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Effect of Initial Microtopography and Ultrasonic Treatment Mode on Steel Surface Layer Quality

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Abstract. The article presents results of studies on the effect of pre-lathed surface micro-relief on surface micro-hardness after ultrasonic plastic treatment, as well as the effect of ultrasonic treatment on structure and properties of surface layers of steels 20 and 40X. The effect of ultrasonic treatment processing modes on roughness and micro-hardness of the surface layers was studied. It is shown that roughness values as well as form of ridges and grooves, obtained by pre-lathing, effect the growth of micro-hardness values after ultrasonic plastic treatment.

1. Introduction

Ultrasonic plastic working (ultrasonic treatment) is a method of high impact to metal surfaces; the essence of the method is that a component surface after machining is treated with the instrument (a ball) vibrating with ultrasonic frequency [1-5].

Ultrasonic plastic treatment causes formation of a modified layer, with a high concentration of dislocations and diffuse interface with the base material, on the surface; formation of dangerous stress concentrators and emergence of fatigue cracks slow down significantly in the surface layer; that blocks a development of fatigue processes [6-8, 17, 18].

For practical application of ultrasonic treatment special ultrasonic equipment is used, that is the ultrasonic head, the ultrasonic generator and tools. Machining of outer and inner surfaces is performed by metal-working machines (turning, milling) of normal accuracy.

The main parameters of ultrasonic hardening are: tool static pressure on the detail surface; rates of vibration movement, longitudinal and lateral feed; a number of strokes; tool dimensions and shape [1, 2, 3, 5].

Auxiliary movement (feeding) and the number of working strokes both determine the number of strokes per unit of in-process surface per unit of time. The ultrasonic instrument size and shape both define the impact force and, thereby, the pressure on the in-process surface [4, 5].

Ultrasonic treatment has several features that distinguish this method from other types of surface deformation. The first feature is impact stress, which is repetitive and is distributed on a relatively small surface area. The second feature is rapidly alternating compression and shear deformations on the workpiece surface.

Specific process factors, namely magnitude of tool static pressure to the workpiece, amplitude and frequency of vibrations, have a great effect on physical-mechanical condition of the surface layer (roughness, micro-hardness, internal residual stresses). Static pressure force ensures contact between the tool (ball) and the surface. Both vibration amplitude and ball static pressure determine surface roughness, degree and depth of hardening, and magnitude of residual stresses in the metal surface layer as well as processing performance, feeding and workpiece rotation rate and a stroke number. Static pressure force is inversely proportional to the workpiece material elasticity; and is directly proportional to the initial roughness, diameters of in-process workpiece and the ball; feeding rate and workpiece rotation velocity.

This paper represents researches on effect of ultrasonic plastic processing modes on roughness and micro-hardness of steel surfaces. The authors investigated impact of initial roughness, indenter feed rate and in-process sample rotation velocity on values of micro-hardness and roughness after ultrasonic treatment.

2. Materials and methods

To determine the effect of lathe-cut initial surface micro-relief on surface hardening magnitude after ultrasonic plastic treatment, test samples were initially processed by lathing. Longitudinal support feed, setting the distance between individual micro-relief surface ridges and cut depth, setting the height of the irregularities, were variable parameters. Geometric parameters of the turning tool were also varied.

Ultrasound plastic treatment of the samples from 20 and 40X steels, 30 mm in diameter, was performed using ultrasound process set UZTK-02 [9, 20, 21]. Modes and processing parameters are as follows: generator output is 300 watts, indenter vibration amplitude is 20 microns, indenter static contact force is 50 N; vibration frequency is 24 kHz, indenter diameter is 5 mm.

Processing (Fig. 1) was carried out as follows: before ultrasonic plastic treatment, pre-lathing of the sample surface was performed by a machine-tool.

