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EFFECT OF DIAMOND BURNISHING PROCESS VELOCITY ON 41Cr4 STEEL SURFACE INTEGRITY

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ABSTRACT

Diamond burnishing (DB) is a static mechanical surface treatment process based on severe plastic deformation on the surface layer of the metal work-pieces. The main feature of the DB is that the tangential contact type between the diamond deforming element and the surface being treated - sliding friction contact. DB significantly reduces the roughness (up to mirror-finish surfaces), increases the surface micro-hardness, introduces the beneficial residual stresses and modifies the microstructure of the surface and subsurface layers in terms of grain refinement. Thus, DB dramatically improves the surface integrity (SI) of the metal components. The basic governing factors of the DB are the radius of the spherical-ended diamond, burnishing force, feed rate and burnishing velocities. This article presents the outcomes from the experimental investigation of the influence of sliding burnishing velocity on SI of 41Cr4 steel. It was established that the burnishing velocity influences slightly on the SI. The increased burnishing velocity leads to slightly decrease of the roughness obtained, slightly increase of the surface micro-hardness and a reduction of the surface axial residual stresses; in contrast with the residual axial stresses, the residual surface hoop stresses increase.

1. INTRODUCTION

Diamond burnishing (DB) is static mechanical surface treatment process implemented through sliding friction contact between the deforming diamond and the surface being treated. Based on severe surface plastic deformation, DB improves significantly surface integrity (SI) of the burnished metal components and thus improves their operating properties as fatigue strength, wear resistance and others. Most often DB is carried out via spherical-ended diamond, what was used in the present study. The sliding friction contact predetermines the thermo-mechanical nature of the DB process. It was established [1] that about three quarters from the external work converts into a heat in the "deforming element – "workpiece" contact area in DB process. This leads to so called softening effect in the surface layers of some alloys. As shows the results obtained for AISI 316Ti chromium-nickel steel [2], this effect is a two-way effect: on the one hand it improves the surface finish due to the increased plasticity of the surface layers (as in the laser-assisted burnishing process for example); on the other hand, this effect reduces the surface micro-hardness and the introduced beneficial residual compressive stresses in the surface layers. In DB process the burnishing (sliding) velocity has substantial contribution to the generated head in the contact area between the diamond and the surface being treated. Taking into account that friction dissipation is significantly greater than the dissipated energy from plastic deformation[1], in first approximation the heat flux density (directed to the surface being burnished) can be expressed as $q_g = \eta \tau v$, where q_g is the heat flux density generated by the friction, $0 < \eta \le 1$ is a coefficient, showing what proportion of the work of friction dissipates into a heat, τ is stress from friction, v is burnishing velocity. According to Coulomb's law, the stress friction τ depends on the burnishing pressure (which, in his turn, depends on the burnishing force and the diamond radius) and on the sliding friction coefficient. As was established [3], the friction coefficient depends on the burnishing force. Based on the above, it can be concluded that burnishing velocity influences the operating properties of the burnished component by means of some characteristics (micro-hardness, residual stresses) of SI, due to the thermal effect.

The conducted literary survey shows that, first of all, the impact of the burnishing velocity on the roughness and micro-hardness was investigated; however the thermal-mechanical nature of the DB process has not been taken into account. The studies were devoted to both steels and non-ferrous materials. The effect of the DB velocity on the roughness obtained was studied by: Yu and Wang [4] for cast Al-alloy; Tanaka et al. [5] for SUS316 stainless stell steel and 7075AA; Shiou and Chen [6] for PDS5 steel; Shiou and Banh [7] for oxygen-free copper; Maximov et al. [8] for 2024-T3 AA; Luo et al. [9] for Al alloy using cylindrical-ended polycrystalline diamond; Hankare et al.

