ORIGINAL STUDY

INVESTIGATION OF THE EFFECT OF UNSM TREATMENT MODES ON THE STRUCTURAL AND MECHANICAL PROPERTIES OF THE SURFACE LAYER OF 45 STEEL

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Abstract. *This study investigates the effect of Ultrasonic Nanocrystal Surface Modification (UNSM) treatment on the microstructure, hardness, roughness, and tribological characteristics of 45 steel. The treatment was carried out under static loads of 20, 40, and 60 N. Microstructural analysis was performed using scanning electron microscopy. Mechanical properties were evaluated by instrumental indentation and Vickers hardness methods. It was established that UNSM treatment promotes the formation of a hardened surface layer and grain refinement due to severe plasticdeformation. The maximum instrumental hardness value, HIT, reached 5722.4 N/mm² at a load of 40 N. At the same time, a decrease in surface roughness and friction coefficient was observed. The obtained results demonstrate the high efficiency of UNSM treatment for improving the performance properties of 45 steel.*

Keywords: Ultrasonic Nanocrystal Surface Modification (UNSM), 45 steel, surface hardening, grain refinement, microhardness, surface roughness, tribological properties, severe plastic deformation.

1. Introduction

Ensuring a high service life and reliability of machine friction units is one of the fundamental tasks of modern materials science. 45 steel, possessing an optimal combination of strength characteristics, machinability, and cost-effectiveness, is widely used in the manufacture of critical components such as shafts, axles, and gears [1,2]. However, under conditions of intensive cyclic loading and abrasive wear, conventional bulk heat treatment methods often fail to provide the required surface durability, leading to premature failure of the components [3].

One of the most promising methods for the targeted modification of surface layer properties is the technology of Ultrasonic Nanocrystal Surface Modification (UNSM). This method belongs to the processes of severe plastic deformation (SPD) and is based on the high-frequency impact action of a hard-alloy indenter on the material surface [4,5]. As a result of ultrasonic treatment, refinement of the initial ferrite-pearlite structure to a nanocrystalline state occurs in the surface layer, leading to a significant increase in microhardness [6,7]. Simultaneously, deep compressive residual stresses are formed, which inhibit the propagation of fatigue microcracks [8,9].

According to literature data, ultrasonic nanocrystal surface modification of medium-carbon steels is characterized by high efficiency in improving fatigue strength and microhardness. In particular, study [10] demonstrated that the application of UNSM treatment to S45C-type steel leads to significant grain refinement and an increase in fatigue life due to the formation of compressive residual stresses. It has been established that one of the determining factors affecting the efficiency of UNSM treatment is the magnitude of the static load. When varying the load within the range of 20–60 N, significant changes in the microstructure and mechanical characteristics of the surface layer are observed. The maximum strengthening effect is generally achieved at intermediate load values, whereas further load increase may result in defect accumulation and partial structural degradation [11].

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The efficiency of surface modification of 45 steel is determined by a combination of technological parameters, including static load, oscillation amplitude, and scanning step [12]. There exists an important scientific problem associated with identifying the optimal energy balance: insufficient treatment does not ensure the formation of a stable nanostructured layer, whereas excessive treatment leads to the “over-peening” effect-degradation of the microstructure and formation of microdefects that reduce the adhesion strength of the hardened layer [13].

In the present study, the static load in the range of 20 N, 40 N, and 60 N was selected as the variable parameter. The choice of these values was determined by the necessity to establish the transition threshold from moderate deformation impact to critical deformation conditions. A load of 20 N was considered as a regime of initial strengthening while maintaining high surface quality. Based on the analysis of literature data for medium-carbon steels [14,15], the value of 40 N appears to be the optimal regime for achieving maximum hardness. A load of 60 N was selected to investigate the risks of surface layer degradation and to determine the upper applicability limit of the method for 45 steel [16-19].

Despite the considerable number of studies devoted to UNSM treatment, the effect of static load on the complex interrelated characteristics of the surface layer of medium-carbon steels, including microstructure, microhardness, and surface roughness, remains insufficiently investigated. In particular, there is still no unambiguous understanding of the optimal load range that provides maximum strengthening without degradation of the surface layer.

