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Influence of parameters of deep grinding on nano-hardness and surface roughness of C45 steel

Wpływ parametrów szlifowania wgłębnego na nanotwardość i chropowatość powierzchni stali C45

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The paper presents the results of investigations on the effect of the depth of concurrent grinding of flat surfaces on the roughness and nano-hardness of the surface layer of C45 steel with a ferritic-pearlitic structure and average grain size of 20 µm. A significant increase in the hardness of the surface layer of the workpiece was obtained for all grinding depths.
KEYWORDS: grinding, nano-hardness, state of the surface layer, ferritic-pearlitic structure, deformation strengthening

The selection of technological parameters in the finishing process allows to meet the assumed design requirements. Properly carried out grinding process allows obtaining a high dimensional and shape accuracy, the appropriate state of the surface layer, as well as the required geometric structure of the surface [1, 2]. Modeling and optimization of the grinding process are usually aimed at achieving a low surface roughness and high machining efficiency [3].

The choice of machining parameters is a factor determining the distribution of hardness and stresses in the surface layer of the workpiece made of material with a defined volume fraction of structure components, which in turn affects, among others, for wear resistance of the treated surface [4, 5].

Experimental research

■ Sample preparation. Workpieces with a height of 10 mm were cut from a C45 steel bar with a diameter of 50 mm on an AccuteX AU-300IA wire cutter. They were subjected to a heat treatment involving normalizing annealing at 850 ° C for 20 min, followed by cooling in still air.

After heat treatment, a ferritic-pearlitic structure was obtained (fig. 1) with an average grain size of 20 µm. In the normalized state, the steel had the following mechanical properties: tensile strength – 490 MPa and hardness – 167 HB [6].

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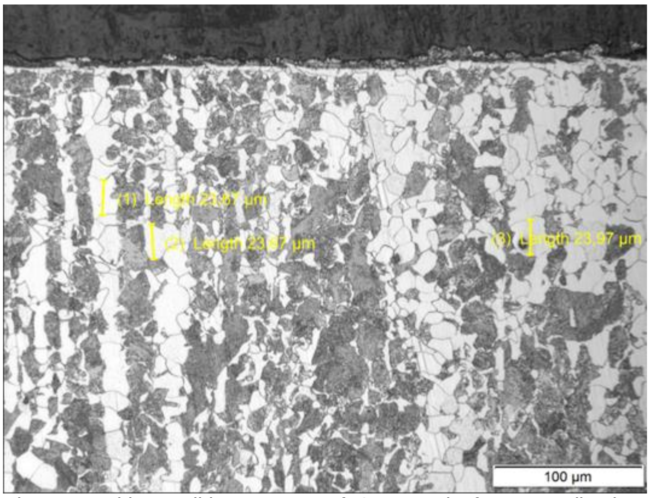

Fig. 1. Ferritic-pearlitic structure of C45 steel after normalization. Sample digested with Nital. Photograph taken with LM Leice light microscope

■ Test conditions. The grinding was carried out on a CNC grinding machine SPG 25 × 60 with a horizontal spindle axis. The Norton grinding wheel with precious alumina grains with technical characteristics 38A60LVS and dimensions: diameter 250 mm and width 25 mm was used for machining. Each test was preceded by the conditioning of the grinding wheel using a single-grain diamond dresser with the following parameters set in the control program:

- depth a_{ed} at a single pass: 0.1 mm,
- number of dressing passes: 4,
- circumferential speed of the grinding wheel: v_{sd} = 23 m/s,
- lateral feed of the grinding wheel: f_{ad} = 0.2 mm/rev.,
- number of shifting passes: 2.

Concurrent deep grinding is carried out with the use of coolant, at constant circumferential speed of the grinding wheel v_s = 25 m/s and constant feed speed v_{ft} = 1 m/min. The variable parameter was the grinding depth set in subsequent tests according to the values: a_e = 2; 8; 14; 20 µm The minimum depth a_e = 2 µm was accepted due to the low hardness of the workpiece.