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[10] for AISI 4140 steel. The impact of DB burnishing velocity on both roughness and surface micro-hardness was investigated by: Buldum and Cagan [11] for AZ91D magnesium alloy; Esme [12] for 7075 AA; Hamadache et al. [13, 14] for Rb40 and 36CrNiMo6vsteels; Sachin et al. [15, 16] for 17-4PH stainless steel; Saldana-Robles et al. [17] for AISI 1045 steel; Shiou et al. [18] for AISI 420 stainless stell steel. Luo et al. [19] studied the influence of DB velocity on roughness and waviness of Ly12 and H62 nonferrous alloys using cylindrical-ended diamond. Maximov et al. [3] investigated experimentally the influence of DB velocity on the friction coefficient between the polycrystalline deforming diamond and the 41Cr4 steel surface being treated. Some authors [10, 12] established that the DB velocity influences most weakly on the surface roughness obtained. However, the impact of the velocity on the residual stresses and the surface micro-hardness can be more materially. Maximov et al. [2] studied by means of finite element simulations and experiment the effect of DB velocity on the residual axial and hoop stress distribution and surface micro-hardness in AISI 316Ti steel taking into account the thermo-mechanical nature of the DB process. They proved the manifestation of the softening effect, expressing in reduction of the residual stresses in the surface and subsurface layers up to depth of $50\mu m$ as well as in reduction of the micro-hardness.

Based on the literary survey conducted, the following conclusion can be made: a careful study, based on the thermo-mechanical nature of DB, of the impact of DB velocity on SI of low alloy medium carbon steels has not been conducted. The results from such study will determine the optimal values of burnishing velocity for different applications of DB – as smoothing, deep or mixed burnishing [20]. Therefore the aim of the present study is to give an answer of this question.

2. MATERIAL AND METHODS

41Cr4 medium-carbon low-alloy steel was used. In order to evaluate the impact of the DB velocity on the roughness, surface micro-hardness and introduced residual hoop and axial stresses, one-factor-at-the-time method was implemented for different combinations of the deforming diamond radius and burnishing force. For each combination the DB velocity was changed of six levels. The feed rate was kept constant ($f = 0.05mm/rev$). Table 1 shows the magnitudes of the governing factors for each experimental point. Five workpieces were used to produce the specimens on a CNC T200 lathe by means of burnishing device with polycrystalline diamond (Fig. 1). Each workpiece was designed for DB of six cylindrical surfaces. Each cylindrical surface with length of $20\,mm$ was diamond burnished with combination of the governing factor magnitudes according to Table 1. DNMG 50608 – RF carbide cutting insert was used for turning. DB was conducted using Hacut 795-H lubricant-cooler. Finally, six specimens were cut from each workpiece or total of 30 specimens.

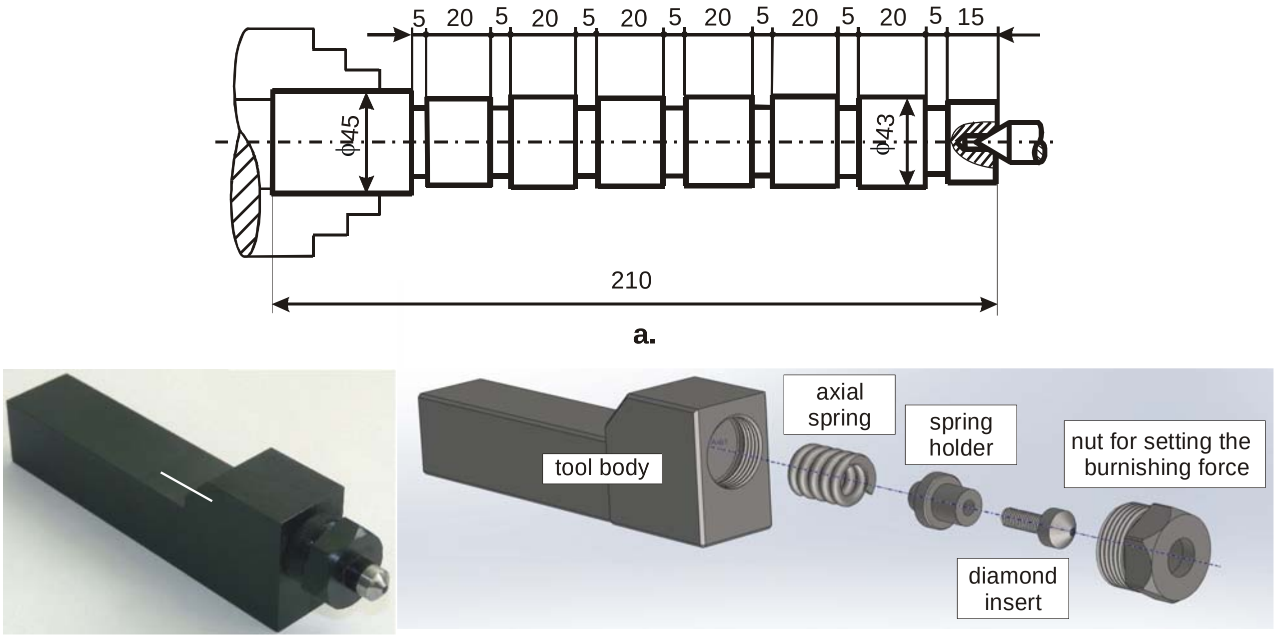
Table 1 *Combinations and magnitudes of the governing factors*