In this regard, the aim of the present work is to investigate the effect of static load during UNSM treatment on the structural state and performance characteristics of the surface layer of 45 steel.

2. Materials and methods

To investigate the effect of UNSM treatment modes on the properties of 45 steel, an experimental methodology was implemented, including specimen preparation, treatment processing, and subsequent analysis of the structural and mechanical characteristics of the surface layer. 45 steel was used as the initial material. The chemical composition was determined by X-ray fluorescence analysis using a portable X-MET 8000 SMART analyzer (China). The results are presented in Table 1.

Table 1. Chemical Composition of 45 Steel.

Elements	**Fe**	**Cr**	**Ni**	**Ti**	**Cu**	**Mn**	**C**	**W**	**Si**
%	71.10	17.17	9.56	0.62	0.27	0.24	0.11	0.07	0.05

Surface treatment was carried out using the Ultrasonic Nanocrystal Surface Modification (UNSM) method [20] under static loads of 20 N, 40 N, and 60 N. The frequency of ultrasonic vibrations was 20 kHz, while the amplitude was 20 µm. The tool feed rate was 2000 mm/min, and the step between adjacent passes was 70 µm.

The microstructure of the surface and cross-section was investigated by scanning electron microscopy using a TESCAN VEGA 4 microscope (TESCAN, Brno, Czech Republic).

Microhardness was measured by the instrumental indentation method using a FISCHERSCOPE HM2000 hardness tester (Helmut Fischer GmbH, Sindelfingen, Germany) at a maximum load of 50 mN, loading time of 15 s, and holding time at maximum load of 5 s. In addition, measurements were carried out using the Vickers method with a semi-automatic HVS-1MDT-AXY microhardness tester (China) under a load of 0.01 kgf and an indentation time of 10 s.

The surface roughness parameters were determined using an SSR-300 profilometer (Shenzhen, Guangdong, China), and the values of Ra and Rz were calculated.

Tribological tests were carried out according to the ball-on-disk scheme using a TRB^3 tribometer (Anton Paar, Austria) with a ball of 6 mm radius. The tests were performed under a load of 6 N, a sliding speed of 3 cm/s, a wear track radius of 3 mm, and a total friction path length of 60 m.

3. Results and discussion

As a result of the conducted experimental investigations, data characterizing the effect of UNSM treatment modes on the structural state and performance properties of the surface layer of 45 steel were obtained. The evaluation included analysis of the microstructure, microhardness, surface roughness parameters, and tribological characteristics.

The microstructure of the surface and cross-sections of the samples was investigated by scanning electron microscopy. For this purpose, cross-sectional specimens were prepared, and their surfaces were subjected to electrolytic etching in a solution containing 10 g of oxalic acid and 90 g of distilled water in accordance with the procedures described in the literature [21].

Imaging was performed at an accelerating voltage of 20 kV in the secondary electron (SE) mode, which made it possible to analyze in detail the surface morphology, relief, and structural features of the material.