In each test, a new workpiece with a ferritic-pearlitic structure obtained after heat treatment was grinded (fig. 1).

In order to ensure the same depth of grinding, the workpiece after fixing on the magnetic table was leveled by whitening with the depth a_e = 1 µm.

■ Measuring apparatus. Nano-hardness tests were carried out on a nanoindenter (NanoTest Vantage, Micro Materials, UK) using a pyramidal, diamond, three-ventral Berkovich indenter with an apical angle of 124.4°.

Each sample was subjected to nanoindentation measurements with maximum force values of 50, 100 and 500 mN, respectively.

Fig. 2 presents exemplary curves obtained in the nanoindentation test performed on the surface of the workpiece after grinding with a depth of a_e = 2 µm, with the maximum load of the indenter of 50 mN. The time of force increase from the zero value was 20 s, the holding time with the maximum force value – 5 s, and the unloading time – 20 s. Individual indentations were 50 µm apart. During the measurement, the load curve was recorded as a function of the Berkovich indentation. The value of nano-hardness (*H*) was determined using the Oliver-Pharra method in the NanoTest program.

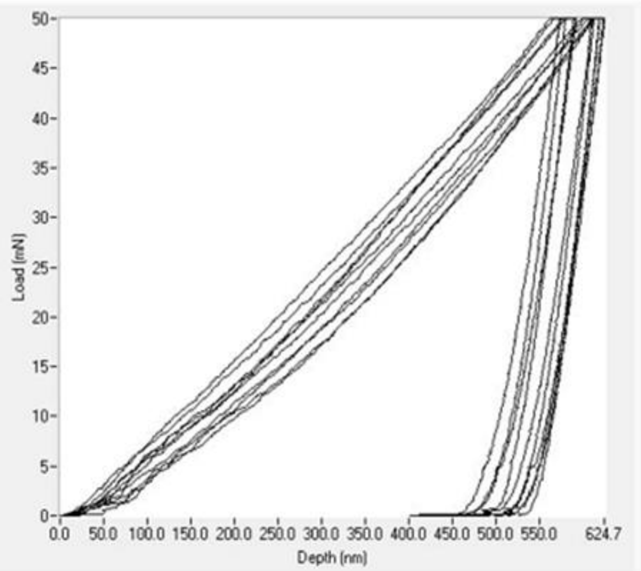

Fig. 2. Exemplary load curves as a function of depth of the Berkovich indentation depth; measurement on the workpiece surface made of C45 steel after grinding with depth a_e = 2 µm

Surface topographies were examined with atomic force microscopy (AFM, NaniteAFM, Great Britain) using a contactless module with a force of 55 mN in the 50 × 50 µm area. Surface roughness parameter Sa was determined.

Research results and discussion

The influence of the grinding depth on the nano-hardness of the surface layer of C45 steel with an average grain size of 20 µm, with different maximum indentation loads, is presented in the table and in fig. 3.

The hardness of the surface layer differed depending on the depth of grinding and the maximum load on the indenter. The smallest hardness variability range, 2.9÷3.4 GPa, was recorded for a maximum load of 500 mN. An almost double increase in hardness was obtained compared to the initial state after normalization, in which the hardness was 167 HB, i.e. about 1.67 GPa. The standard deviation for the measurements was relatively small and was within 0.2÷0.3 GPa.

As shown by metallographic examinations using a scanning microscope (fig. 4), plastic deformations in both the ferrite grains and perlite grains were formed at a depth of 2 µm, which contributed to an almost two-fold increase in hardness in the surface layer.

