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Superficial hardened layer of cut surface by turning

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Abstract. One of research methods in metal cutting process is to measure hardness in the contact zone between cutting tool and workpiece. The objective of the performed research was to determine thickness and hardness of the superficial layer of cut surface due to cutting process, both orthogonal and complex cutting. The most important finding was that thickness of the superficial hardened layer is very thin under considered conditions, less than 0.01 … 0.02 mm. This research should be continued.

1 Introduction

This paper is part of a study related to the hardness of the cut surface in case of orthogonal cutting [1] and complex cutting [2] of C45 steel. It presents a review of the mentioned papers and some new SEM micrographs. These lead to some new conclusions.

There are several classic methods to research the chip formation process in the workpiece material [3, 4]: method of deformed net, method of metallographic examination, method of measuring hardness in different points of the contact zone between workpiece, chip and cutting tool. Until present (see references [5-6]), the last method did not detail characteristics of the deformed and hardened superficial layer of the cut surface.

Research on chip formation was performed since a half century ago [7], but new technologies related to computers development, both hardware and software, allow today greater possibilities to perform this research [5-6, 8].

Present paper is part of the studies on depth and hardness of the cut surface performed in Politehnica University of Bucharest. Cutting experiments were performed in the Cutting Process and Cutting Tools Laboratory, Department of Machines and Manufacturing Systems. Hardness measurements and optical microscopy were performed in the Metallographic Tests Laboratory, Department of Materials Technology and Welding. SEM microscopy was performed in the National Centre for Scientific Research on Food Safety.

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2 Orthogonal cutting by turning

Orthogonal cutting is a theoretical case of cutting process. It is obtained in special cases of plane and radial turning, when width of the workpiece is less than of the cutter.

Design of experiments is presented in the following.

Cutter was made of HSS for easiness of sharpening different geometrical parameters of the cutting edge. Time of effective cutting process is small, so the wear was not important.

Clearance angle was fixed at α=10°. Rake angle and tool edge radius were considered to have the following values: γ= –10°, 0°, 10°, respectively ρ=0.1 mm, 0.2 mm, 0.4 mm.

Workpiece was made of C45 steel so maximum cutting speed was v_c=60 m/min.

In case of orthogonal turning cutting depth is the radial feed. Its values were chosen a_p= f_r= 0.1 mm; 0.2 mm and 0.4 mm.

Experimental plan is not presented in the paper. However, there were performed 40 tests, both theoretical and experimental, for different combinations of the mentioned cutting process parameters. For these experiments we present only samples which obtained higher hardness and, as well, qualitative aspects and trends observed in all tests.

A Romanian lathe, SN400, was used for the orthogonal cutting experiments because on this lathe the dynamometer's table could be assembled.

2.1 Theoretical research and preliminary presumptions

DEFORM™ (2D and 3D) [9] is a software package used to simulate plastic deformation processes of metallic parts using Finite Element Method for plastic or elastic-plastic deformation processes, in motion. Tool and workpiece are defined as meshes inside a closed contour (2D) or a closed surface (3D). Active part of the tool is simulated incrementally in its relative movement to the workpiece and, in case the deformation of finite elements mesh of the workpiece lead to errors, a new mesh is defined automatically and the data processing is continued.

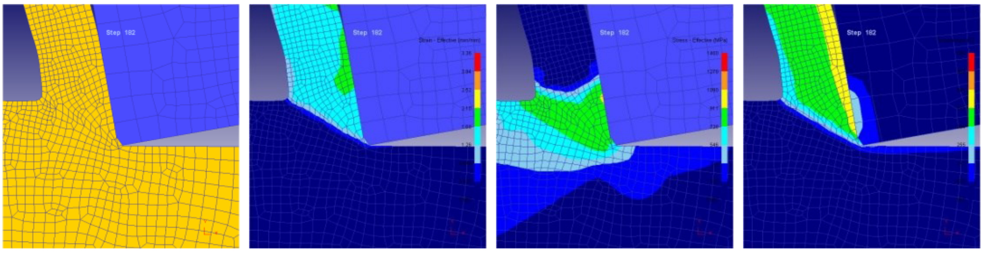
In case of orthogonal cutting process DEFORM 2D™ software was used and in case of complex cutting process (see next paragraph 3.1) DEFORM 3D™ software was used.

