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Wojciech KACALAK[1*]
Lukasz RYPINA[1]
Katarzyna TANDECKA[1]

MODELLING AND ANALYSIS OF DISPLACEMENT OF MATERIALS CHARACTERIZED BY DIFFERENT PROPERTIES IN THE ZONE OF MICROCUTTING

This paper presents the results of numerical studies conducted using Ansys system, the impact of model's parameters on the workpiece displacement formation. In the simulation, one used the model of real grain. The authors analyzed the influence of material's properties on the formation of lateral flow in the machining zone. Observation was also made for the material's stagnation zone, which depends on geometrical characteristics of the blade, shape of its surface and characteristics of the workpiece.

1. INTRODUCTION

Modelling of material displacement in the zone of microcutting is very difficult due to the complexity of the phenomena occurring in the process itself. Depth of the blade inside the workpiece affects features which characterize not only the contact surface area, but also the shape of the contact zone and the conditions of displacement of the material molecules characterized by a specific initial position [5]. An important issue is the selection of the constitutive model and its parameters which will properly describe the properties of material under triaxial compression characteristic for large contact areas of the blade and the workpiece.

When building a computer model of microcutting process, it is important to know and evaluate stress conditions occurring in the zone of the influence of the grain corner. The cognitive importance of the modelling results from the fact that experimental evaluation of phenomena occurring in micro-volumes concentrated in the area of grain vertex is not possible or significantly hampered [6].

Review of the research studies aimed at modelling of chip treatment processes with the use of finite element method carried out in many academic centers worldwide, indicates that

[1] Department of Precision Engineering, Faculty of Mechanical Engineering, Koszalin University of Technology, Koszalin, Poland
[*] E-mail: wk5@tu.koszalin.pl

the authors of simulation typically use the Johnson-Cook models. This model also known as viscoplastic model is suitable for solving problems in which the strain speed varies in a wide range and causes energy dissipation due to changes in temperature of the plastic material [1],[2],[17].

In the studies conducted by J.C. Outeiro, D. Umbrello, R. M'Saoubi [16], the authors analyze the results of experimental studies and simulation processes of orthogonal cutting. They compared the results obtained in the studies on residual stresses carried out by means of diffraction of residual stresses within the machined surface to the results of simulation studies. Models developed up to now relate to simple processes such as orthogonal cutting and cutting with blades of easily defined shape. The results of such studies are limited to two-dimensional analysis with the possibility of evaluation of the process of stagnation zone formation in front of the cutting blade.

In the present study, one conducted the analysis of the impact of material model's properties on the process of workpiece flow formation. In order to provide authentic results of the simulation study, abrasive grain was scanned using 3D scanner [13] followed by its import to the Ansys system, in which simulation studies were performed.

2. DESCRIPTION OF NUMERICAL ANALYSIS

Modelling was conducted using Ansys system for different abrasive grains and alloys. Microcutting speed in each case considered was v_s=25 m/s. In order to obtain data regarding the process for different depth, the surface of the workpiece was inclined in relation to the direction of blade displacement. Studies were conducted for a grain of considerable

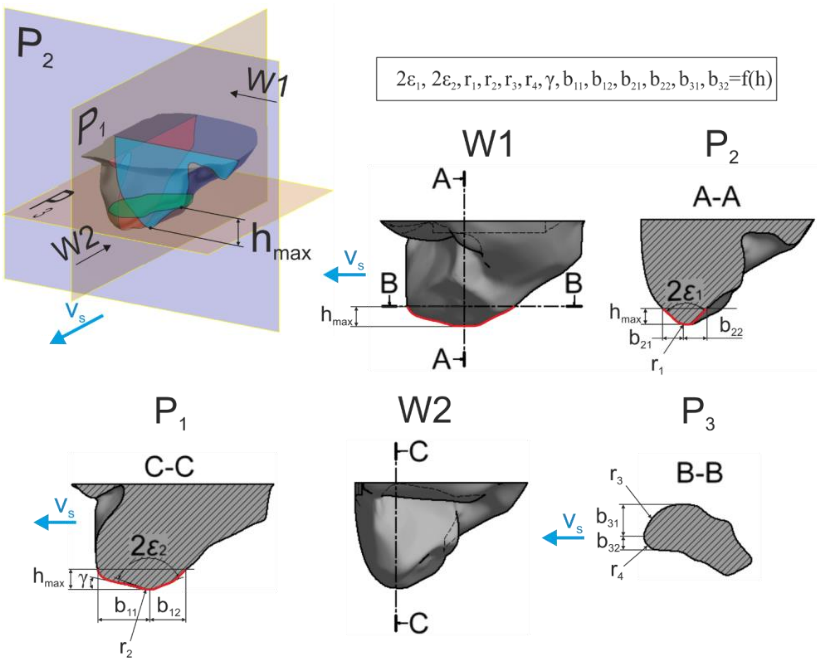


Fig. 1. Geometrical characteristics of abrasive grain for simulation of microcutting process. P1, P2, P3, - planes of cross-section, W1, W2, direction of observation; γ=f (h) typically a nonmonotonic function

dimensions (Fig. 1). An example of abrasive grains used for modeling purposes and computer simulation is characterized by the shape consistent with the real grain that was previously scanned and processed into 3D solid geometry.