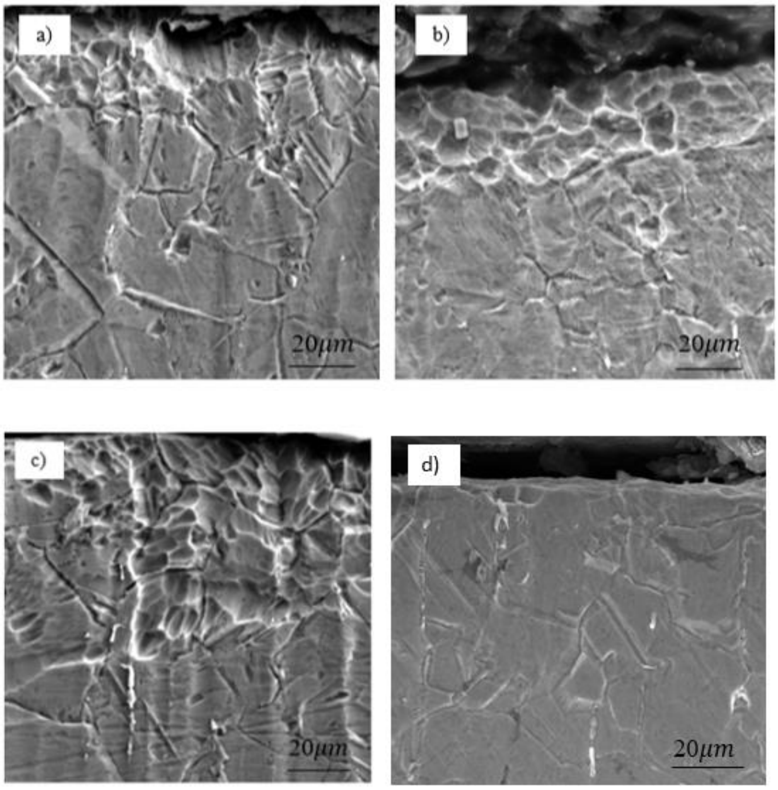

Fig. 1. Results of SEM analysis: (a) U 20N, (b) U 40N, (c) U 60N, (d) initial state.

Based on the SEM analysis results (Fig.1), a comparative investigation of the surface microstructure of the samples in the initial state (d) and after UNSM treatment under loads of 20 N, 40 N, and 60 N (a–c) was carried out.

The initial sample is characterized by a relatively homogeneous surface without pronounced signs of plastic deformation. After treatment under a load of 20 N (a), changes in the surface layer are observed: the grain boundaries become more pronounced, indicating the initial stage of severe plastic deformation. With an increase in load to 40 N (b), the degree of deformation impact increases. A more homogeneous fine-dispersed structure with a higher density of grain boundaries is formed, which indicates active refinement of the surface layer. The most pronounced changes are observed under a load of 60 N (c). The increase in static load during UNSM treatment leads to intensification of plastic deformation and structural refinement, which is the determining factor in improving the microhardness and wear resistance of the material.

To quantitatively evaluate the strengthening of the surface layer after UNSM treatment, microhardness measurements of the investigated samples were carried out using the instrumental indentation method. The values of the mechanical characteristics in the surface zone were determined. The microhardness measurement results are presented in Table 2.

Table 2. Surface Microhardness after UNSM Treatment.

Loads	HM [N/mm^2]	Elastic Modulus, GPa	HV	Hit [N/mm^2]
initial	3196.25	208.76	389.29	4120.67
U 20 N	4246.91	252.77	524.48	5552.55
U 40 N	4361.7	253.9	540.8	5722.4
U 60 N	4357.7	249.4	540.2	5716.1

Analysis of the data presented in Table 2 shows that UNSM treatment leads to a significant increase in surface microhardness compared with the initial state. The obtained results are consistent with the microstructural analysis data, indicating grain refinement and the formation of a hardened surface layer. For the initial state, the hardness value was hit=4120.67 N/mm². After UNSM treatment, an increase in all investigated characteristics was observed. Under a load of 20 N, the hardness increased to 5552.55 N/mm², which is approximately 34.7% higher than the initial value. This indicates an increase in resistance to plastic deformation and contact strength of the surface.

The maximum values were achieved at a load of 40 N: 5722.4 N/mm², indicating the most effective surface strengthening under this treatment condition. With a further increase in load to 60 N, the values remained high at 5716.1 N/mm²; however, they were slightly lower than those obtained at 40 N. This indicates the effect of deformation hardening saturation, in which a further increase in load does not lead to a significant improvement in mechanical properties.