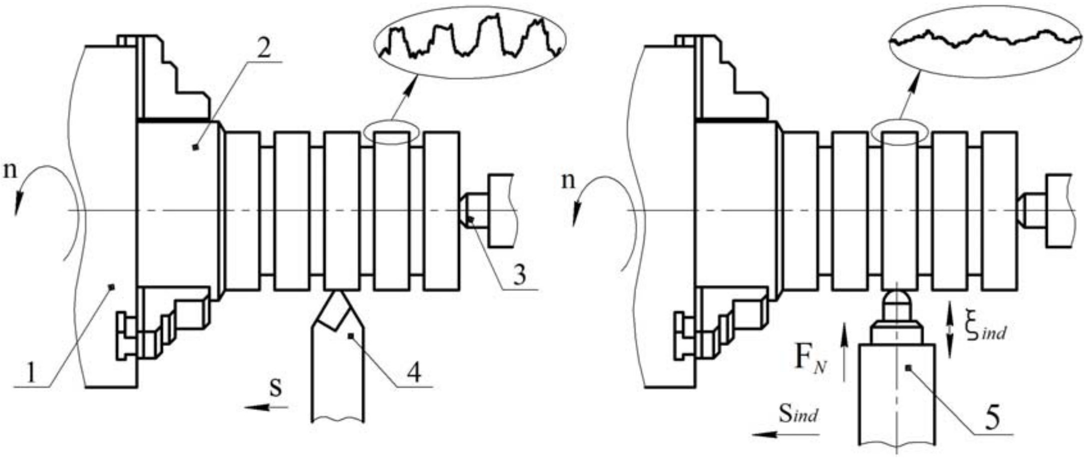

Figure 1. Ultrasonic treatment scheme: 1 - Three-jaw chuck;
2 – Workpiece (Sample); 3 - Rear Center; 4 - Cutter; 5 - Ultrasonic Tool

The sample 2 was placed in the three-jaw chuck 1 of the lathe and pressed by the rear center 3. Lathing of sample necks was performed in the following modes: support longitudinal feed was from 0.04 to 0.28 mm/rev; cutting depth - from 0.5 to 1 mm; lathing tool plan angle φ - from 40^o to 85^o, processing velocity - from 17 to 50 m/min. Then the cutter 4 was replaced by the ultrasonic impact tool 5. Sample necks were processed with the hard-metal indenter vibrating at an ultrasonic frequency. Sixteen necks of each workpiece were subjected to treatment

To determine the effect of ultrasonic treatment on indentation hardness of the metal surface, surface treatment was carried out without longitudinal feed by two modes: with ultrasonic action and without ultrasonic action.

3. Results and discussion

Tool stroke ultrasonic frequency modifies surfaces to a much greater extent than conventional methods of surface plastic deformation. A complex surface topography is formed by rotating the in-process sample and movement of the tool traverse manipulator. The surface topography is formed by waves of deformable metal, extruded under the indenter stroke displacements at an ultrasonic frequency.

In a local area of the indenter contact with the in-process surface, a plastic deformation zone occurs, which shifts with the indenter. Roughness Rz in the range of 3.5-5.5 mc was formed on sample surfaces after treatment with the ultrasound tool. Thus, decrease of surface roughness is achieved by indenter levelling impact on the thin surface layer, namely, on the roughness ridges formed after pre-lathing. The magnitude of surface hardening after ultrasonic treatment was evaluated by increase in micro-hardness. Table 1 shows the results of micro-hardness measurement on sample surfaces after ultrasonic treatment, comparing the highest (sample 2) and the lowest (sample 1) values of hardness.

Table 1

Micro-hardness value after ultrasonic treatment

	Steel 20			Steel 40X		
	Initial	Sample 1	Sample 2	Initial	Sample 1	Sample 2
Micro-hardness, MPa	1800 ± 200	2500 ± 250	3300 ± 250	2500 ± 150	3100 ± 200	4300 ± 200

Ultrasonic metal treatment significantly improves structure of surface and near-surface layers and increases micro-hardness values [6, 7, 10, 11, 23, 22]. Metallographic structure image (Fig. 2) shows a non-pickling 2-3 micron thick surface layer; non-equiaxed elongated grains, following machine direction, are located depthward, at a depth of 3-12 microns. Even below the treated layer transits gradually to the initial steel structure [3, 5, 12].