In the analysis, one used material models corresponding to materials with different properties. One used different models describing material properties to evaluate their impact on the process of displacement of material molecules and formation of micro-chips. The following assumptions were adopted: “A” model describes material characterized by a wide range of plastic deformation, significant strengthening and high strength of the material reaching R_m=1200 MPa, „B” model describes material with a moderate range of plastic deformation and medium strengthening with strength of R_m=920 MPa. Model of “C” type is characterized by a large range of plastic deformation and plastic strengthening with simultaneous low strength R_m=280 MPa (Fig. 2).

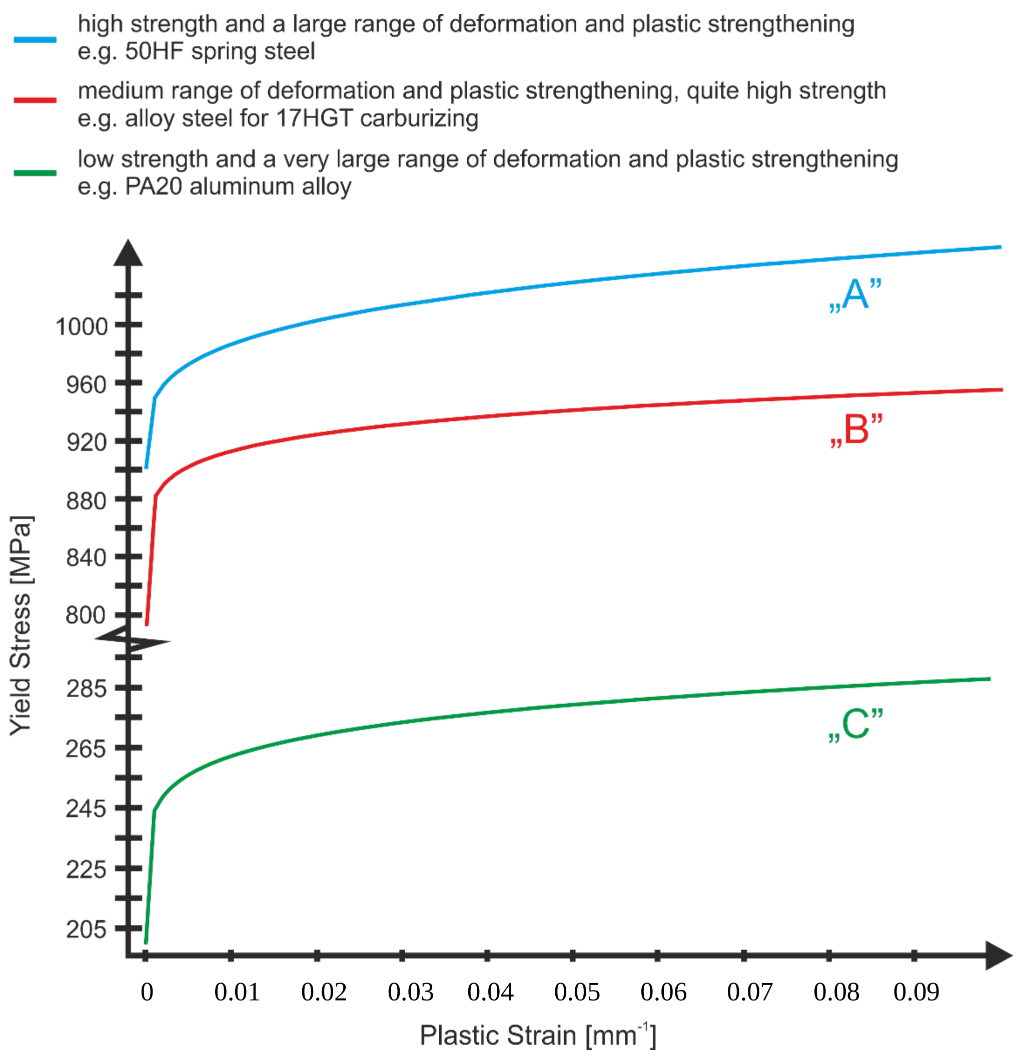


Fig. 2. Material models characterized by different properties

During computer analysis, one used Johnson-Cook material model, which refers to the distribution of stresses, deformations, speed of deformations and temperature in the tested object. Johnson-Cook equations are commonly used to model materials exposed to deformation within a wide range of deformation speed and temperature [4],[16]. The values of parameters of constitutive models describing different properties of the material are shown in Table 1.