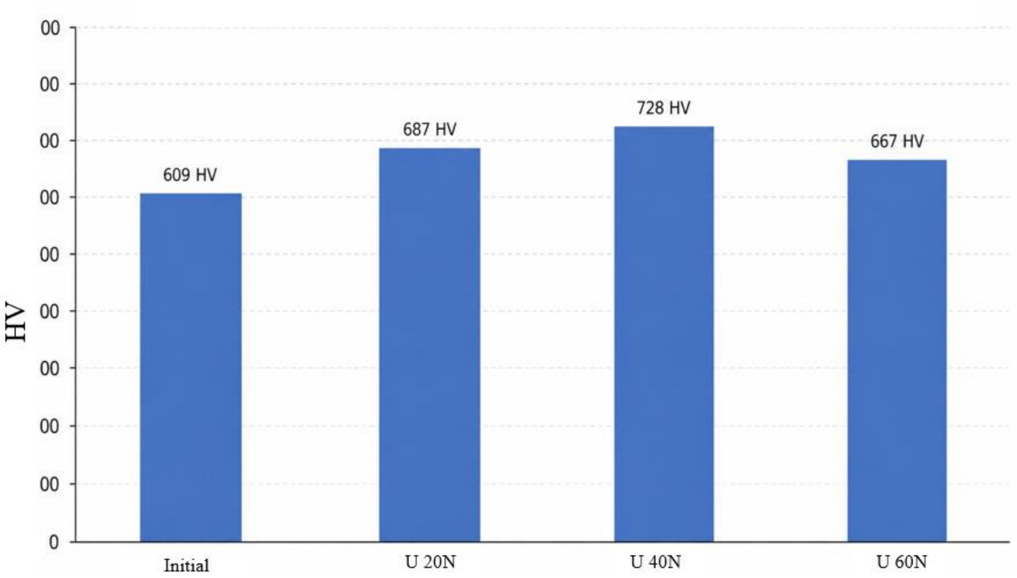

Fig. 2. Dependence of the Microhardness of 45 Steel on Static Load during UNSM Treatment (Vickers Method).

To additionally evaluate the mechanical properties of the surface layer after UNSM treatment, hardness measurements were carried out using the Vickers method with a semi-automatic microhardness tester. The obtained values were as follows: 687 HV at a load of 20 N, 728 HV at 40 N, and 667 HV at 60 N.

Fig. 2 shows the dependence of microhardness on the magnitude of the static load. As can be seen, the hardness increases with increasing load up to 40 N, reaching its maximum value, after which a decrease in hardness is observed with a further increase in load to 60 N.

The obtained dependence indicates the presence of an optimal treatment regime corresponding to a load of 40 N. The decrease in hardness at a load of 60 N is associated with the effect of deformation hardening saturation and the possible development of local defects in the surface layer. Despite the difference in the absolute values obtained by the Vickers method and the instrumental indentation method, the trend in hardness variation depending on the load remains the same. This confirms the reliability of the obtained results and indicates the formation of a hardened layer after UNSM treatment.

To evaluate the effect of UNSM treatment on the surface condition of the investigated samples, surface roughness parameters were determined.

The results of the surface roughness measurements are presented in Table 3.

Table 3. Results of Surface Roughness Measurements of 45 Steel in the Initial State and after UNSM Treatment.

Loads	Ra (µm)	Rz (µm)
initial	0.031	0.538
U 20 N	0.022	0.364
U 40 N	0.027	0.418
U 60 N	0.024	0.343

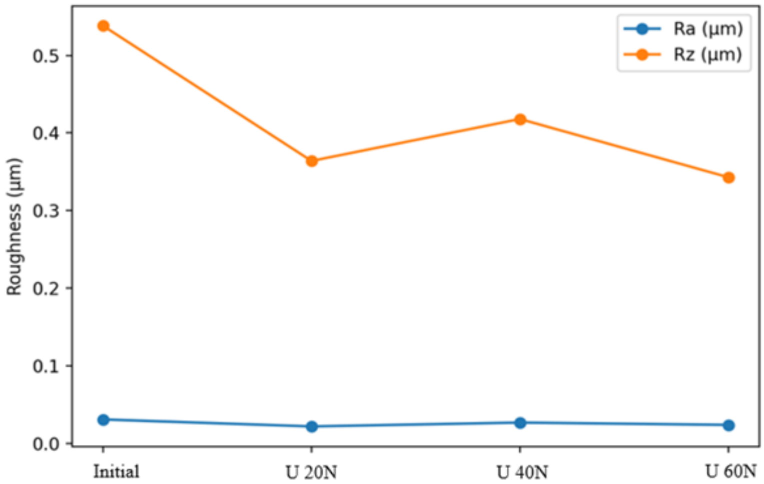

Fig. 3. Variation of Surface Roughness Parameters (Ra and Rz) of 45 Steel in the Initial State and after UNSM Treatment under Different Loads.