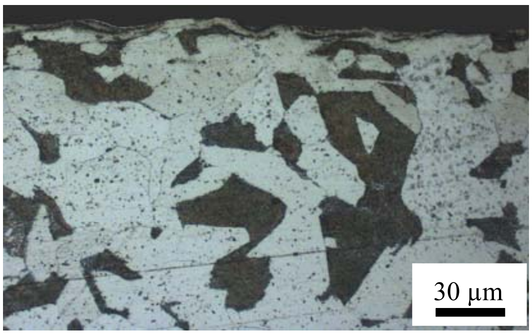

Figure 2. Metallography steel 20 after ultrasonic treatment

The results of micro-hardness value distribution of the most hardened samples (samples 2 of Table 1) are shown in Fig. 3.

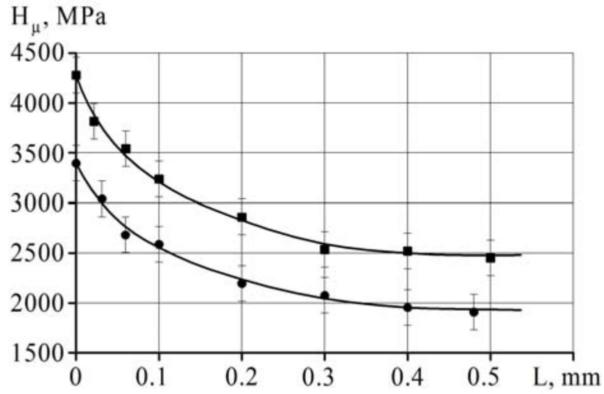

Figure 3. Depthward distribution of micro-hardness after ultrasonic treatment:
● - Steel 20; ■ - steel 40X

After ultrasonic treatment micro-hardness has a maximum value at the sample surface. Below the surface, micro-hardness monotonically diminishes to the initial level of material micro-hardness. Monotonic micro-hardness diminishing is resulted from changes in macro-, micro- and sub-microstructure of the steel, as well as changes of residual compressive stress conditions during the ultrasonic treatment [1, 2, 13, 14, 19]. Both absolute maximum value of surface micro-hardness and a hardened layer depth depend on carbon concentration in steel, and increase with carbon content [4, 6, 7, 8, 15].

In this part of the study it is found, that maximum surface hardening is achieved on surfaces with micro-relief as shown in Figure 4, and minimum hardening - on surface with micro-relief as shown in Figure 5.