Table 1. Parameters of Johnson-Cook constitutive models

Material model	A, MPa	B, MPa	C	n	m
„A”	900	250	0.015	0.25	1.03
„B”	792	220	0.014	0.1	1.03
„C”	200	125	0.01	0.15	1.03

General form of Johnson-Cook equation [3]:

$$\sigma = \left(\mathrm{A} + \mathrm{B}(\bar{\varepsilon}_{\mathrm{p}})^{n}\right)(1 + C ln\dot{\varepsilon}^{*})(1 - (\mathrm{T}^{*})^{\mathrm{m}}) \quad (1)$$

where:
A – initial static yield stress,
B – parameter of plastic strength,
n – exponent of plastic deformation strength,
m – exponent of thermal plasticity,
C – material parameter specifying the impact of the intensity of plastic speed deformation,
$\bar{\varepsilon}_{\mathrm{p}}$ – real plastic deformation,
$\dot{\varepsilon}^{*}$ – intensity of plastic deformation,
T^{*} – homologous temperature defined as:

$$\mathrm{T}^{*} = \frac{\mathrm{T} - \mathrm{T}_{\mathrm{otocz}}}{\mathrm{T}_{\mathrm{top}} - \mathrm{T}_{\mathrm{otocz}}} \quad (2)$$

where:
T – initial temperature of material,
$\mathrm{T}_{\mathrm{otocz}}$ – environmental temperature,
$\mathrm{T}_{\mathrm{top}}$ – melting temperature of material,

The procedure of model building included the following steps:

1. Formation of tool–workpiece geometric model.
2. Determination of computing method and discretization scale.
3. Definition of material characteristics in the model used for simulation.
4. Selection of contact characteristics between the tool and the workpiece.
5. Definition of parameters describing boundary conditions.

Geometry of the abrasive grain and material processed was prepared in Inventor environment followed by its import as a solid model (3D) to the Ansys system (Fig. 3).

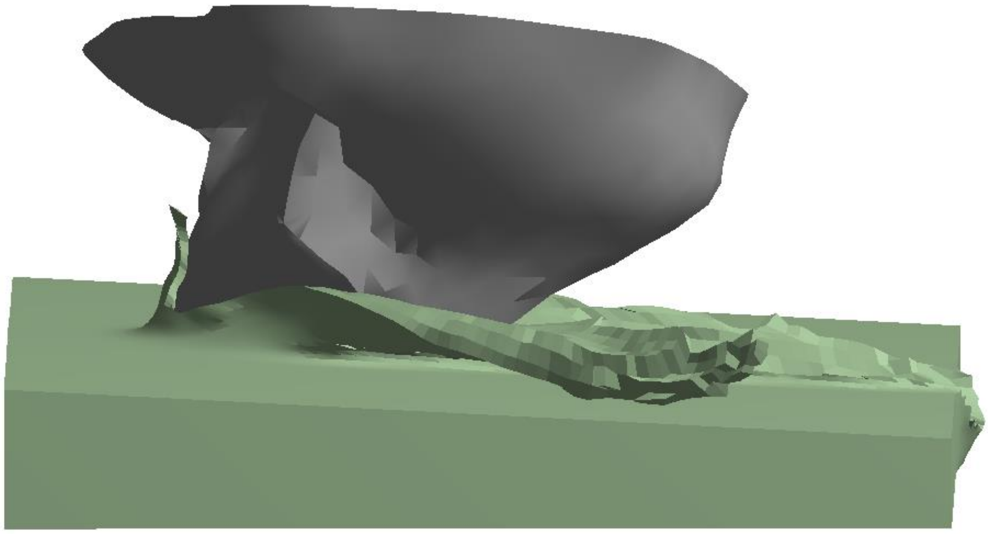


Fig. 3. Visualization of microcutting process with particular abrasive grain corner

Simulation was performed for the case of spatial deformation state. In order to solve the stated problem which related to evaluation of stresses and displacements of workpiece, one used integration method also known as central difference method or explicit method. The abrasive grain and the workpiece were modeled as a perfectly rigid structure and viscoplastic material, respectively. The object was discretized with over 80000 8-node-type Solid elements. In the workpiece, translational and rotational degrees of freedom for the nodes at the base material were obtained. Then, boundary conditions for the speed of grain were introduced [7],[14],[15],[18].

3. ANALYSIS OF MATERIAL DISPLACEMENT

Modelling of microcutting process with a single grain using materials with different properties enables accurate analysis of displacements of burrs and chips. Decisive role in evaluation of the formation of material is played by features of abrasive corner (Fig. 4).

Abrasive grain used in the simulations has two wedge-shaped planes of rubbing. Large radii of abrasive grain’s rounding and high angles of rubbing induce the formation of lateral burrs. The results of the analysis of materials’ displacement characterized by different properties allow claiming that not only the properties of abrasive corner affect the way of displacement of the workpiece. The simulation results show that properties of workpiece are essential in the process of formation of burrs and chips (Fig. 5, 6).

