Surface roughness variation in ultrasonic assisted burnishing of high-strength steels

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Abstract. Ultrasonic assisted burnishing process is a newly developed alternative of conventional burnishing process that enhances the surface properties of engineering materials. The process needs careful selection of design parameters to improve the quality of surface layer of workpieces made of high-strength steel that are difficult to deform. The analytical models to predict the surface roughness after the ultrasonic assisted burnishing process for surfaces are developed. Feed, ultrasonic influence power and static static force could be considered as main factors influencing to surface roughness at that feed has the greatest impact among other parameters. The models are verified by experimental studies with various ultrasonic burnishing parameters. Technological parameters of the ultrasonic burning are found, which decrease surface roughness from 1-2 µm to 0.05-0.55 µm. It is experimentally proved that feed increase results in surface roughness increase. To low the surface roughness of high-strength steel workpieces it is necessary to increase ultrasonic influence power with simultaneous static force lowering. The analytical models obtained in the present work may be employed in determining the best conditions for ultrasonic assisted burnishing in industrial field.

1. Introduction
High performance properties of parts used in mechanical engineering, as back-to-back endurance, corrosion resistance and reduce fatigue resistance significantly depend on the quality of the surface layer. The surfaces quality improvement is mainly based on abrasive methods, such as grinding, superfinishing, honing and polishing. Unlike these traditional methods, where there is no controlled changes of physical and mechanical properties of the surface, burnishing, which utilises surface plastic deformation of the asperities, producing a specific surface integrity, and can also increase the fatigue strength and wear resistance of a workpiece [1], owing to the residual compressive stress [2, 3], hardening of the material on the surface [1, 3] and microlief character [4]. The generated surfaces post ball and roller burnishing possess highly improved surface texture, surface integrity and surface morphology. However their applications are excluded to products made of hard-to-work materials, low rigidity parts and thin coatings [5] due to occurrence considerable efforts and intense friction in the treatment area [1, 2, 3]. In order to overcome those problems, extra energies like ultrasonic vibration [6], heat energy [7] and laser energy [8, 9] have been adopted in micro forming [5, 10, 11]. Ultrasonic vibration assistance, as a relatively more efficient and effective approach to micro forming, has been attracting more and more attention from not only academic field but also industrial field. Using
ultrasonic vibrations we are not limited to the workpiece rigidity, the ability of various materials to treatment, the shapes and sizes of finishing surface [1, 11, 12].

Nowadays the ultrasonic plastic burnishing is an effective way of modifying and quality improvement of the surface layer of machine parts [5, 10, 13-20]. High energy effect of ultrasonic frequency harmonic vibrations simultaneously creates static and dynamic loading extending to a relatively small area [5]. High-rate deformations result in excitation of elastic-plastic stress waves reducing initial surface roughness, increasing microhardness and forming residual compressive stresses [21]. In comparison with conventional methods of surface plastic deformation, ultrasonic finishing is high-performance and less power-consuming, while easy machining process allows it to be implemented on the basis of universal metal-cutting machine tools. It should be noted that due to absence of significant deformation stresses, the ultrasonic finishing method is applicable to machine low-rigid and thin-wall parts [3, 9, 22].

To provide the required quality of machining some authors present different analytical models and optimal modes of using ultrasound in the hardening and finishing machining [19, 21, 23-27]. The roughness of surface layer is one of the parameters that we can control during finishing. The shape, microroughness of the working surfaces largely affects the strength, break-in and wear resistance, setting resistance, lubricant retention ability, lubricant film thickness, reflection of electromagnetic and ultrasonic vibrations and other operational properties of parts. The species of the microrelief (height, pitch, angle of inclination of irregularities and their relative position) is formed by the method and deforming conditions [10, 28]. High heterogeneity of the geometric shape of the irregularities of microliefs affects the performance properties of surface layer adversely. Research data [5, 10, 13, 29, 30] indicate ultrasonic plastic deforming make microrelief more uniform and decrease the surface roughness in several times in one pass.

That is why it is important and actual to obtain the regularities that allow us to predict the state of the surface layer with the required quality after ultrasonic plastic deforming. Note that the available experimental data regarding the surface quality refer to a small number of materials especially for a group of materials that are difficult to finishing due to mechanical properties of initial of workpiece or resulted from its heat treatment. So, this paper is devoted to determine dependencies of surface layer roughness on ultrasonic finishing process parameters for high-strength steel parts that are difficult to deform.

2. Materials and Methods

Experimental studies were performed according to the procedure developed by the authors and described in works [23] with turning machine under laboratory conditions using an experimental ultrasonic process complex. The experimental ultrasonic process complex includes the following: generator UZG-04M1, ultrasonic probe with magnetostrictive converter and hard-alloy indenter with an operating part made of tungsten solid carbide with diameter of 6 mm. The ultrasonic probe is attached on the machine stand using a fixture. The ultrasonic generator (power 0.25 kW, operating frequency 22 kHz) has staged machining power switching system.

For ultrasonic plastic deforming we prepare samples made of structural steel (17Kh18N9 and 20Kh1M1F1TR: diameter 35 mm, length 300 mm) with initial roughness Ra = 1-2 μm, and as well as ground end surfaces of specimens made of R6M5 high-speed and 9KHS tool steels (diameter 48 mm, thickness 10 mm), the lubricant coolant is I-20A industrial oil.