Presumptions for the simulations were the following:

- Cutting tool edge is considered to be perfectly rigid, made of metal carbide (24% Cobalt).
- Cutting movement is translation, 20 mm stroke.
- Mesh generation and ambient conditions were chosen automatically by the software;
- Cutting speed, cutting depth, rake angle and clearance angle were set as in the experimental plan.
- Only the interaction zone between workpiece and cutter's edge was modeled.

The main output data were the following:

- Deformed shape of the workpiece, (see Fig. 1,*a* – test No. 28, step 182).



a) b) c) d)

Fig. 1. Output simulation data for test No. 40 (v_c=60 m/min; a_p=0.4 mm, α=10°, γ=-10°, ρ=0.4 mm). a) Deformed shape; b) Strain Effective; c) Stress Effective; d) Temperature.

- Strain – effective (see Fig. 1, b– test No. 28, step 182).
- Stress – effective (see Fig. 1, c– test No. 28, step 182).
- Temperature distribution during the cutting process (see Fig. 1, d– test No. 28, step 182).

Because of the presumption that hardening of the superficial layer of cut surface is caused by the crushing of the workpiece material, the most important output data of the simulations were considered the effective stress (possibly above the yield strength of the material) and vertical component of the cutting force.

After simulations the following qualitative conclusions were noticed:

- Stress distribution varies, along the tool point trajectory.
- The most important input variables which influence hardening of the cut surface in orthogonal cutting are cutting depth and tool edge radius. Stresses over yield strength of the workpiece's material seem to affect (crush) this superficial layer on a depth of (1.5...2)a_p. Stresses of almost the same size are revealed in the surface layer even in case the tool edge radius ρ is null.

2.2 Experimental research and results

Experimental stand for orthogonal cutting research by turning is presented in Fig. 2.

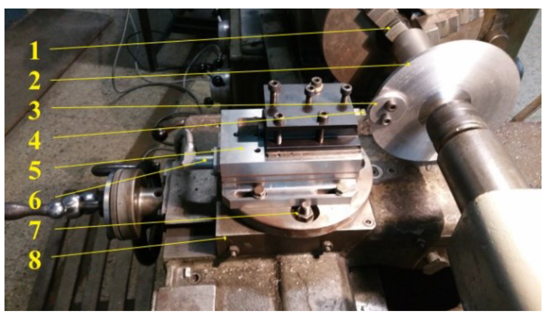
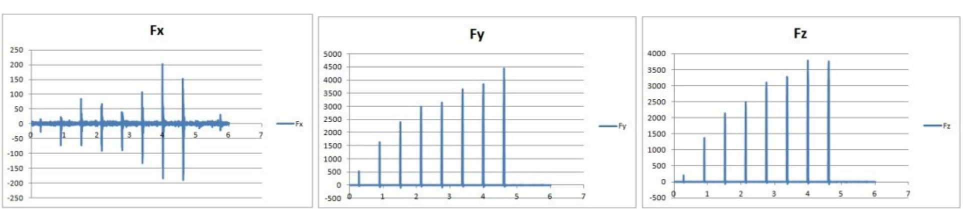


Fig. 2. Experimental stand - orthogonal cutting.

In the universal chuck *1* of the lathe an axle with a disc *2* is fixed on which the workpiece *3* is fixed. This fixture of the workpiece was chosen in order to obtain greater cutting speed at a lower number of spindle's rpm, for a better control of the experiments. On the transversal slide *8* of the lathe the dynamometric table *5* of a KISTLER dynamometer is fixed on cutter's slide fixture *7*.