Fig. 3 presents the results of surface roughness measurements for the initial sample and the samples after UNSM treatment under loads of 20 N, 40 N, and 60 N. The evaluation was carried out using the parameters of average arithmetic roughness Ra and profile height Rz. For the initial state, the roughness values were Ra=0.031 µm and Rz=0.538 µm, corresponding to the most pronounced surface microrelief. Although UNSM treatment can lead to an increase in roughness due to the impact action of the indenter, in the present case a decrease in roughness parameters was observed. This is associated with the preliminary grinding and polishing of the surface, as well as with the effect of plastic smoothing of micro-irregularities during ultrasonic treatment.

After UNSM treatment under a load of 20 N, a noticeable decrease in roughness was observed: Ra decreased to 0.022 µm and Rz to 0.364 µm, indicating smoothing of surface micro-irregularities due to plastic deformation of the surface layer. With an increase in load to 40 N, the value of Ra increased to 0.027 µm and Rz to 0.418 µm compared with the 20 N regime. This change may be associated with local material redistribution and the formation of additional micro-irregularities under higher impact intensity.

The lowest roughness values were obtained at a load of 60 N: Ra=0.024 µm and Rz=0.343 µm, indicating the most effective surface leveling under this treatment condition. The decrease in roughness after UNSM treatment is confirmed by literature data, according to which severe plastic deformation of the surface layer leads to smoothing of micro-irregularities and reduction of the Ra and Rz parameters [22–24]. The reduction in roughness is caused by plastic flow of the material in the surface layer, resulting in smoothing of micro-irregularities and the formation of a more homogeneous surface relief.

To evaluate the performance characteristics of the surface layer after UNSM treatment, tribological tests were carried out using the ball-on-disk scheme.

The results of the tribological tests are presented in Fig. 4.

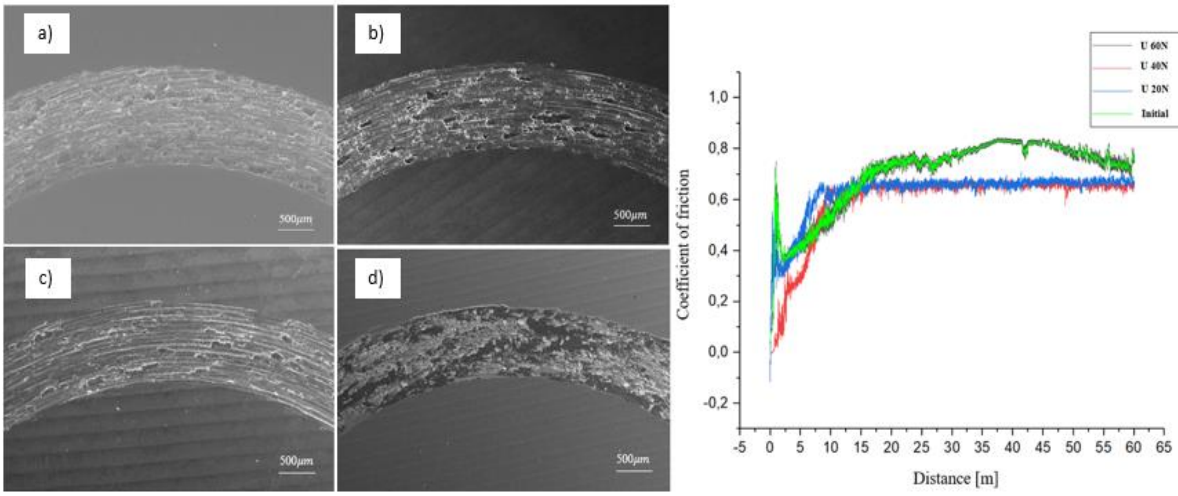

Fig. 4. Results of Tribological Tests of 45 Steel: (a) Initial State; (b) U 20 N; (c) U 40 N; (d) U 60 N.