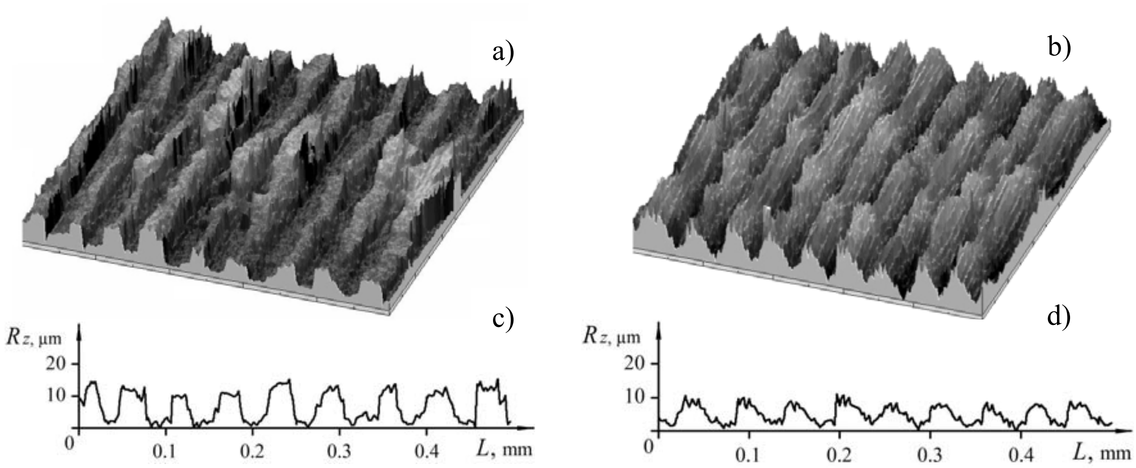

Figure 4. 3D-image of the surface (a, b) and profilogram (c, d) after pre-turning:

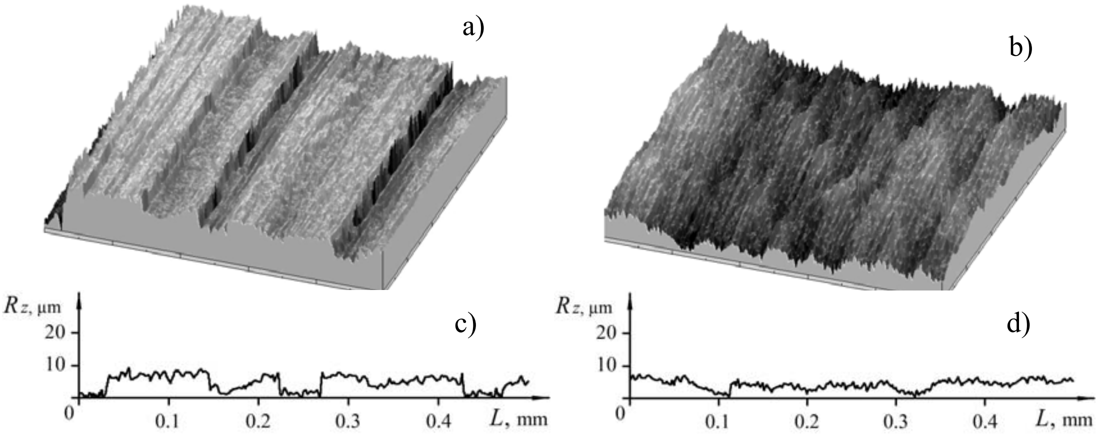

Figure 5. 3D-image of the surface (a, b) and profilogram (c, d) after pre-turning: a, c - Steel 20; b, d - steel 40X

The surfaces shown in Figure 4 are formed by lathe cutting, with the following modes: 0.05 mm/rev feed; 1 mm cutting depth. Surface roughness has a regular mode; micro-relief is an alternation of ridges and grooves [16] of trapezoidal shape with roughness value Rz 10-15 mc.

The surfaces shown in Figure 5 are formed by lathe cutting, with the following modes: 0.02 mm/rev feed; 1 mm cutting depth. Micro-relief is irregular; ridges and grooves vary in shape and size; roughness value after treatment is Rz 7-12 mc.

Subsequent ultrasound treatment of surfaces shown in Figures 4 and 5 was conducted with the following modes: feed - 0.2 mm / rev; ultrasonic action power - 300 W.

Figure 6 shows the surface, shown in Fig. 4, after ultrasonic plastic treatment, which has maximum hardening value. Figure 7 shows the surface, shown in Fig. 5, after ultrasonic plastic treatment, which has minimum hardening value.