Analyzing the results of microcutting process simulation for “A” model, it was observed that significant portion of the treated material was transformed into a form of lateral band chips (Fig. 5). The results of the material displacement for “B” model also indicate the formation of lateral band chips. However, detailed analysis shows that the results of displacement and the shape of the crack bottom for “B” and "A" models significantly differ from each other. In Fig. 4 and 5 in the “B” model, one can observe the

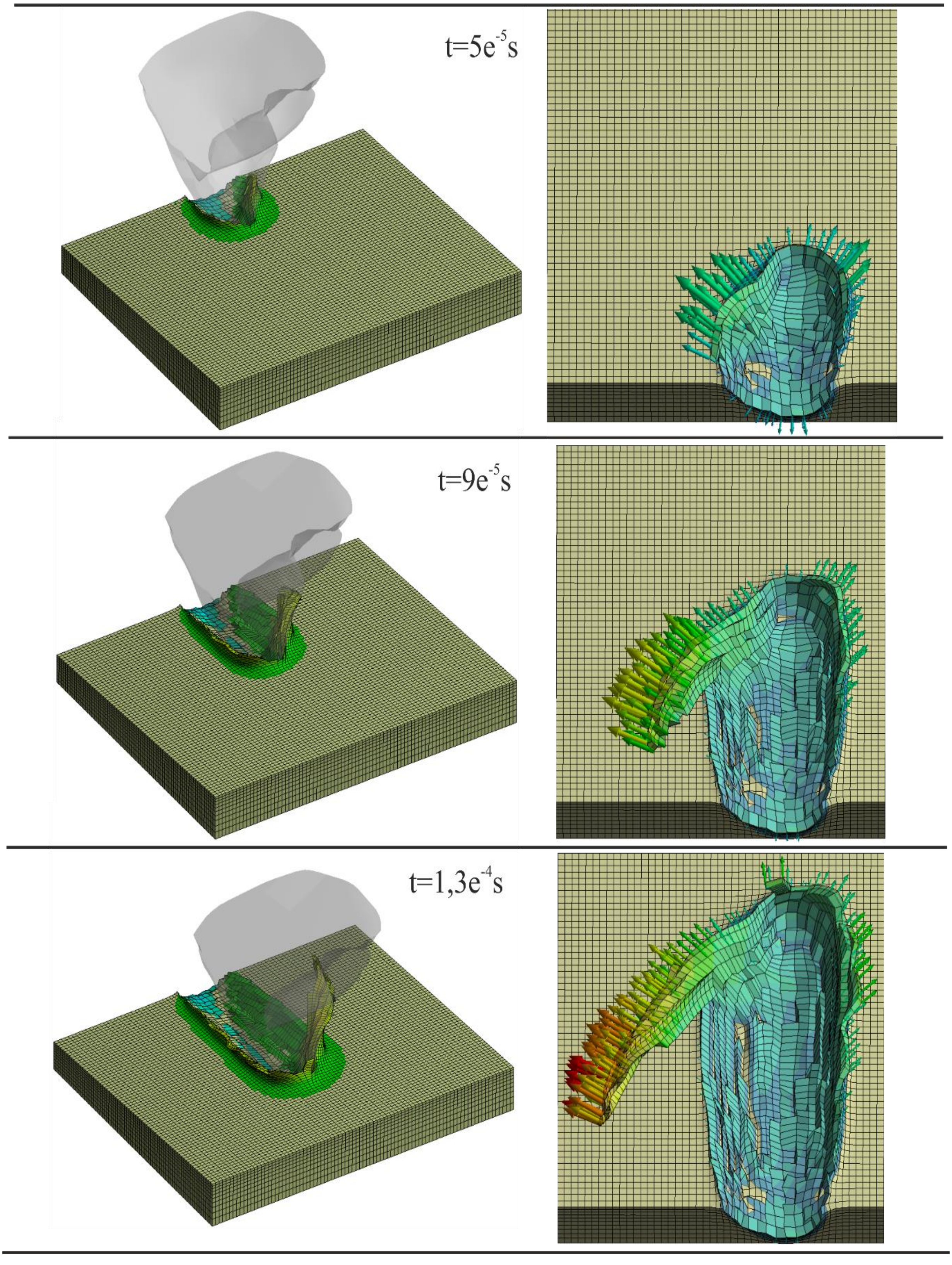


Fig. 4. Results of the displacement of the material in three different blade positions at *t* time for the model of "A" material (vectors in the right hand side of the figures illustrate the direction of material displacement and their color shows the value of displacement)

phenomenon of the occurrence of rugged burrs and chips. The results of computer simulation for “C” model are characterized by a strong tendency towards formation of the material as lateral burrs. This is a typical characteristic of materials with a very high plasticity, in which separation of material is extremely difficult.