$v, m/min$	50	100	150	200	250	300
$r = 2mm$, $F_b = 250N$, $f = 0.5mm/rev$						
№ of specimen	1	2	3	4	5	6
$r = 3mm$, $F_b = 250N$, $f = 0.5mm/rev$						
№ of specimen	7	8	9	10	11	12
$r = 4mm$, $F_b = 250N$, $f = 0.5mm/rev$						
№ of specimen	13	14	15	16	17	18
$r = 3mm$, $F_b = 100N$, $f = 0.5mm/rev$						
№ of specimen	19	20	21	22	23	24
$r = 3mm$, $F_b = 400N$, $f = 0.5mm/rev$						
№ of specimen	25	26	27	28	29	30

Mitutoyo Surftest – 4 was used to measure the surface roughness R_a . Each experimental value was obtained as an arithmetic mean of the obtained roughness for three generatrixes. One-factor-at-the-time method was used for roughness and micro-hardness measurements.

The micro-hardness measurements were conducted on $ZHV\mu$ microtester. A total of 60 measurements per specimen were made. For each specimen a statistical graph of the measurements was. The scattering interval and the center of clustering (median) were found. The micro-hardness, which corresponds to the median, was accepted as the final result for the corresponding specimen.

X-ray diffraction technique was implemented to measure the residual stresses in the diamond burnished specimens. The material layers were gradually removed by electrolytic polishing in order to established the stress gradient under the surface layer. A vertical θ/θ X'Pert PRO MPD diffractometer with a pin-hole collimator of $1.0 \times 1.0\ mm^2$ in the primary beam was used for diffraction measurements. Positioning of the measured specimen used a six degrees of freedom system and laser triangulation with an accuracy of approximately $5\ \mu m$. The effective penetration depth of the CrKα radiation into the investigated steel was approximately $4\ \mu m$. Therefore 2D stressed state was adopted and the $sin^2 \psi$ method was used to estimate the residual stresses using the least squares method. The measured diffraction profile of the α-Fe {211} planes were a maximum at $2\theta \approx 156.4^{\,o}$ for the filtered CrKα radiation. Diffraction profiles were fitted using the Pearson VII function, and the lattice strains were calculated. X-ray elastic constants, $s_1 = 1.25 \times 10^{-6}$ MPa^{-1} and $1/2\ s_2 = 5.76 \times 10^{-6}\ MPa^{-1}$, were used in Hooke's law.



a.

b.

c.

Fig. 1. Specimens preparation: a. specimen's dimentions; b. SDB device – general view; c. SDB device – construction

3. RESULTS AND DISCUSSIONS

Fig. 2 shows the surface roughness depending on DB velocity. Obviously, the burnishing velocity influences slightly on the roughness obtained. It can be concluded that the increased burnishing velocity leads to slightly decrease of the roughness obtained for all combination of the radius and the burnishing force. An exception is the combination $r = 4mm$ and $F_b = 250N$, for which the roughness slightly increases.

