Surface nanocrystallization of low-alloyed steel by multidirectional severe plastic deformation for improved mechanical and tribological properties

Olha Maksymiv, Volodymyr Gurey, Volodymyr Kyryliv, Ihor Hurey, Yaroslav Kyryliv,
and Olha Zvirko

Abstract— **Surface nanocrystallization of the low-alloyed structural 40X steel by severe plastic deformation (SPD) was realized due to mechanical-pulse treatment (MPT) with different modes: unidirectional and multidirectional. The strengthened layers with nanocrystalline structure (NCS) formed in the steel by both mode of deformation were characterized by improved mechanical properties and wear resistance compared with the heat-treated steel. Moreover, multidirectional deformation during MPT resulted in lower grain size of the surface layer, its higher microhardness and the depth of the strengthening, and favourable surface parameters providing higher wear resistance compared with that produced with unidirectional deformation.**

I. INTRODUCTION

Surface nanocrystallization of the structural steels is widely employed to improve their comprehensive properties and enhance residual life of the machine components working under combined action of high loads and aggressive environments. Many different methods based on application of SPD are used to form surface NCS applicable for enhancement of the mechanical and tribological properties of the surface [1]. Among of these methods is MPT based on using high-speed friction between strengthening tool and treated component to generate SPD of the surface layer [2]. It provides simultaneous action of three factors on treated metal: i) severe plastic deformation; ii) surface alloying by components of technological environment supplied to the treatment zone; iii) heat treatment of alloyed and highly deformed surface layer. The degree of SPD is determined by the dislocation density, the mechanism of their nucleation and movement. Multiple cross-sliding is simple and effective mechanism for dislocation multiplication which depends on the direction of the SPD during treatment and its variability [3]. The unidirectional and multidirectional SPD were realized in our study to indicate their effect on the structure and properties of strengthened surface layer with NCS.

II. EXPERIMENTAL

The low-alloyed structural 40X (mass. % 0.4 C, 1.1 Cr, 0.8 Mn, 0.3 Si, 0.01 S, 0.01 P) steel was studied. MPT was carried out on modernized grinding machine. The metal strengthening tools with two geometries of working part were installed instead of grinding wheel: with smooth working surface (Figure 1*a*) – for unidirectional shear deformation and with oppositely directed grooves (Figure 2*b*) – for multidirectional deformation. Mineral oil with the additive of low-molecular polyethylene for simultaneous additional carburizing a steel during MPT was used as a technological environment.

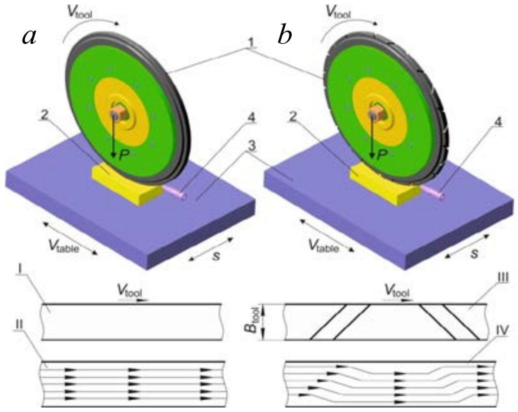

Figure 1: Scheme of MPT of flat specimens by strengthening tools with smooth working surface (*a*) and with oppositely directed grooves (*b*): 1 – tool; 2 – specimen; 3 – table of surface grinding machine; 4 – nozzle for supplying technological environment; (I, III) – working cross-sections and (II, IV) – directions of shear deformations of both tools. V_{tool} is linear speed of strengthening tool, V_{table} – is speed of machine tool's table, f and B_{tool} are transverse feed and width of working part of strengthening tool, respectively.

The structure was investigated using optical microscope Neophot-21. The phase composition and average grain size of the steel's surface layer after MPT were determined by X-Ray analysis. The measurements of microhardness H_μ were carried out using PMT-3 equipment at the load of 50 g on metallographic sections.

The wear behaviour of the specimens of 40X steel after MPT in the tribological system without lubrication was evaluated according to the insert-on-ring scheme at a load of 1 MPa and a sliding velocity of 1 m/s. The ring specimens were made of 40X steel and the inserts specimens were made of grey cast iron GJL-200. Wear resistance was estimated by the weight loss of rings and inserts and compared with specimens of 40X steel after quenching and tempering at 200 °C. The friction coefficient was determined as ratio between friction force

O. Maksymiv (corresponding author: phone: +38(032) 229-62-11; fax: +38(032) 264-94-27; e-mail: okyryliv@yahoo.com), V. Kyryliv (e-mail: kyryliv@ipm.lviv.ua) and O. Zvirko (e-mail: olha.zvirko@gmail.com) are with Department of Diagnostics of Materials Corrosion-Hydrogen Degradation, Karpenko Physico-Mechanical Institute of the NAS of Ukraine, Lviv, 79060 Ukraine.

V. Gurey (e-mail: vgurey@gmail.com) and I. Hurey (e-mail: ihor.hurey@gmail.com) are with Department of Robotics and Integrated Mechanical Engineering Technologies, Lviv Polytechnic National University,Lviv, 79013 Ukraine. I. Hurey is also with Faculty of Mechanics and Technology, Rzeszow University of Technology, Rzeszow, 35-959 Poland.

Y. Kyryliv (yaroslav_kyryliv@ukr.net) is with Department of Organization of Scientific and Research Activities, Lviv State University of Life Safety, Lviv, 79007 Ukraine.

and normal force recorded by dynamometer. Temperature in the friction zone was recorded using a thermocouple.