The cutter 4 is fixed onto the dynamometric table by means of a clamping device. Measuring data is sent to the dynamometer's amplifier by means of a data cable 6.



a) b) c)

Fig. 3. Measured cutting forces in test No. 28.

Cutting forces were measured using the experimental stand presented in figure 2 (KISTLER dynamometer), see figure 3. Cutting forces were as following: F_x – axial force, F_y – radial force and F_z – tangential force. F_x variation – which should have been null –

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showed the lathe used for cutting experiments was not stiff enough. This lathe should be changed for the next experiments.

Micrographs, both optical and SEM (see Figs. 5 and 6) showed superficial deformation (crushing) on cut surface, which was expected.

Microhardness HV 0.1 was measured. After all tests were done, the samples were polished on lateral surface and microhardness HV 0.1 was measured in maximum 6 points from the cut/manufactured surface, at distances of 0.05 mm, up to 0.3 mm (see Fig. 4).

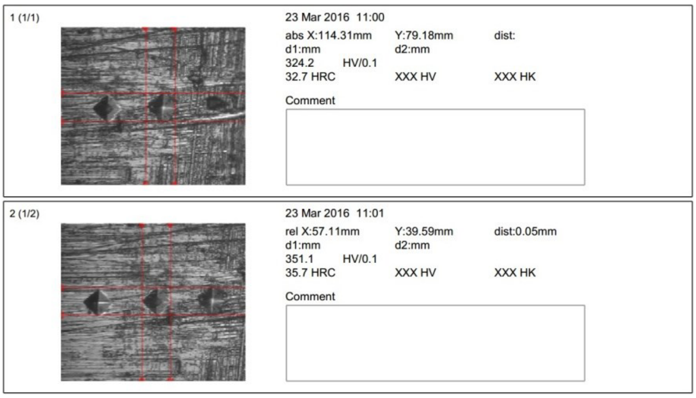
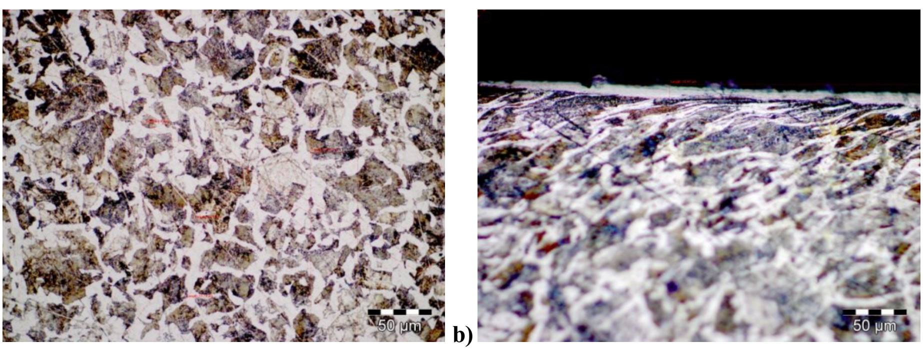
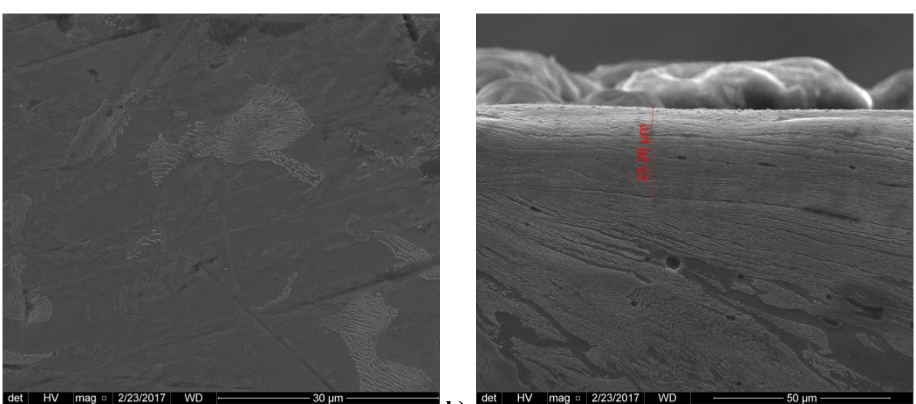