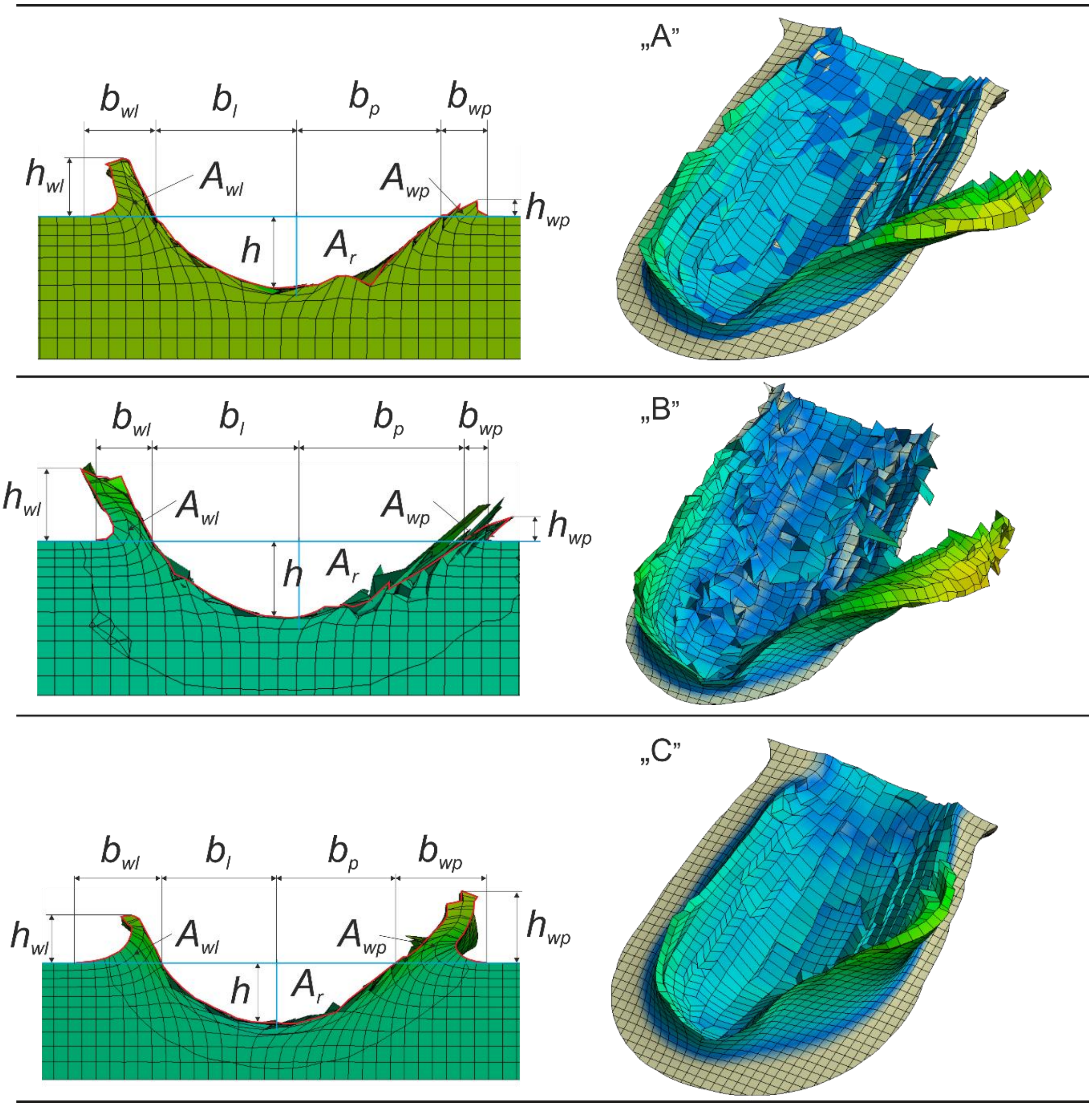


Fig. 5. The results of geometrical characteristics of lateral burrs and shape of crack bottom when grain covers a distance of 2 mm for different models of properties of „A”, „B”, „C” workpiece

The results presented in Table 2 show how big influence on the process of lateral burrs formation is affected by properties of the workpiece. In each of the analyzed models, one can observe significant differences in the results: the high of lateral burrs h_{wl} and h_{wp}, the width of the lateral burrs, b_{wl} and b_{wp}.

For a given grain shape and depth of microcutting, depth of crack bottom *h* is not the same. It can be concluded that the mechanism of removal of materials of different characteristics during microcutting process has a substantial influence on the process of formation of the crack bottom. It can be concluded that under triaxial stress in the grain's contact zone and the workpiece, plasticity and plastic strengthening of material are of great importance for the process efficiency (Fig. 6).

Table 2. Results of analysis of lateral material displacement

Model	h_{wl} [mm]	b_{wl} [mm]	b_l [mm]	b_p [mm]	b_{wp} [mm]	h_{wp} [mm]	A_{wl} [mm^2]	A_{wp} [mm^2]	A_r [mm^2]	h [mm]
A	0.245	0.287	0.574	0.581	0.189	0.070	0.026	0.006	0.234	0.280
B	0.273	0.210	0.574	0.581	0.084	0.091	0.032	0.005	0.215	0.283
C	0.238	0.427	0.574	0.581	0.455	0.350	0.031	0.056	0.238	0.294

In Fig. 7 at positions I, II and III, where one can observe a zone of intense plastic deformations and material stagnation, significant differences in the directions of material flow are observed. "A" model just before the abrasive corner begins the formation as a front chip. In the "B" model, workpiece tends to form two lateral chips. The most plastic "C" model used in the microcutting process forms the workpiece as two lateral burrs. Among all three cases, the largest zone of stagnation and intensity of plastic deformation is observed in "C" model.

