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Experimental Measurement of Strain Rate when Cutting

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***Abstract*—A technique of experimental strain measurement in the chip formation zone when free cutting copper of grade M1 is considered in the paper. Digital image correlation was used for the study. This method enables real time estimating the degree of material strain. Obtained results are more precise as if compared with those of grid method.**

***Index Terms*— cutting of materials, plastic strain, strain rate, cutting, digital correlation of images, nondestructive test.**

I. Introduction

The results of the study on mechanisms of strain, initiating and evolving in the chip formation zone, support decision making in manufacturing industry. For instance, fatigue strength of a machine part can be improved, i. d. its lifetime in a product can be prolonged if residual compressive or tensile stresses are artificially created in the surface layer. Residual stresses can be controlled in a half-finished product via cutting modes, efficient geometry of a tool, and by means of special cutting fluids. When changing the conditions of cutting processes there are substantial changes in the chip formation zone. They are the causes of unpredictable changes in stress-strain state. That is why, it is necessary to carry out research to gain some new knowledge concerning the limits of plastic strain, propagating in material to be processed and stresses in a cutting tool. Fundamental principles of this field of science are outlined in works by M. Kronenberg [1], G. Sellergren [2], E.J.A. Armarego [3], A.M. Rozenberg [4], N.N. Zorev [5], G.L. Kufarev [6], G.D. Del [7], A.A. Briks [5], K.A. Zvorykin [5] etc. The works by these researchers are based on experimental study on measuring strains in the zone of cutting. The experiments are referred to two groups of methods: examination of a lateral face of the cutting zone and study on the structure of a “chip root” in cuts, made along the main cutting plane. The method of coordinate grids was one of the most widely applicable. It involved plotting a coordinate grid on the lateral surface of material to be processed. Strain was measured according to geometric distortions of the grids as soon as cutting had been stopped. The results found in researchers’ works enable drawing general conclusions about a degree of strain and its propagating zone. However, available information is insufficient to develop a unified mathematical model of stress-strain state in the chip formation zone. Hence, it is a burning issue to find new methods of precise investigating the strain, which propagates in the zone near the cutting edge of a tool.

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The digital correlation speckle interferometry method [10, 11] is one of the up to date and widely used techniques of experimental measuring material strain.

II. Methods of experiments

Experiments were carried out on a laboratory test bench depicted in Figure 1 and comprised the following steps. A disc-shaped specimen 1 was mounted on the cylindrical mandrel, fixed in a conical bore of a faceplate in a turning gear. There were some grooves on the disk to place experimental plates. Cutting tool 2 with rectilinear cutting edge was placed in the tool holder perpendicularly to the axis of specimen rotation and bolted down on the top. The tool holder was mounted by a special dynamometrical staple on a sliding support of the lathe. The support could be moved along one coordinate only along the axis of specimen rotation.

First, using metallic plates the edge of the cutting tool was to be placed at the same height as the axis of a specimen. The tool was brought by the support to the specimen at the specified cutting depth. An AC asynchronous motor turned a double reduction worm gear and supported faceplate rotation.

The optical system consisted of a monochromatic digital camera 3 and a laser unit with collimator 4. The system was to be placed so that a lateral face of the specimen under consideration was in the object plane of the video camera. The zone of cutting was lightened by coherent monochromatic radiation of the laser unit with collimator. For the purpose of eliminating optical disturbances and obtaining more precise results surfaces reflecting laser light were to be removed. Therefore, a dull surface was preliminary made on lateral faces of a specimen and the cutting tool. Moreover, all surfaces of the test bench with

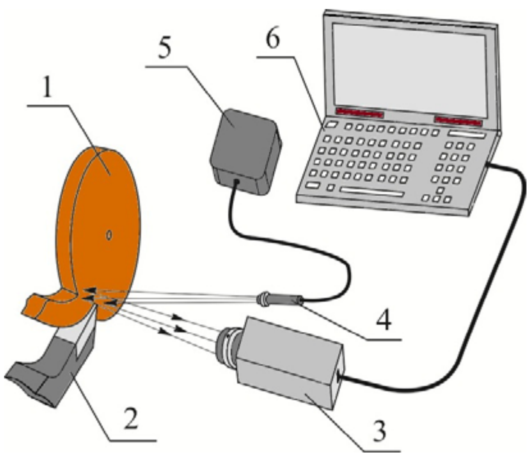

Fig. 2 Fig. 1 Laboratory test bench: 1 – disk (specimen), 2 – cutting tool with a dynamometer, 3 – digital video camera, 4 – laser, 5 – laser power supply unit, 6 – PC;

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metallic luster were covered with black paper.