Fig. 4. HV 0.1 measurement in points 1 and 2 for Test No. 28 sample.

a) 

b)

Fig. 5. Optical microscopy – Test No. 28. *a)* base material, *b)* deformed superficial layer.

a) 

b)

Fig. 6. SEM microscopy – Test No. 28. a) base material, b) deformed superficial layer.

In all tests minimum hardness was HV 0.1 = 253.34, maximum hardness was HV 0.1 = 338.28, average hardness was HV 0.1 = 300.66. This could mean that C45 steel is not homogenous. However, all hardness measurements had the diminishing trend of HV 0.1 hardness as the distance from the cut surface increases.

The only problem was the crushed and hardened layer was very thin, thinner than expected (0.01…0.02 μm). This implies the measurement of superficial hardness is not exactly credible, because the pushing prism of the hardness measuring machine punches this layer, so the measured hardness may vary significantly.

Furthermore, C45 steel was composed of ferrite and pearlite, phases which have different hardness [10]: 60…100 HV for ferrite and 240…400 HV for pearlite.

3 Complex cutting by longitudinal turning

Complex cutting is the real general case of cutting process. The most common cutting operation is longitudinal turning, which was chosen for the study.

Design of experiments is presented in the following.

Cutter was made of HSS for easiness of sharpening different geometrical parameters of the cutting edge. Time of effective cutting process is small, so the wear was not important. Effectively, after each test the tool was resharpened.

Clearance angle value was fixed at α=10°. Rake angle and tool edge radius were considered to have values: γ= –5°…15°, respectively ρ=0.1…0.2 mm.

Workpiece was made of C45 steel.

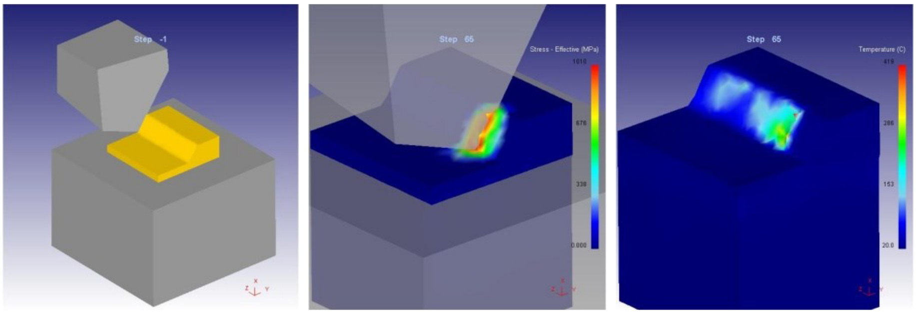
Cutting regime parameters were as follows: cutting speed v_c=20 … 60 m/min, cutting depth a_p= 0.5 … 2.5 mm, longitudinal feed f= 0.05 … 0.2 mm.

Experimental plan is not presented in the paper. However, there were performed 17 experiments for different combinations of the mentioned cutting process parameters. Some of them failed. From these experiments we present only sample of test No. 1, which failed due to the hardest cutting conditions (highest cutting speed) and obtained higher hardness and, as well, we present qualitative aspects and trends observed in all complex cutting tests.

3.1 Theoretical research and preliminary presumptions

Presumptions for the 3D simulations were the following:
- Cutting tool edge is considered to be perfectly rigid, made of metal carbide (24%Cobalt);
- Cutting movement is translation, 10 mm stroke.
- Mesh generation and ambient conditions were chosen automatically by the software.
- Cutting speed, cutting depth, rake angle and clearance angle were set as in the experimental plan (not presented).
- Only the interaction zone between workpiece and cutter's edge was modeled (see Fig. 7).
- Workpiece is fixed into a clamping device (see Fig. 7, a).