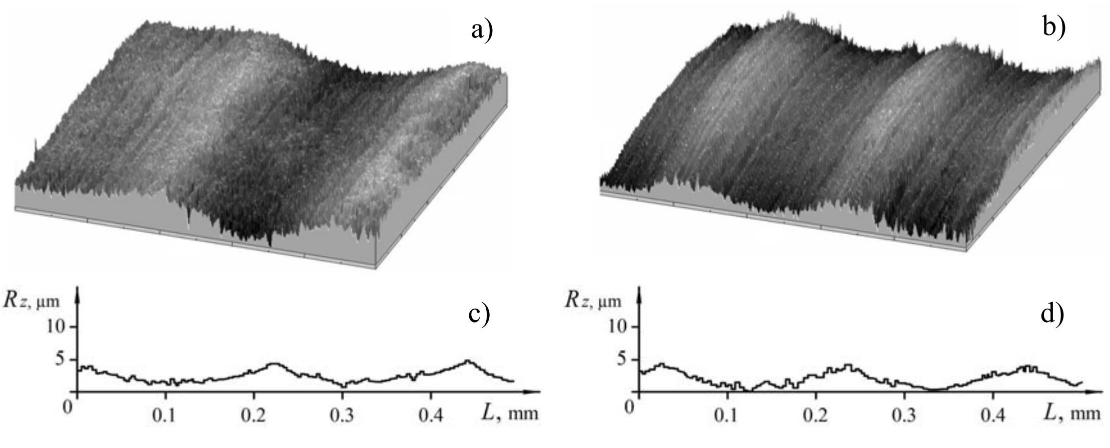

Figure 6. 3D-image of the surface (a, b) and profilogram (c, d) after pre-turning: a, c - Steel 20; b, d - steel 40X

Surface micro-relief (Fig.6) has a regular mode formed by alternation of ridges and grooves with roughness value Rz 5–6 mc. Surface micro-relief (Fig.7) is irregular; roughness value is Rz 5–6 mc.

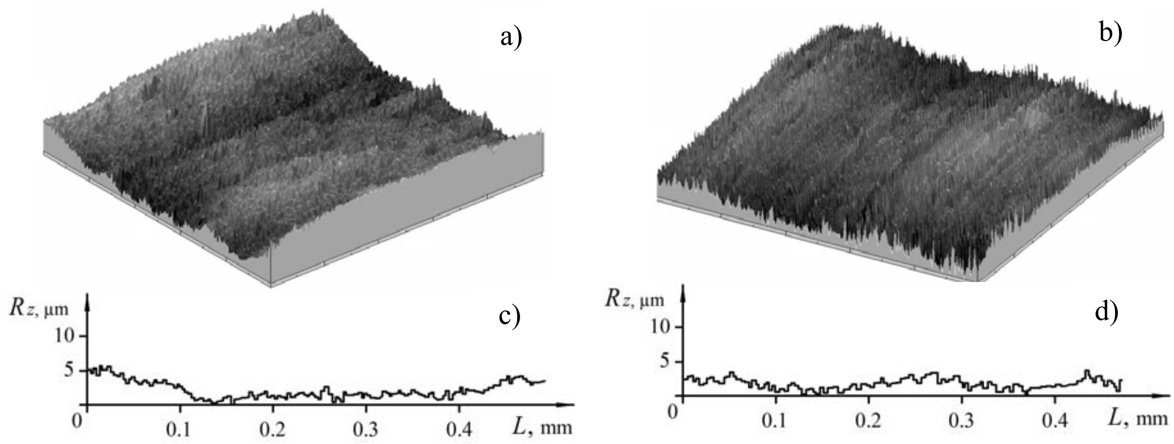

Figure 7. 3D-image of the surface (a, b) and profilogram (c, d) after pre-turning: a, c - Steel 20; b, d - steel 40X

Figure 8 shows a diagram of material surface layer deformation if contact of the hard-alloy indenter with the sample surface without both longitudinal feed and ultrasonic action. When loading the indenter by static force FN it is impressed in the in-process material. With the increase of pressing force, first elastic deformation of the surface occurs, then plastic deformation. After unloading, residual plastic deformation is expressed by indent sizes, namely, H groove width and h groove depth. Indentation depth was determined using the following formulas:

$$h = BC = OC - OB \quad (1)$$

$$OB = \sqrt{r^2 - \left(\frac{H}{2}\right)^2} \quad (2)$$

AO = OC = r; AB = H/2

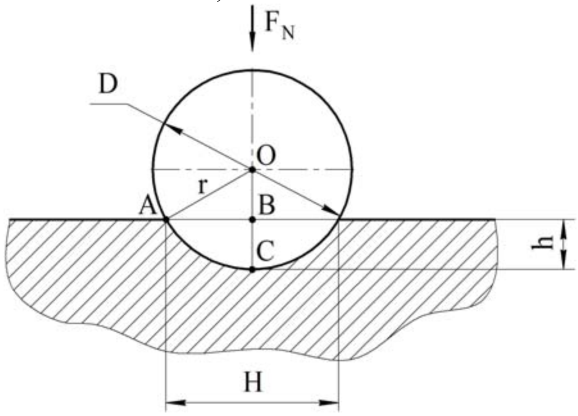

Figure 8. Scheme of surface deformation with indenter: F_N - static force; D - 5 mm indenter diameter; h - groove depth; H - groove width

Table 2 shows the results of contact of the hard-alloy indenter with the sample surface without both longitudinal feed and ultrasonic action. H groove width and h groove depth were determined using formulae (1) и (2). Table 2 shows that indentation width and depth are significantly larger if ultrasound treatment.

Table 2

Groove dimensions after contact of indenter with sample surface

Sample material	With ultrasonic action		Without ultrasonic action	
	Indentation groove width H, mm	Indentation groove depth h, mm	Indentation groove width H, mm	Indentation groove depth h, mm
Steel 20	1.6	0.13	0.8	0.03
Steel 40X	1.0	0.06	0.6	0.02

It was studied how indenter feed rate and in-process sample rotation velocity both affect roughness and micro-hardness values at ultrasonic treatment. Graph (Fig. 9) shows that heights of surface micro-roughness enhance with indenter feed increase. Simplistically we can assume that surface micro-relief is formed by arcs of equal radii; centers of the arcs are spaced from each other by an indenter feed advance. Accordingly, the larger indenter feed rate is, the smaller is groove interpenetration formed by deformation; hence, a value of machined surface roughness is higher.

The graph (Fig. 10) shows that surface roughness is diminished with increasing of rotation velocity and at 23 m/min has a minimum value; if a further increase in rotation velocity, roughness enhances. Roughness enhance is caused by reduction in number of indenter strokes per unit area because of increase of sample rotation velocity. At lower rotation velocity roughening enhances due to increasing number of indenter strokes per unit area. There is a phenomenon of over-hardening and metal particles flaking thereby roughness enhances.

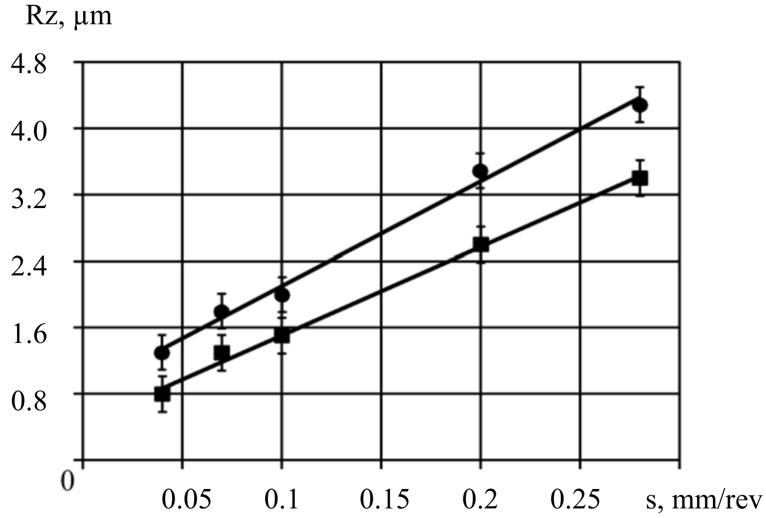

Figure 9. Influence of the supply amount of the indenter to a height of asperities after ultrasonic treatment: ● - Steel 20; ■ - Steel 40X. Processing velocity 23