III. RESULTS AND DISCUSSION

MPT of 40X steel by both strengthening tools resulted in obtaining of gradient surface layer with NCS. The martensite structure after MPT by the tool with smooth working surface and martensite-austenite structure after MPT by the tool with oppositely directed grooves in the strengthened surface layer of 40X steel were revealed. The cumulative value of grain size of α-phase determined by X-ray analysis at the penetration of X-ray beam on ~ 18 μm from the surface was 10.7 nm after MPT by the first tool and 8.6 nm after MPT by the second one. The observed difference in an average grain size in the surface layers treated using different tools was explained by generating SPD with higher degree during MPT by multidirectional deformation which confirmed by a higher dislocation density ρ (0.65 sm^{-2}) and a lattice relative deformation ε (0.086 %) compared with that for unidirectional deformation (ρ= 0.48 sm^{-2} and ε = 0.077 %).

The microhardness of the surface layers of specimens after MPT by both tools differed insignificantly: it was 8.6–9.1 GPa; however, it was remarkably higher than that of the base material (1.7 GPa) (Figure 2*a*).

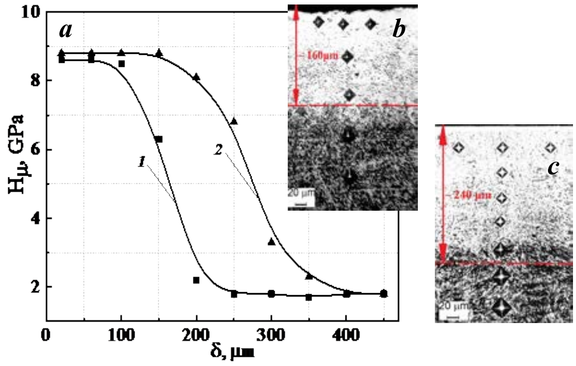

Figure 2: Microhardness (*a*) and structure (*b, c*) of the surface layer of 40X steel after MPT by strengthening tool with smooth working surface (*curve 1, b*) and with oppositely directed grooves (*curve 2, c*).

The depth of the hardened layer with surface NCS after MPT by the tool with oppositely directed grooves was higher and equal to ~ 240 μm (Figure 2*c*) compared with 160 μm (Figure 2*b*) after MPT by the other tool. The growth of the depth of strengthening was achieved due to multidirectional deformation generating in the strengthened surface layer, which simplified the nucleation of dislocations and structure fragmentation [4].

MPT by both strengthening tools provided enhancement of the wear resistance of the friction pair: by 2.4 times using strengthening tool with smooth working surface and by 2.1 times – with oppositely directed grooves in comparison with the heat-treated steel. It should be noted that inserts in the friction pairs were not subjected to MPT, however, their weight loss was also decreased (Figure 3*a*).

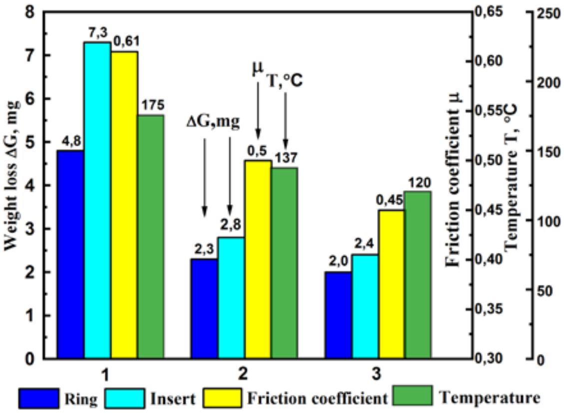

Figure 3: Wear resistance of the friction pair 40X steel-cast iron GJL-200: weight loss of the elements of friction pair (blue and cyan); friction coefficient (yellow) and temperature (green) in the friction zone: heat-treated (1), after MPT after MPT by strengthening tool with smooth working surface (2) and with oppositely directed grooves (3).

The decrease of friction coefficient and temperature in the friction contact zone of pairs can be explained by the formation of NCS in strengthened surface layer, changing phase composition, stress state and increasing surface microhardness, which contributed to the significant improvement of wear resistance of the studied friction pairs.

The roughness of the specimens after MPT by unidirectional SPD was in 1.3 times higher than that of the specimens after the treatment by multidirectional one. The location of the peaks is more uniform for the surface after MPT by multidirectional SPD.

Therefore, the multidirectional SPD is considerably more efficient at generating surface NCS compared with the unidirectional deformation of simple shear, because of providing higher microhardness and thickness of the strengthened surface layer, lower friction coefficient and temperature in the contact zone, and favourable surface parameters, and, as a result, higher wear resistance of the steel with surface NCS.

REFERENCES

[1] Quintino, L. "Overview of coating technologies". *Surface Modification by Solid State Processing* (pp. 1-24). Elsevier: Cambridge, UK, 2014.

[2] Nykyforchyn, H.,*et al.*, "Mechanical fabrication methods of nanostructured surfaces". *Handbook of Modern Coating Technologies. Fabrication Methods and Functional Properties* (pp. 25-67). Elsevier: Amsterdam, The Netherlands, 2021.

[3] Van Swygenhoven, H., *et al.* "Nucleation and propagation of dislocations in nanocrystalline fcc metals". *Acta Materialia* 54(7), 1975-1983, 2006.

[4] Grosdidier, T., *et al.*, "Recent developments in the application of surface mechanical attrition treatments for improved gradient structures: Processing parameters and surface reactivity". *Materials Transactions* 60(7), 1344-1355, 2019.