The simulation of the workpiece and saw teeth heating during the high-speed cutting process

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Abstract. The paper presents the result of the simulation of the workpiece and saw teeth heating during high-speed cutting using the Deform 3D software package. The distribution of temperature and stressing fields during the high-speed cutting process was obtained. The investigation was confirmed by metallographic analysis, and it shows good convergence of simulation results with practical results for the temperature fields.

1. Introduction
The process of metal cutting proceeds under the condition of intense plastic deformation and chipping. The mechanical energy of the process is converted into heat, which affects plastic properties of the cut-off layer and its deformation, cutting forces, wear and tool life [1]. The existing studies contain little information on the high-speed cutting processes at high temperatures. There are some examples of works describing the influence of temperature on strength characteristics of the material at the high-speed cutting process [2–4]. The cutting process simulation can be performed via the finite element method (FEM) because the method considers a large number of material's properties and is suitable for multi-physics tasks. FEM allows one to reduce costs of new products development, to reduce or eliminate the necessity in field experiments; besides, it is one of the most informative and illustrative method among other modern research methods.

The present study aims to verify the suitability of FEM for the cutting process simulation. Temperature fields in the processed material as well as in the saw teeth during high-speed cutting of cylindrical workpieces are obtained.

2. Materials and methods
FEM simulations of the cutting process of the cylindrical steel workpiece was carried out using the Deform 3D software package. The longest time contact of the saw teeth with the hot workpiece (fig. 1) was considered via the simulation of the evolution of the saw teeth passing through the middle cross-section of the workpiece.

Model parameters: the diameter of the workpiece and the saw is 350 mm and 2500 mm, respectively, and the thickness of the workpiece and the saw is 100 mm and 12 mm, respectively. Saw tooth dimensions are shown in Figure 2. To simulate the heat transfer process and the stress-strain state, the finite element tetrahedral mesh was applied (fig. 3). When deformation exceeds 20%, the mesh is automatically rebuilt. The initial temperature of the workpiece was 1200°C while the initial temperature of the saw and the surrounding air was considered 20°C. The heat transfer coefficient between the workpiece and the saw – 30 W/(m²×C), between the air and the parts – 0.002 W/(m²×C). Side ends of the workpiece are fixed. The saw rotation speed is 1070 RPM, the feed rate is 3.5 m/sec.
Figure 1. The general view of the assembled model.

Figure 2. Saw tooth dimensions.

Figure 3. The original mesh (a) and remeshing during chip formation (b, the section along the median plane).

The workpiece material was steel 0.08%C, while the saw material – AISI 4140. 3D deformation has an inbuilt base of temperature and strain dependent functions of Young’s modulus, flow stress (graphs for steel AISI 4140 are shown in fig. 4a, b, c), heat capacity and thermal conductivity (graphs for both steels are shown in fig. 4d, e) for these steels. For steel 0.08%C, the strength properties are set using the Johnson-
Cook model [5] (table 1). As a criterion for the destruction of both steels, the Cockcroft-Latham model was used [6].

| A, MPa | B, MPa | m   | n   | ε′₀, sec⁻¹ | Tₘₑ, K | Tₜ, K |
|--------|--------|-----|-----|------------|--------|-------|
| 350    | 275    | 1   | 0.36| 1          | 293    | 1790  |

To verify the simulation results, metallographic studies of the saw teeth, the structure and microhardness research was carried out. Optical images of the saw teeth were investigated by the AnalisYS software for the Olympus BX61 microscope. The microhardness distribution was measured using a standard microhardness tester (PMT-3) with the Vickers indenter, carried out with loads of 50 g for 15 sec.

Figure 4. The graph of flow stress-strain dependence with respect to temperature (a) and a strain rate (b); the Young’s modulus dependence on temperature (c), and heat capacity (d); and thermal conductivity (e) dependence on temperature.

3. Results and discussion
The simulation of temperature fields in the workpiece, the chip and the saw teeth during high-speed cutting showed that during intensive plastic deformation of the workpiece a thin layer is significantly heated along the plane of contact with the saw tooth of about 1500ºC. The depth of heating the workpiece metal is approximately 5 mm (fig. 5a, b). Significant heating of the metal workpiece is
confirmed by the high-speed movie of the cutting process on the seamless pipes cutting line [7].

The heated volume of saw teeth localized in the contact zone with the workpiece. The maximum heating temperature of the saw teeth was about 1220°C. The depth of the zone heated up to temperatures of phase transformations in steel (> 727°C) does not exceed 150 µm. During cutting of a workpiece, the deformation occurs both along and perpendicular to the cutting direction. Therefore, the cutting width is slightly greater than the thickness of the saw, and hence almost has no heating through the tooth sides (fig. 5c).

![Figure 5](image)

**Figure 5.** The temperature distribution along (a) and transverse (b) the section along the median plane of the workpiece, and the section along the median plane of the saw (c).

Maximum Mises stress values in the workpiece are located in the area of the contact with the top of the tooth (fig. 6a, b), and in the tip and the gullet of the tooth for the saw (fig. 6c).

![Figure 6](image)

**Figure 6.** Stress distribution along (a) and transverse (b) the section along the median plane of the workpiece, and the section along the median plane of the saw (c).

To verify the simulation results, the metallographic examination of the saw tooth structure before and after the cutting process was carried out. Changes in the structure allowed us to determine the approximate depth of the saw metal heating during the cutting process up to the temperature above the temperature of phase transformations.

Initially, the microstructure of the saw tooth metal is heterogeneous etched tempered sorbite (fig. 7a). The heterogeneity of the tooth steel structure led to the variance of the measured microhardness from 2.5 to 3.8 GPa (fig. 7b) (the average value of microhardness was 2.9 GPa).

Metallographic examination of the tooth after the exploitation revealed the emergence of the metal layer in the workpiece-saw contact area. The layer formed as a result of hot metal adhesion [8]. The microhardness of the formed layer was 4.7-5.5 GPa (fig. 8). High speed of deformation restricts recrystallization processes even at temperatures of 1200°C. The formed layer gives off heat in the tooth and cools down rapidly after exiting the cutting zone. The high-etched zone (fig. 8a) consisting of structureless martensite and carbides formed during rapid cooling after pulse heating above the \( A_{C3} \) of the thin layer of tooth metal was found near the top of the working part of the tooth. The thickness
of this zone is 130-180 µm, and the microhardness is ranged from 6 to 3.5 GPa by the distance from the surface. Figure 8b shows the distribution of microhardness from the surface into the depth in the working and non-working parts of the tooth. The structural change leading to the increase of the microhardness was found only in the working part of the tooth which is in contact with the hot workpiece. The depth of structural transformations is in good agreement with the results of temperature fields simulation.

4. Conclusion
FEM simulation of the high-speed cutting process of the hot steel cylindrical workpiece using the Deform 3D software package was carried out. The simulation has allowed defining the distribution of both temperature and stressing fields during the high-speed cutting process.

Metallographic analysis of the saw tooth structure for high-speed hot cutting has revealed the hardened layer in the surface area formed due to the high thermal exposure. The thickness of this layer confirms the simulation results of heat transfer processes in the Deform 3D software package.

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