TABLE. Nano-hardness and surface roughness parameter *Sa* after concurrent deep grinding of C45 steel objects with an average grain size of 20 µm

Grain 20 µm			
Grinding depth, mm	Force, mN	Nano-hardness, GPa	Roughness *Sa*, nm
0.002	50	5.59	82.542
	100	4.79	
	500	3.40	
0.008	50	7.53	81.608
	100	7.10	
	500	3.47	
0.014	50	5.59	91.455
	100	4.19	
	500	3.00	
0.020	50	7.49	113.31
	100	7.49	
	500	2.90	

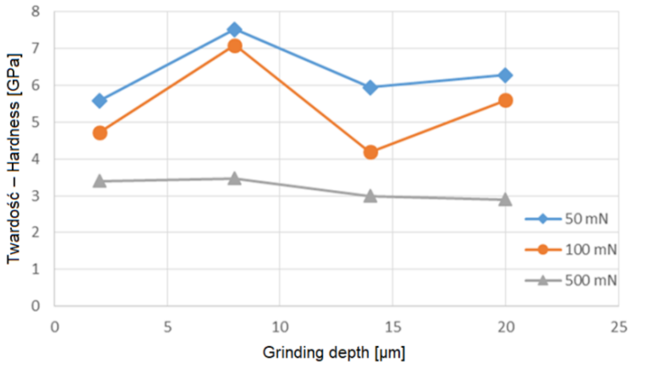

Fig. 3. Influence of the grinding depth on the hardness of the surface layer of C45 steel with an average grain size of 20 µm, with different maximum indentation loads

During the nanoindentation test, using a maximum load of 500 mN, the indenter delved into approx. 2600 nm ±100 nm, which is assumed to be the minimum depth for the deformation of the material for a given load. At a lower maximum load in the nanoindentation test, 50 mN and 100 mN respectively, a greater increase in the hardness of the surface layer was noted. The hardness variability range was 4.17÷7.1 GPa for 100 mN load and 5.59÷7.53 GPa for 50 mN load. At 50 mN load, the indenter penetrated into the material at approx. 600 nm ±20 nm, and at 100 mN load – to a depth of 950 nm ±50 nm. As expected, the hardness increased due to the deformation of ferrite grains and perlite grains after grinding, while the hardness in the surface layer of the ground workpiece surface decreased with the distance from this surface into the material.

As can be seen in fig. 3, the hardness distribution in the surface layer of the workpiece surface, resulting from the different indentation of the indentations used, also depended on the depth of grinding. The greatest surface hardness (for a load of 50 mN) – 7.53 GPa – was achieved for the grinding depth a_e = 8 µm.

In the case of a larger grinding depth – 14 µm and 20 µm, other hardness distributions were obtained from the workpiece surface into the material. As shown in fig. 3, the maximum hardness at the workpiece surface for these grinding depths was about 6 GPa. This hardness is approx. 20% lower than after sanding with depth a_e = 8 µm. As in the case of grinding with smaller depths, also here there was a decrease in hardness along with the distance from the ground workpiece surface, with a larger drop for the grinding depth of 14 µm than for 20 µm.

The metallographic examination of the workpiece surface layer polished with a depth of a_e = 20 µm, made with the use of a scanning microscope, revealed an additional layer of changed material with a clear limit of separation from ferrite and pearlite grains. This layer adhered well to the ferritic-pearlitic substrate – fig. 5.

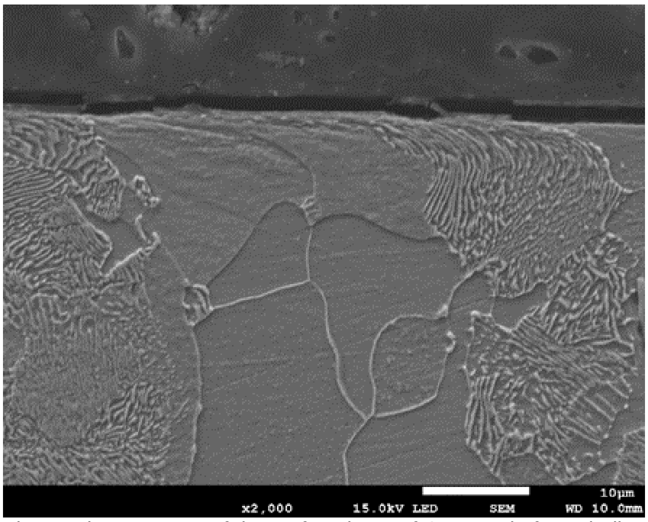

Fig. 4. Microstructure of the surface layer of C45 steel after grinding with a depth of 2 µm. Visible plastic deformation of perlite and ferrite grains (JEOL JSM-7800 F scanning electron microscope)