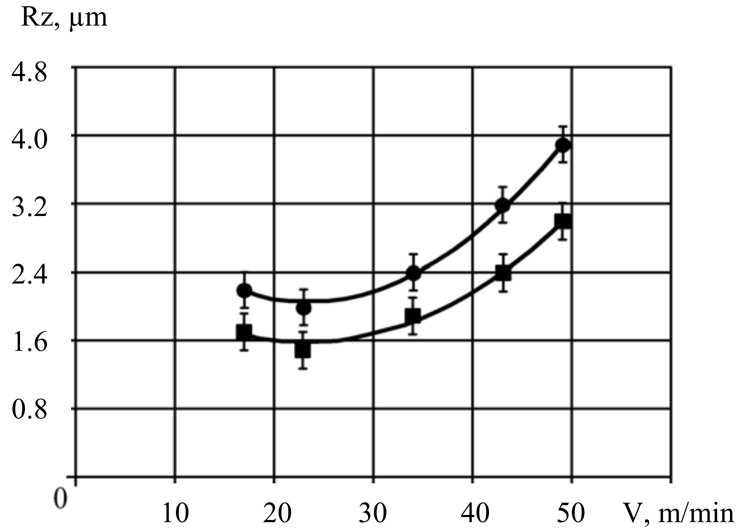

Figure 10. Effect of workpiece rotation velocity on micro-roughness heights after ultrasonic treatment: ● - Steel 20; ■ - Steel 40X. Indenter feed 0.1 mm/rev

The graphs (Fig. 11) shows that indenter feed increase diminishes surface microhardness at ultrasonic treatment. The larger indenter feed rate is, the smaller are both number of strokes per unit area and groove interpenetration formed by deformation; hence, values of plastic deformation and micro-hardness go down.

Graph (Fig. 12) shows that with increase of ultrasonic treatment rate, surface micro-hardness enhances and takes a maximum value at a speed of 23 m/min; then it gradually diminishes. At lower rotation velocities a number of indenter strokes per unit area increases; hence, a phenomenon of over-hardening occurs; thereby micro-hardness degrades.

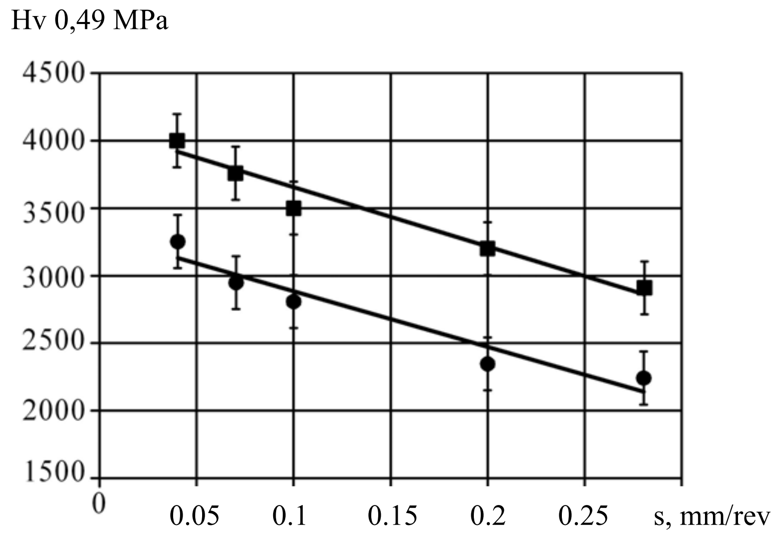

Figure 11. Effect of indenter feed on micro-hardness after ultrasonic treatment: ● - Steel 20; ■ - steel 40X. Processing velocity 23 m/min

Further increase in processing velocity leads to micro-hardness enhance to a maximum value for given treatment conditions and materials. From the turning-point a gradual micro-hardness decrease begins. This is caused by reduction in number of indenter strokes per unit area and, therefore, a degradation of surface plastic deformation.