Surface roughness was measured within specimen sections before and after ultrasonic finishing. According to the preliminary experiments the main parameters of ultrasonic assisted burnishing process are identified. These four factors are feed (S, 0.04 – 0.3 mm/Rev), the speed of workpeace rotation (n, 80 – 315 rpm), static forces (P, 50 - 400N) and the ultrasonic power (N, W, it corresponds to the vibration amplitude 3.0 - 12.0 μm). In the experiments, a D-optimal Hartley–Kono design for four factors is employed. The static force created by means of an ultrasonic probe spring was recorded by electronic indicator Mitutoyo 543-790B. Authors in [21] apply the similar parameters of ultrasonic burnishing.
In order to exclude effect of accidental factors during regression analysis average Ra value calculated according to the results of 5 measurements within each section was used. Measurements were performed with automated mobile profilometer Mitutoyo SJ-201. During ultrasonic finishing specimens made of 17Kh18N9, 20Kh1M1F1TR steels were attached in the centres of turning machine, specimens made of R6M5, 9KHS steels were attached in a three-jaw self-centering chuck with increased accuracy, in previously bored jaws with grooves for workpiece end locating. In order to reduce specimen runout they were ground. Specimens were ground with a special tool fixed in a cutter holder of the turning machine. Specimen runout after reinstallation was measured by electronic indicator Mitutoyo 543-790B fixed on a magnetic stand and was 0.01 mm maximum.

3. Results and Discussion

We employ linear regression analysis to obtain the dependencies of surface layer roughness on ultrasonic finishing process parameters. The adequacy of mathematical models was checked by the Fisher test at the 5% significance level for the Student statistic. All statistically insignificant factors are excluded, and significant ones are re-analyzed. Based on the experimental results we obtain the following dependences of surface layer roughness on ultrasonic burnishing process parameters for high-strength steel parts:

\[ \text{Ra} = 1.9706 \times S + 0.0013 \times P - 0.0011 \times N \] (1)
\[ \text{Ra} = 0.3745 + 0.5774 \times S - 0.0017 \times P - 0.0003 \times N \] (2)
\[ \text{Ra} = 0.3212 + 0.4795 \times S - 0.0002 \times P - 0.0583 \times N \] (3)
\[ \text{Ra} = 0.4628 + 0.2385 \times S - 0.0005 \times P - 0.0457 \times N \] (4)

where \( \text{Ra} \) – surface roughness (\( \mu \)m), \( S \) – feed (mm/Rev); \( P \) – force of indenter holddown to workpiece (N); and \( N \) – generator power level (W) accordingly.

From regression analysis of experimental data the burnishing process is carried out taking into account feed, ultrasonic influence power and static force as main factors. Regression factors for the speed of workpiece rotation (\( n \), rpm) turned out to be insignificant for all grades of studied steels. Obtained results completely correlate with investigations [21]. For all presented steels an increase in feed results in increase of surface fine irregularities. When ultrasonic influence power is increased, area and depth of plastic deformation is increased, which causes smoothing of fine irregularities of initial surface and reduce microrelief height. Value of static force has the similar effect. Moreover, it should be noted that effect of vibrations, which can occur during machining, is significantly less than during cutting that is associated with nature of machining by plastic deformation. It explains the possibility to achieve minimum surface roughness with ultrasonic finishing with non-rigid equipment. Form and area of tool and workpiece contact depends on static force, power of ultrasonic effect and indenter diameter, thus it can be supposed that effect of these factors is significant. This is consistent with what has been found in previous works [15, 21, 31, 32].

To make more demonstrative the influence of ultrasonic finishing to the surface layer roughness we build the diagrams of the experiment results (Fig. 1). Surface roughness is measured for the premachined workpieces, as well as for the postdeformed surfaces. Multiple measurements are made and average values are calculated for surfaces representing the same parameters of finishing. Analyzing the diagrams (Fig. 1) it can be stated generally that the ultrasonic deforming improves the surface layer finishing by reducing the peak height of the surface asperities by 90–120%. The similar results are obtained by authors [3, 21, 33, 34]. The rougher the premachined surface, the greater the difference between the surface roughness values. The surface roughness decreased to 0.05–0.55 \( \mu \)m (for structural steels Fig.1a and Fig.1b) and 0.1–0.3 \( \mu \)m (for high-speed and tool steels Fig.1c and Fig.1d respectively), depending on the starting quality of the surface and the grade of steel.

Our results show that analytical or numerical methods can demonstrate what way technological ultrasonic finishing parameters influence on surface layer quality including height, pitch, angle of
inclination of irregularities and their relative position. As a result it becomes possible to predict the actual contact surface value of the mating parts.

![Figure 1. The surface layer roughness before and after ultrasonic finishing for high-strength steel: (a) 20Kh1M1F1TR; (b) 17Kh18N9; (c) R6M5; (d) 9KhS.](image-url)

4. Conclusions

The influence of ultrasonic assisted burnishing of different high-strength steel parts is investigated in the present work. The results presented here give proof that surface roughness is affected by the ultrasonic deforming parameters and could be predictable choosing various mode of burnishing. Within this work the obtained results can be summarized as follows:

1. The analytical models to predict the surface roughness after the ultrasonic assisted burnishing process for surfaces are developed.
2. Feed, ultrasonic influence power and static force could be considered as main factors influencing to surface roughness at that feed has the greatest impact among other parameters.
3. Technological parameters of the ultrasonic burnishing are found, which decrease surface roughness from 1.5 µm to 0.1-0.2 µm. It is experimentally proved that feed increase results in surface roughness increase. To low the surface roughness of high-strength steel workpieces it is necessary to increase ultrasonic influence power with simultaneous static force lowering.
4. The analytical models obtained in the present work may be employed in determining the best conditions for ultrasonic assisted burnishing in industrial field.

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