When cutting the chip formation zone lightened by laser was being shot by the digital monochromatic camera with the frequency 25 frames a second. Images were sent to the PC, making it possible to form reference points of a particular size on the digital images. The number of points depended on image sensor resolution of the video camera.

Video recording was divided into sequential frames, subjected to further division into cells with a specified grid size in the range from 80 μm. When analyzing two sequential frames a displacement vector was determined for each pixel. So a vector field of strain was formed for the zone under consideration (Fig. 2).

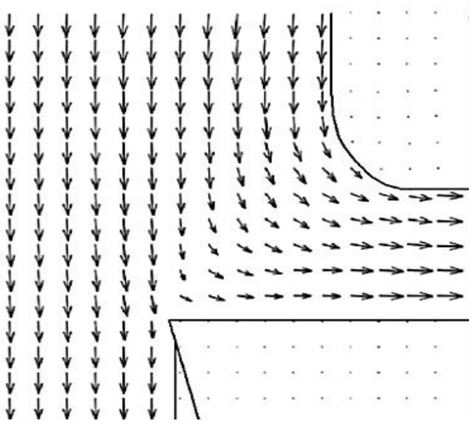

Fig. 2 Vector field of strain

III. Results and Discussion

The method of digital correlation speckle interferometry was used to measure values of strain when free cutting copper discs at micro-rates (V=13 mm/min).

As the result of correlation analyzing fragments of experiment video records displacement value matrixes were developed by special software module for each pixel of a fragment with a specified grid size along the coordinate axes oz – vertical axis and oy – horizontal axis.

Values of sum displacement vectors $\vec{V}_{s\,i}$ and its rotation Wi were calculated on the base of obtained field of displacements in the rectangular coordinate system.

$$\vec{V}_{s\,i}=\vec{U}_i+\vec{V}_i;\quad W_i=\mathrm{arctg}(\vec{U}_i/\vec{V}_i) \tag{1}$$

where $\vec{U}_i$ and $\vec{V}_i$ – displacement vector projections along the coordinate axes Z and Y respectively.

Numbers in Figure 3 a indicate values of sum displacements measured in μm for the carried out experiment. Fig. 3 b outlines the arrangement topogram of areas where direction of material flow in the chip formation zone can be specified according to changing rotation angle of displacement vectors.

As the time interval between two sequential frames is known, rates of material flow under plastic strain can be calculated. For this purpose each value in the displacement matrix is to be divided by the time between two adjacent frames of video recording.

The value of strain is calculated as a derivative of rate with respect to the selected coordinate position. Therefore, formulae to evaluate the degree of strain are as follows:

$$\vartheta_z=\frac{dV_z}{dt};\quad \vartheta_y=\frac{dV_y}{dt};\quad \dot{\varepsilon}_z=\frac{d\upsilon_z}{dz};\quad \dot{\varepsilon}_y=\frac{d\upsilon_y}{dy};$$
$$\dot{\gamma}_{zy}=\frac{d\upsilon_z}{dy}+\frac{d\upsilon_y}{dz}. \tag{2}$$

where dt – registration time of two sequential video recording frames.

Intensity of strain rate is associated with stress state in the deformation zone in terms of Levy-Mises equation [10], calculated according to formula:

$$\dot{\varepsilon}_i=\frac{\sqrt{2}}{3}\sqrt{\left(\dot{\varepsilon}_z-\dot{\varepsilon}_y\right)^2+\dot{\varepsilon}_z^2+\dot{\varepsilon}_y^2+\frac{3}{2}\cdot\dot{\gamma}_{zy}^2}. \tag{3}$$

As the result of calculations according to formulae (2) and (3) we have topograms, depicted in Fig. 4. Ratings of strain rate were joined by smooth lines displaying equal strain areas in the chip formation zone.

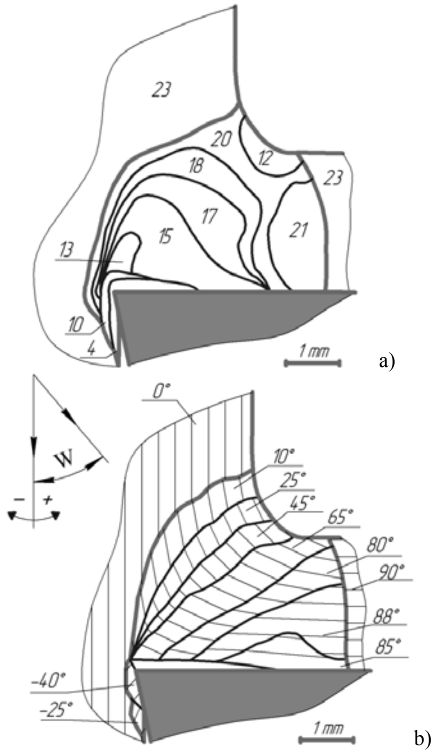

Fig. 3 – Topograms of material displacement fields (a) and rotation of displacement vectors (b) when free cutting copper of grade M1 at the rate V= 13 mm/min

The topograms given above demonstrate that in the chip formation zone there are strain processes with various intensity. This fact confirms anisotropy in process under consideration.