The main output data was considered to be the effective stress (possibly above the yield strength of the material) (see Fig. 7,b– test No. 1, step 65) because of the presumption that hardening of the superficial layer of cut surface is caused by the deformation/crushing of the workpiece material by the cutting tool.



a) **b)** **c)**

Fig. 7. Output simulation data for test No. 1 (v_c=60 m/min; a_p=1.5 mm, f=0.1 mm/cicle, α=10°, γ=10°, ρ=0 mm). a) Initial set; b) Stress Effective (step 65); c) Temperature (step 65).

After simulations some interpretations and conclusions issued, as follows.

1. As in orthogonal cutting process, in complex cutting process occur stresses above yield stress of the workpiece material (σ_rC45=630…700 MPa).
2. Effective stress distribution in the surface layer is different in case of intermediary cut surface connecting the initial workpiece surface and the final manufactured surface than in case of the very final manufactured surface. Values of the effective stress are higher in first case. This confirms the higher hardness of the chip than the hardness of the manufactured surface. As well, higher hardness occur in the intermediary cut surface connecting the initial workpiece surface and final cut surface than in the very final cut surface.
3. Cutting temperature is not so high to imply a hardening heat treatment. Consequently, hardening occurs due to the plastic deformation of the workpiece material. In case of using coolant this is obvious.
4. Probable crushed/hardened surface layer thickness is higher under the intermediary cut surface connecting the initial workpiece surface and final cut surface, than under the very final cut surface. This means there are important differences between orthogonal and complex cutting processes related to deformation of superficial layer of the cut surface.

3.2 Experimental research and results

Experimental stand of complex cutting by longitudinal turning is presented in Fig. 8. A MAZAK Quick Turn 6T lathe was used for the longitudinal turning of the samples. Cutter 1 was fixed into the turret of the lathe and setting its position was made using the positioning device 2. Workpiece 3, having tracks for the different experiments, was fixed into the chuck of the lathe.

Some experiments failed due to the following reasons: too high cutting speed (above 60 m/min), too high feed (operator's error), collision (operator's error).

Measurements of hardness were performed both onto the external cylindrical surface and onto the frontal surface, along the radius of the sample.

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Fig. 8. Experimental stand for complex cutting (detail).

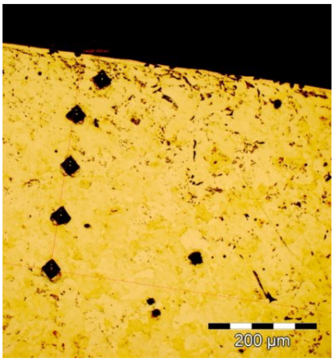

Fig. 9. Optical microscopy Test No. 1.

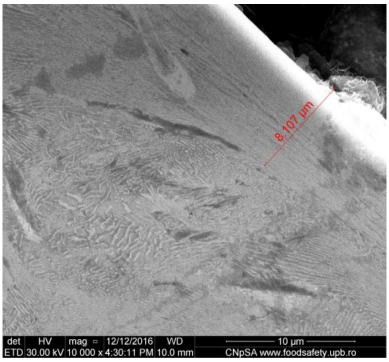

Fig. 10. SEM microscopyTest No. 1.

Values of the HV hardness of the external cylindrical surface varied between 185-240 HV and values of microhardness HV 0.2 varied between 230-300 HV for workpiece and between 300- 400 HV for the detached chip.

It may be stated that hardness of the cut surface is not constant from point to point, even if they are close to each other. It is the same in case of orthogonal cutting. The explanation is C45 steel is not homogeneous, being composed of ferrite and pearlite, which have different hardness. Furthermore, depth of the deformed/crushed superficial layer of the cut surface is very thin and not constant, as we should see in the following.