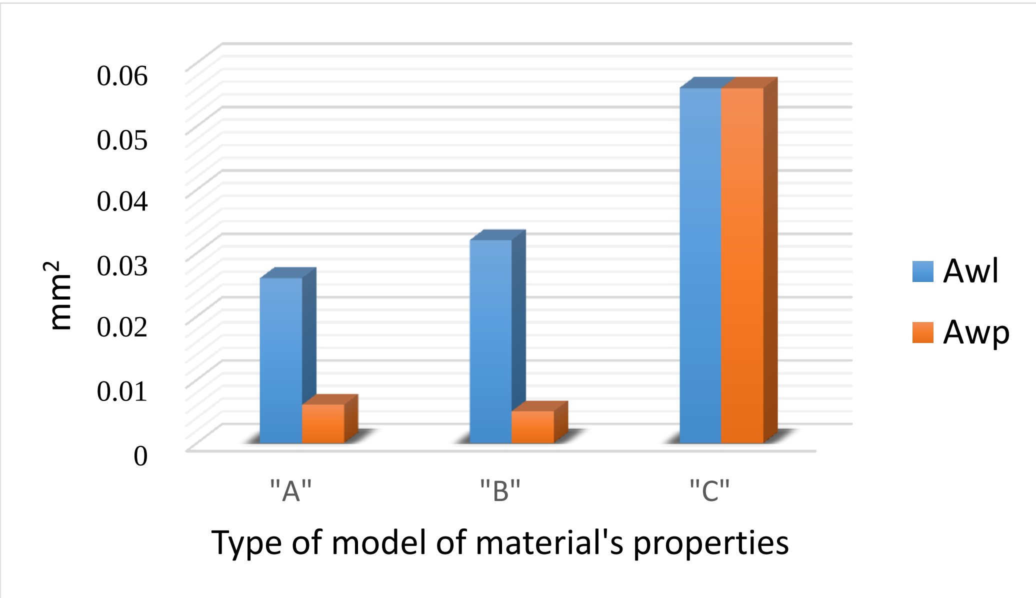


Fig. 6. Surfaces of burrs' cross-sections (A_{wl} – area of burr in the left hand side of the track, A_{wp} – on the right) for different models of properties of the treated material and for depth of the blade *h* according to Table 2