Analysis of the tribological test results showed that UNSM treatment significantly affects the friction behavior of 45 steel. The initial state is characterized by a high coefficient of friction (μ≈0.697) and pronounced surface wear. After treatment under a load of 20 N, a decrease in the coefficient of friction to μ≈0.630 was observed, which is associated with partial surface leveling and strengthening of the surface layer. The minimum coefficient of friction (μ≈0.597) was achieved at a load of 40 N, indicating the formation of an optimal hardened layer with high wear resistance. With an increase in load to 60 N, the coefficient of friction increased to μ≈0.703, which may be associated with the development of microdefects. The tribological test results confirm that the optimal UNSM treatment regime corresponds to a load of 40 N.

4. Discussion

The obtained results demonstrate the complex nature of the effect of UNSM treatment on the properties of 45 steel. It was established that the increase in microhardness is accompanied by changes in the microstructure and a decrease in surface roughness, indicating the interrelation of the strengthening processes.

The increase in hardness is caused by plastic deformation of the surface layer under the action of repeated impact impulses, leading to grain refinement and the formation of a hardened layer. Simultaneously, smoothing of micro-irregularities occurs, resulting in a decrease in surface roughness.

After UNSM treatment, a decrease in the coefficient of friction and a reduction in surface wear are observed compared with the initial state. The most pronounced effect is achieved at a load of 40 N, at which the minimum coefficient of friction is recorded, corresponding to maximum strengthening and the formation of a homogeneous fine-dispersed structure. With an increase in load to 60 N, the tribological characteristics deteriorate, which is manifested by an increase in the coefficient of friction and greater wear.

The optimal treatment regime (40 N) provides a balance between the intensity of plastic deformation and preservation of the structural integrity of the surface, resulting in maximum improvement of the mechanical and tribological properties. Overall, UNSM treatment is an effective method for surface modification of 45 steel and can be recommended for improving the wear resistance and service life of engineering components.

5. Conclusion

In this work, a comprehensive investigation of the effect of Ultrasonic Nanocrystal Surface Modification (UNSM) treatment modes on the structural state and performance characteristics of the surface layer of 45 steel was carried out. The obtained results confirm the high efficiency of this surface modification method.

According to scanning electron microscopy data, it was established that UNSM treatment leads to intensive structural refinement and the formation of a hardened surface layer. The microstructural changes are caused by the development of severe plastic deformation under repeated impact loading.

The results of microhardness measurements by the instrumental indentation method showed that, compared with the initial state (4120.67), a significant increase in hardness was observed after treatment: up to 5552.55 N/mm² at a load of 20 N, up to 5722.4 N/mm² at 40 N, and up to 5716.1 N/mm² at 60 N. According to the Vickers method, the values were 609 HV (initial state), 687 HV (20 N), 728 HV (40 N), and 667 HV (60 N). The maximum strengthening effect was achieved at a load of 40 N.

Surface roughness analysis showed a decrease in the surface parameters from Ra=0.031 μm and Rz=0.538 μm in the initial state to minimum values of Ra=0.022 μm and Rz=0.364 μm after treatment at 20 N, as well as Ra=0.024 μm and Rz=0.343 μm at 60 N, indicating smoothing of surface micro-irregularities.

The results of tribological tests showed that the coefficient of friction decreased from $\mu \approx 0.697$ for the initial state to $\mu \approx 0.630$ at a load of 20 N and reached a minimum value of $\mu \approx 0.597$ at a load of 40 N. With an increase in load to 60 N, the coefficient of friction increased to $\mu \approx 0.703$, which is associated with the possible formation of defects.

Thus, UNSM treatment provides a comprehensive improvement in the properties of 45 steel, including increased microhardness, reduced surface roughness, and improved tribological characteristics. The optimal treatment regime corresponds to a load of 40 N, at which the best combination of structural, mechanical, and performance properties is achieved.

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Conflict of interest

The authors declare that they have no competing interests.

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