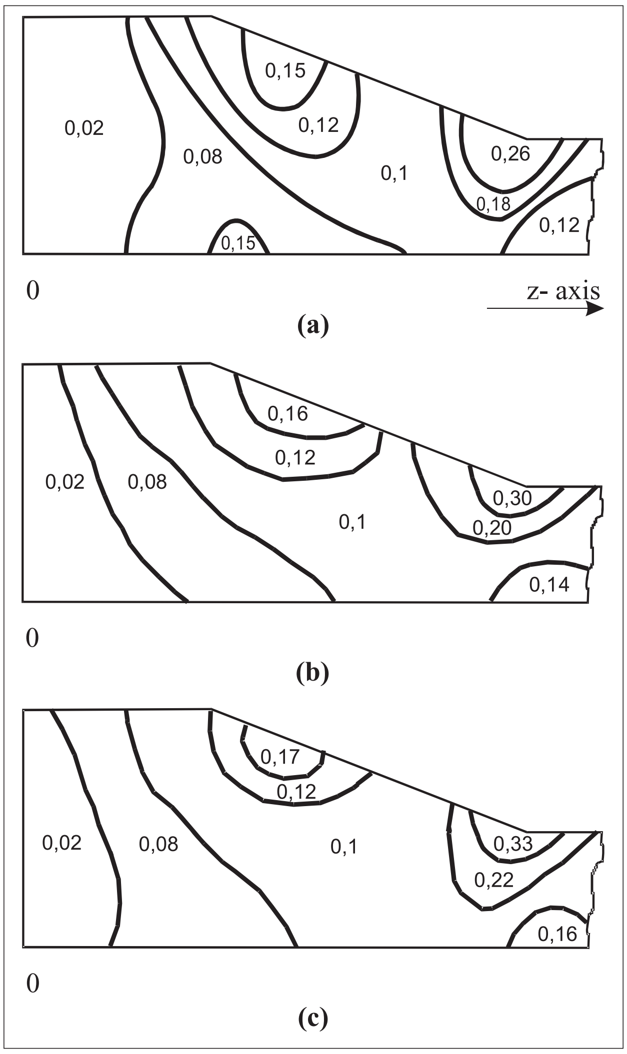

**Figure 6.** The contours of shear strain rate $\dot{\varepsilon}_{rz} / s^{-1}$ ($v_{punch}$ = 12 mm/s, $R_{area}$= 73 %) for: (a) = 0,05, (b) $\mu$ = 0,11, (c) $\mu$ = 0,16

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