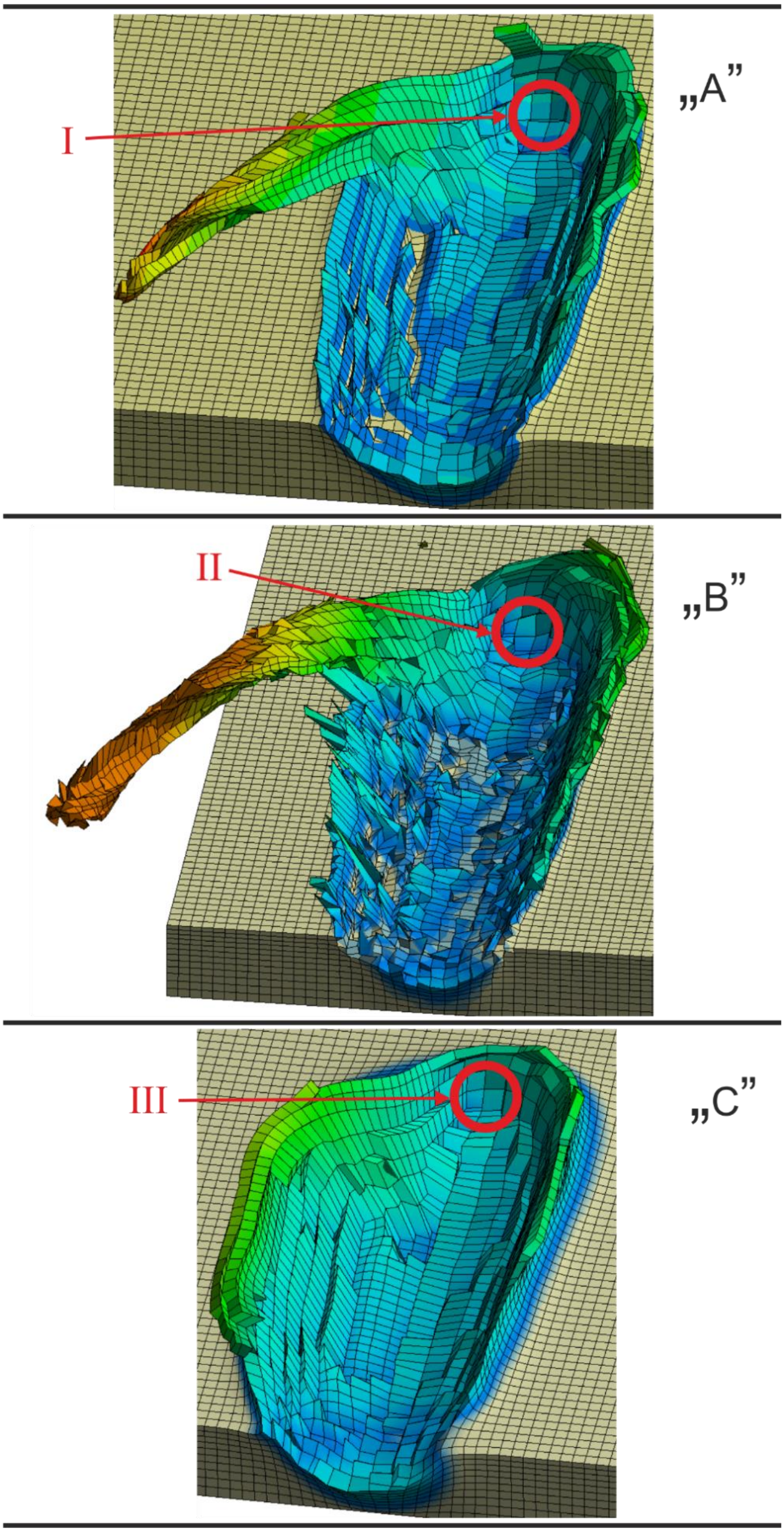


Fig. 7. The results of displacement analysis of burrs and chips when grain covered a distance of 2 mm. I, II, III – zone of intensive plastic deformations and material stagnation

4. ANALYSIS OF MOCRO-CHIPS' FEATURES IN THE PROCESS OF MICROCUTTING

Analyses of the construction of micro-chips formed in the process of grinding were carried out using the following parameters: depth of grinding 20 μm, feed speed 4 m/min, circumferential speed of grinding wheel 35 m/s, workpiece, grinding wheel characteristics 1-200×20×32 M60K5IVTE – 35.

One observed a characteristic stepped shaped micro-chips' structure [8],[10],[11] as a result of discontinuity of material separation (Fig. 8a). The observed characteristics of the micro-chips allow determining the frequency of tabular elements. For the data presented, it accounts for 500–2000 kHz. It can be observed, that the chips are twisted depending on the shape of active fragments of blade surface in the process of workpiece separation (Fig. 8b). A similar phenomenon was observed in simulation studies (Fig. 7). It can therefore be concluded that based on the shape of micro-chips, one can evaluate the impact of the direction of its formation and geometric characteristics of the cutting blade. Depending on the cutting conditions and characteristics of the blade, diverse width of the occurring micro-chips can be observed (Fig. 9).

a) b)

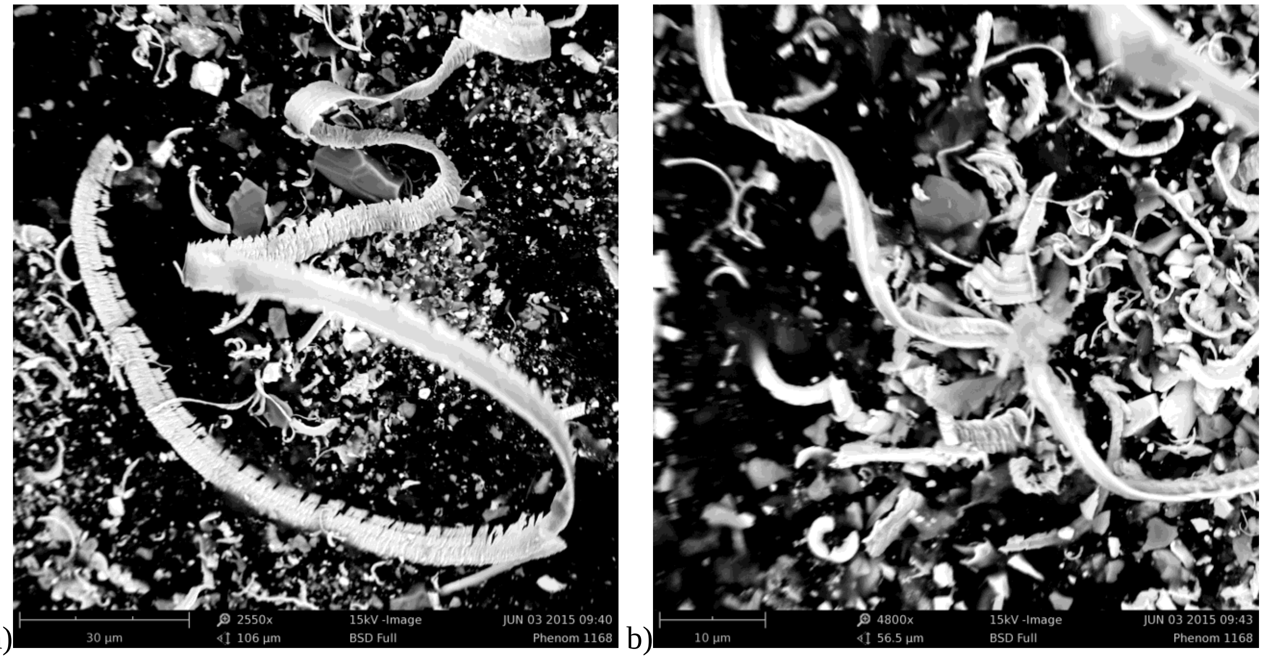
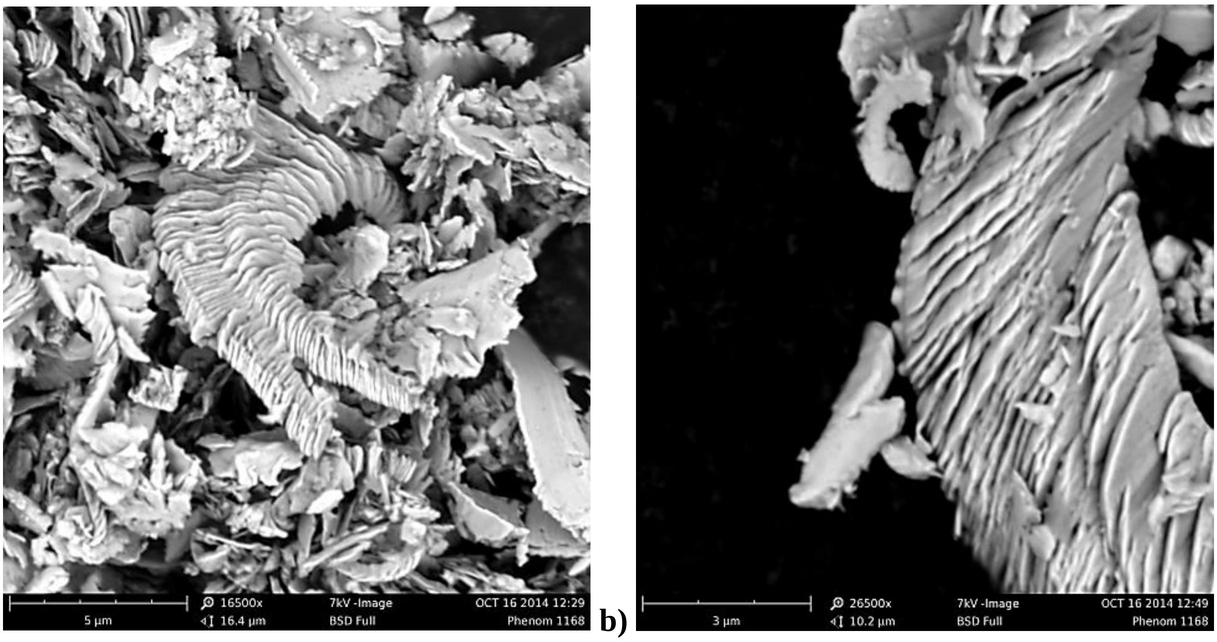