Micrographs, both optical and SEM (see Figs. 9 and 10) showed superficial deformation (crushing) on cut surface in complex cutting case, which was expected. The deformed crushed superficial layer seems to be even thinner in case of complex cutting than in case of orthogonal cutting. Its thickness was not constant and it was rarely above 10…15 μm.

This shows that the deformed/crushed/hardened superficial layer of cut surface is thicker in case of orthogonal cutting than in case of complex cutting. However, its thickness is very small, possibly not significant.

4 Conclusions

Research presented in this paper is not final. This research objective was to determine thickness and hardness of superficial layer of cut surface due to cutting process, both orthogonal and complex cutting. The most important finding is thickness of the superficial hardened layer is very thin under studied conditions, less than 0.01…0.02 mm. This research should be continued.

Performed research had good aspects: revealing the hardened cut surface layer both by means of theoretical simulations and by real experiments, and not so good aspects: the low stiffness of the used lathe in case of orthogonal cutting and the not homogenous workpiece material of the samples.

Theoretical research was performed by simulations using DEFORM 2D™ v.9.0 and DEFORM 3D™ v.6.1 software package [9]. These simulations showed that stress in the just cut surface (just under the tool point) is not constant. It has values above yield strength of the workpiece material. Such stress values occur down to a depth of approximately $(1.5...2)a_p$ below the cut surface. This leads to the idea of deformed/crushed/hardened surface layer occurrence. Both stress in the workpiece and probable thickness of the crushed/hardened layer of the cut surface depend more on the cutting depth in case of orthogonal cutting, respectively on the feed in case of complex cutting, they depend more on tool edge radius and less on the cutting speed. Superficial layer hardness increases when cutting speed decreases. This reminds the idea of hardening by broaching.

Experimental research was performed for C45 steel by orthogonal turning on a SN 400 lathe and by complex cutting on a MAZAK Quick Turn 6T lathe.

Cutting forces were measured online and HV 0.1 microhardness was measured off-line, after orthogonal turning. Each orthogonal cutting test meant to detach several chips from a disc sample fixed onto a flange, which was fixed into the lathe's spindle. The samples were laterally polished in order to measure hardness under the cut surface. Some of the samples were super-polished for optical and SEM microscopy.

In case of complex cutting measurements of hardness HV, microhardness HV 0.2 and optical and SEM microscopy were performed. Complex cutting experiments revealed the hardened cut surface layer, which imply greater hardness of the workpiece on the cut surface layer. However, hardness increase is not so important on the cut surface layer than in the detached chip. Greater hardness of the chip is one important reason of tool crater wear occurrence.

Important differences between orthogonal and complex cutting were revealed. This means the hardened cut surface layer should be studied for each and every cutting case.

Cutting parameters which influence hardness increase are the following: cutting speed decrease, cutting depth decrease, feed increase, null to negative rake angle and greater tool edge radius.

As consequences of the presented research some questions occurred:

- Does the coolant influence the hardened cut surface layer related to its microstructure, deformed superficial layer thickness and hardness?
- Other cutting operations than turning lead to a greater hardness of the cut surface layer?

Hardness is relatively difficult to be determined, having dispersion due to the inhomogeneous workpiece material and cutting process parameters variation.

Future research related to the deformed/crushed/hardened superficial layer of cut surface should be done, at least, in the following ways:
- Redo the experimental research in better conditions: lathe with greater stiffness, homogenous C45 steel, setting its initial hardness by heat treatment.
- Possibly change the studied workpiece material with another homogeneous one.
- Change the values range of the input parameters, in order to set the case of hardening by broaching, grinding or the case of burnishing [11].
- Research other complex cutting operations than turning or even plastic deformation operations (because cutting process is, essentially, a plastic deformation process: hardening broaches suggested by [1] or ball burnishing suggested by [1, 11].
- Research the influence of all cutting process conditions, including coolant use.

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