Having analyzed the obtained topogram of strain rate intensity more precisely we come to a conclusion that intensity values rise gradually along the left border of the chip formation zone and get maximal on the section adjacent to the cutting tool back face. Moreover, the value of intensity hardly changes along the line from free surface to the chip formation zone and forms a closed domain. This topogram makes it also possible to identify a secondary strain zone. Values can be negative in this area because of widening chip under lateral strain.

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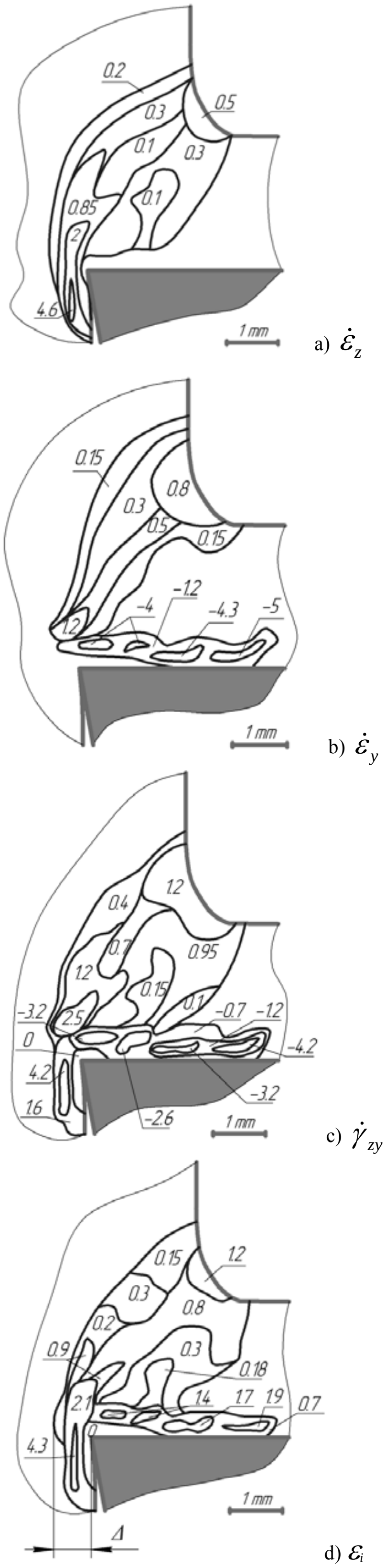

Fig. 4 – Topograms of strain rate in the chip formation zone when cutting copper of grade M1 at the rate V=13 mm/min

Having analyzed the obtained topogram of strain rate intensity more precisely we come to a conclusion that intensity values rise gradually along the left border of the chip formation zone and get maximal on the section adjacent to the cutting tool back face. Moreover, the value of intensity hardly changes along the line from free surface to the chip formation zone and forms a closed domain. This topogram makes it also possible to identify a secondary strain zone. Values can be negative in this area because of widening chip under lateral strain.

The obtained data agree well with information of experiments made by Professor G. L. Kufarev in similar conditions and given in paper [6]. For instance, strain rate values in the secondary stain zone.

The obtained topogram of strain rate intensity agrees with the form of plasticity zone, determined in experiments according to photomicrographs of flow chip roots [5].

Stress-strain state can be measured if the stress-strain diagram of material to be processed is considered in conditions of stress-strain. It is to be noted, most of processed materials are strengthened in the course of plastic strain. As soon as yield strength is reached and transition to plastic state is completed, the stress necessary for straining increases with the growing degree of strain. As the consequence, physical and mechanical properties of chip material and material of the processed surface (cold worked surface layer) differ from the rest specimen material. At the same time plastic strain is a thermosetting process like friction. These processes are accompanied with heat formation in the zone of friction fields. Material to be processed loses its strength when heating.

IV. Conclusions

The method of digital correlation speckle interferometry made it possible to measure strain rate intensity accurate within from 80 μm. The use of a PC and automated special software module enabled real time calculation. However, plastic materials with slow temperatures were used for experiments in this field at slow rates. Therefore, rate of cutting is to be increased and a high-speed camera is to be used to approximate strain to real values.

The study how strain rate influences strains in the chip formation zone when cutting main engineering structural materials at rates similar to real production is among outlooks of the work.

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