Fig. 8. Microscopic images of micro-chips in the process of microcutting (SEM PHENOM PROX), ŁH15 bearing steel material improved to 65 HRC, 99A120P7BMOD-45 grinding wheel, longitudinal feed 25 m/min, infeed 20 μm, circumferential speed of grinding wheel 35 m/s

Based on geometrical parameters of the chips formed, one can determine statistical properties of cross-sections of machined layers, and based on the shape of chips it is possible to determine geometric features of vertices of active grains.



a) b)

Fig. 9. Microscopic images of micro-chips in the process of microcutting (SEM PHENOM PROX) with abrasive film of a nominal grain size of 15 µm (15IMFF), workpiece – 40H steel thermally improved to 40 HRC, film shifting speed 160 mm/min, object shifting speed 35 m/min, clamping force towards the workpiece tool 60 N

5. CONCLUSION

Form previous studies carried out by the authors one can conclude that in the process of microcutting, unfavorable phenomenon of the occurrence of burrs on the sides of the groove formed with abrasive grain corner is affected by the relationship between the lateral resistance of the material flow and the resistance of the material moving along the surface of blade rubbing. This phenomenon exerts a decisive effect on the shape of the abrasive grain. The conducted simulation study shows that in the zone of micro-grinding for a particular blade, material properties determine the direction of material flow.

Simulation studies conducted by the authors provide a basis for further studies evaluating phenomena occurring in the abrasive corner. In many publications one can find significant contradictions in results regarding conditions that must be met to provide separation of the material. There are several causes of these discrepancies. It should be noted that in microcutting, lateral (with respect to the path of a grain) material flows are dominated, while typically one examines only the geometric conditions of chip formation, in the perpendicular cross-section to the surface of the object and parallel to the direction of blade displacement.

The importance of stagnation zone for the microcutting process is not clear in the light of previous studies, because its size, much smaller than the radii of rounding of grain vertices and variability of the zone's characteristics for the individual blades, are difficult for accurate measurements. The simulation results, which were presented in this report, clearly show that the stagnation zone is also affected by the properties of the workpiece and not just the features of abrasive corner.

The use of tools based on finite element method to study microcutting processes in conjunction with experimental studies, provides a broad spectrum of new opportunities to look at grinding processes and polishing of the surface.

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INNOVATIVE ECONOMY NATIONAL COHESION STRATEGY

EUROPEAN UNION EUROPEAN REGIONAL DEVELOPMENT FUND

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