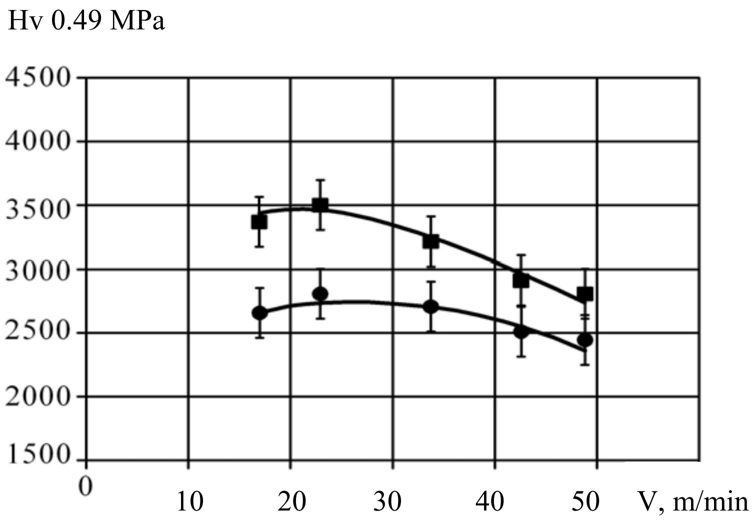

Figure 12. Effect of processing velocity on surface micro-hardness after ultrasonic treatment: ● - Steel 20; ■ - steel 40X. Indenter feed 0.1 mm/rev

Surface roughness-feed relation is linear within the research range. Roughness-peripheral speed relation is clearly nonlinear and approximated satisfactorily by a second order polynomial.
The following empirical relations are obtained by mathematical processing, for calculation of micro-relief Rz (3), (4), (7), (8) and micro-hardness HV (5), (6), (9), (10) of material.

For steel 20: $R_z = 12.64 \cdot s + 0.834$, (mc) (3)

$$R_z = 0.002 \cdot V^2 - 0.129 \cdot V + 3.558, \text{ (mc)} \tag{4}$$

$$HV = -4039 \cdot s + 3277, \text{ (MPa)} \tag{5}$$

$$HV = -0.627 \cdot V^2 + 32.698 \cdot V + 2315.4, \text{ (MPa)} \tag{6}$$

For steel 40X:

$$R_z = 10.59 \cdot s + 0.458, \text{ (mc)} \tag{7}$$

$$R_z = 0.002 \cdot V^2 - 0.096 \cdot V + 2.694, \text{ (mc)} \tag{8}$$

$$HV = -4279 \cdot s + 4060, \text{ (MPa)} \tag{9}$$

$$HV = -0.633 \cdot V^2 + 20.997 \cdot V + 3241.6, \text{ (MPa)} \tag{10}$$

Where: s – indenter feed, mm/rev; V – surface velocity, m/min.

The graphs (Figs. 11 and 12) contain processing velocity extreme points providing minimum roughness values and maximum micro-hardness values.

Conclusion

1. It is found that ultrasonic plastic processing ensures 2-2.5 times maximum micro-hardness increase, if roughness (Rz 15 mc for steel 20 and Rz 10 mc for steel 40X) with trapezoidal ridges and grooves, obtained after turning.

2. Parameters of indenter feed and rotation velocity at ultrasonic plastic treatment are determined, which enable forming of minimum roughness Rz 3.5-5.5 mc and maximum micro-hardness 3200-4200 MPa for given processing conditions.

3. Modes of turning and geometric parameters of cutting tool are determined, which allow forming of surface micro-topography with the most effective form of ridges and grooves for subsequent ultrasonic treatment.

4. Modes of ultrasonic plastic deformation are determined, which allow forming a regular micro-topography with a maximum surface layer hardening and ensuring gradual micro-hardness transition to initial material.

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