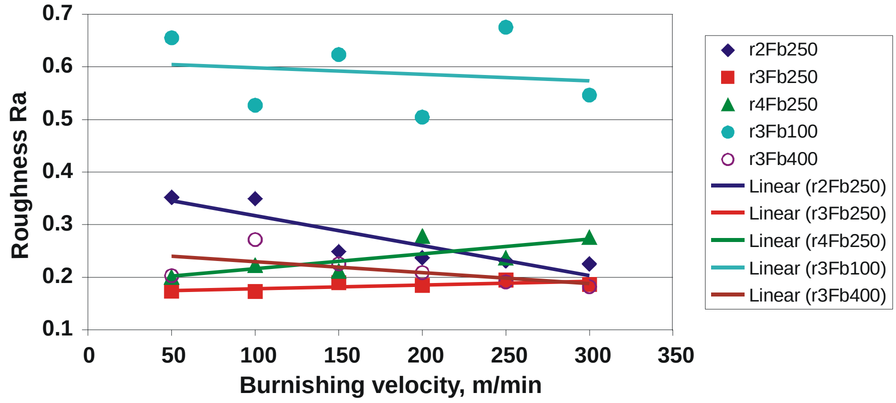


Fig. 2. Effect of the burnishing velocity on the roughness

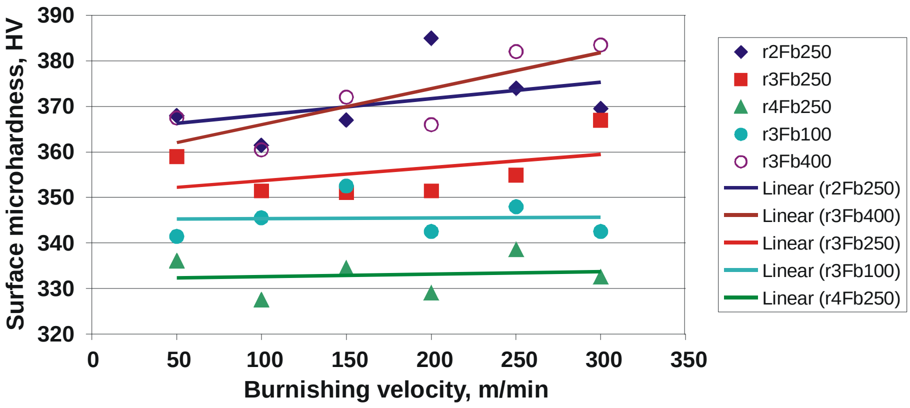


Fig. 3. Effect of the burnishing velocity on the surface microhardness in contrast with the residual axial stresses, the residual surface hoop stresses increase slightly.

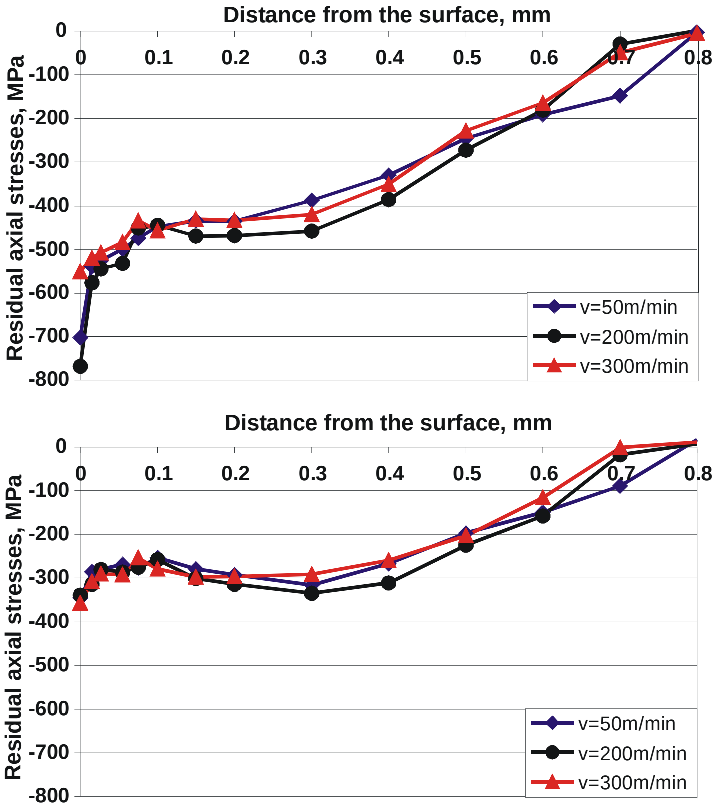


Fig. 4. Effect of the burnishing velocity on the residual stress distribution

4. CONCLUSIONS

This article presents the outcomes from the experimental investigation of the influence of sliding burnishing velocity on SI of 41Cr4 steel. It was established that the burnishing velocity influences slightly on the SI. The increased burnishing velocity leads to slightly decrease of the roughness obtained, slightly increase of the surface micro-hardness and a reduction of the surface axial residual stresses; in contrast with the residual axial stresses, the residual surface hoop stresses increase.

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