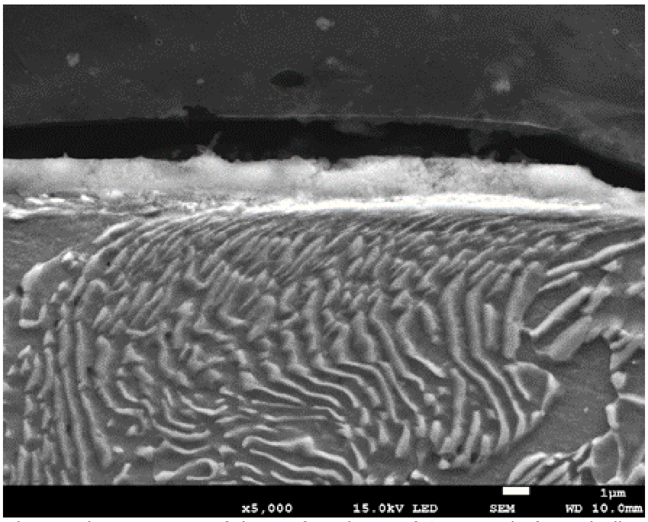

Fig. 5. Microstructure of the surface layer of C45 steel after grinding with a depth of 20 µm. Visible oxidized surface layer with a thickness of approx. 3-4 µm, under which there is a plastically deformed pearlite grain (JEOL JSM-7800 F scanning electron microscope)

The influence of the grinding depth on the workpiece surface roughness is shown in fig. 6. The surface roughness parameter *Sa* remained at the same level for the two initial grinding depths. Roughness increase occurred with the increase of the grinding depth – from a_e = 14 µm.

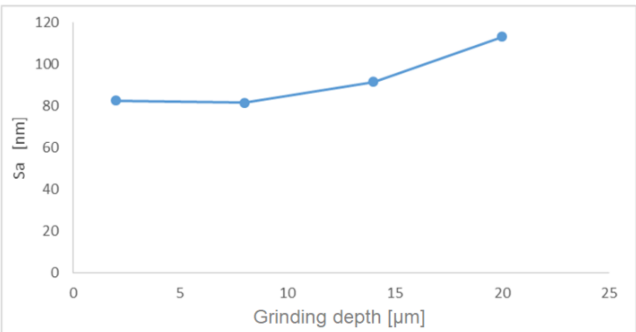

Fig. 6. Influence of the grinding depth on the surface roughness of C45 steel objects with an average grain size of 20 µm

Conclusions

Based on the results of the research, the following conclusions can be made:

- Grinding of normalized C45 steel with an average grain size of 20 µm with the given parameters results in a significant increase in hardness of the surface layer of the processed material.
- The greatest increase in hardness of the surface layer occurred in the case of grinding with a depth of a_e = 8 µm. The hardness of the material at the workpiece surface amounted to 7.53 GPa, which means a four and a half increase in hardness compared to the hardness of the material before grinding. This increase was caused by the deformation of both ferrite and pearlite grains.
- When sanding steel with a depth of 14 µm and 20 µm, the increase in hardness was less than at the sanding depth of 8 µm. The hardness at the surface of the surface layer after grinding was 6 GPa, which means an increase of 350% in relation to the hardness of the material before grinding.
- The surface roughness parameter *Sa* was maintained at the same level for the two initial grinding depths of 2 µm and 8 µm. Roughness increase occurred with the increase of the grinding depth from a_e = 14 µm.

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