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Influence of vibratory-centrifugal strain hardening on surface quality of cylindric long-sized machine parts

Z.A. Stotsko [a], B.I. Sokil [b], J.M. Kusyy [c], V.G. Topilnytskyy [a]
[a] Department of electrical machine building
[b] Department of theoretical mechanics
[c] Department of technology of machine building
Institute of Engineering Mechanics and Transport, Lviv Polytechnic National University, 12, St. Bandery Str., Lviv, 79013, Ukraine
* Corresponding author: E-mail address: stotsko@polynet.lviv.ua

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Analysis and modelling

ABSTRACT

Purpose: The objective of this work is to develop mathematical models based on experimental data that enables us to predict the values of physico-mechanical parameters of surface quality of MLSMP (microhardness, depth of hardened layer, level of hardening) when VCSH is applied.
Design/methodology/approach: For all round studying of the effect of main technological factors on physico-mechanical parameters of MLSMP surface layer quality (microhardness, depth of hardening layer, level of hardening) it is expedient to use the method of factor planning with applying plane 2k, where k is the number of variation factors.
Findings: The obtained empiric relations enable us to predict the values of physico-mechanical parameters of MLSMP made of alloyed steels (especially of 40XH2MA steel) depending technological parameters of VCSH, the parameters being within their ranges.
Research limitations/implications: The effect of technological parameters of VCSH and that of constructional dimensions of the hardening device equipped with electromagnetic drive and elastic system parameters of MLSMP surface hardening qualities is ambiguous.
Originality/value: The hardening devices equipped with electromagnetic drive and elastic systems for treating internal and external MLSD surfaces are designed to solve the problem.
Keywords: Computational materials science; Vibratory-centrifugal hardening (VCSH); Metal long-sized machine parts (MLSMP)

1. Introduction

The experience in operating machines, devices, apparatus convincingly affirms that their reliability and durability depend on the character of the contact of conjugated parts with each other or with liquid, gaseous or other kinds of media; this determines the state of surface layers of conjugated parts [1, 2]. It is known that physico-mechanical parameters of surface quality are the prevalent factor both in forming stress and structural state and in increase in durability and ensuring reliability of the articles manufactured. They also determine wear resistance, strength, corrosive resistance and other qualities of machine parts.

The problem of the technology of treatment of long-sized ($l \geq 5d$) articles, whose shapes are of bodies of revolution (the articles being non-rigid ones) occupies an especial place in the general set of technological tasks concerning the improvement of performance characteristics of machine parts and units; ensuring their reliability and increasing durability by means of technological methods of controlling parameters of surface quality (especially in finishing operations) determine working resource of units and machines containing such parts. The effect of technological parameters of finishing treatment of metal long-sized machine parts (MLSMP) and units on physico-mechanical parameters of surface quality is investigated and described not enough in sci-tech literature. Recommendations concerning the choice of treatment modes for proper elaborating vibratory hardening operations are lacking (this concerns modern productive technologies of manufacturing metal long-sized cylindrical articles).

On the basis of works written by Parshev D.D., Shneider Yu.H., Proskryakov Yu.H., Yaschericin P.A., Chepa P.A., Pshibylskyy V. and other scientists, the following conclusions are drawn:

- as to the improvement of working characteristics of long-sized rod-shaped articles, the method of surface plastic deformation (SPD) treatment is of the most prospect among the known strengtening finishing operations;
- presently known kinds of hardening finishing operations for MLSP as well as the equipment for their carrying out are not effective enough.

As to the efficiency of application, vibratory methods of strengtening finishing treatment deserve attention among the group of SPD methods. By efforts of foreign scientists and those of our country, a number of vibratory methods of strengterning treatment were elaborated; these methods gave us possibilities to increase labour productivity and to form regular microrlief of surface. However, as it follows from theoretico-experimental investigations and from the experience of industrial application of vibrations for strengtening finishing operations, the energy of deformation is restricted by the mass and the acceleration in motion of individual treating body (a steel bead or a roller); this occurs practically in all cases, and this sometimes prevents from optimal values of operating parameters. Besides, vibratory treatment as well as almost all methods of this kinds of dynamical deformating SPD is of small efficiency, when internal surfaces of long-sized tubular articles are treated.

2. Statement of the problem

The objective of this work is to develop mathematical models based on experimental data that enables us to predict the values of physico-mechanical parameters of surface quality of MLSMP (microhardness, depth of hardened layer, level of hardening) when VCSH is applied.

3. Techniques of experimental investigations

Surveying and diligent analysis of literature affirmes that responsible long-sized machine parts shaped as bodies of revolution which operat in the conditions of alternate and impact stresses, intensive wear are, as a rule, matle of alloy-free steels which have carbon contents 0.3 – 0.5 % (named heat-hardenable carbon steels) and alloyed quenched-and-tempered steels. Contents of alloys determines the depth of quenched layer during thermal treatment and physico-mechanical and technological properties of the workpiece.

The results of experimental investigations of the specimens prepared from alloyed chromium-nickel-molybdenum steel 40XH2MA, the chemical composition of which is C – 0,40 %, Si – 0,25 %, Mn – 0,65 %, Cr – 0,85%, Ni – 1,58 %, Mo – 0,23 %, P – 0,024 %, S – 0,022 % are analyzed in this paper.

The hardening devices equipped with electromagnetic drive and elastic systems for treating internal and external MLSD surfaces are designed to solve the problem [4]. The conceptual design of the special electromagnetic vibratory-centrifugal hardening device equipped with the drive and the elastic systems is presented in Fig. 1

The laboratory electromagnetic vibratory-centrifugal hardening device equipped with the drive and the elastic systems which is designed for finishing internal MLSMP surfaces, consists of two elastic-vibrating systems containing the rotor 2 and the stator 3 with three uniformly located on circle magnet coils 4 of the electromagnetic drive, disk separators 5, 6 with deforming bodies 7 (in this case there are the steel quenched beads) and the common element – the base 1. The elements of elastic-vibrating systems are connected with each other by elastic-torsion rods 8, 9. The hardening device is based on the MLSMP treated surface 11 by the guiding rubber rollers 10. When voltage is supplying to the magnet coils of the stator 3, the rotor 2 is attracted in turn to each coil by electromagnetic force. Antiphase oscillation of the rotor and the stator are transmitted to connected with them disk separators 5, 6.
They begin to realize rotational-oscillatory movements accompanied with internal surface impacts by the protuberance deforming bodies 7. In each moment, contact of the article and the impact hardeners occurs with impact through small amount of the beads located along tne generating lines of a treating part surface that results in development of great contact stresses in the material of the treated part in contact places and hardening of surface layer.

Experimental investigations for determining physico-mechanical parameters of surface quality has been carried out with the use of the ring-shaped specimen made of 40XH2MA steel. The depth of hardening layer has been evaluated according to microhardness Hμ distribution in the surface layer. Microhardness Hμ has been determined by the method of impress resumption.

The level of hardening has been calculated using the following formula [5]:

$$\varepsilon = \left(HM_{sur} - HM_{inp}\right) \cdot 100 / HM_{inp} \; [\%] \tag{1}$$

where:
HM_{sur} is microhardness of hardened surface;
HM_{inp} is microhardness of matrix (basic material).

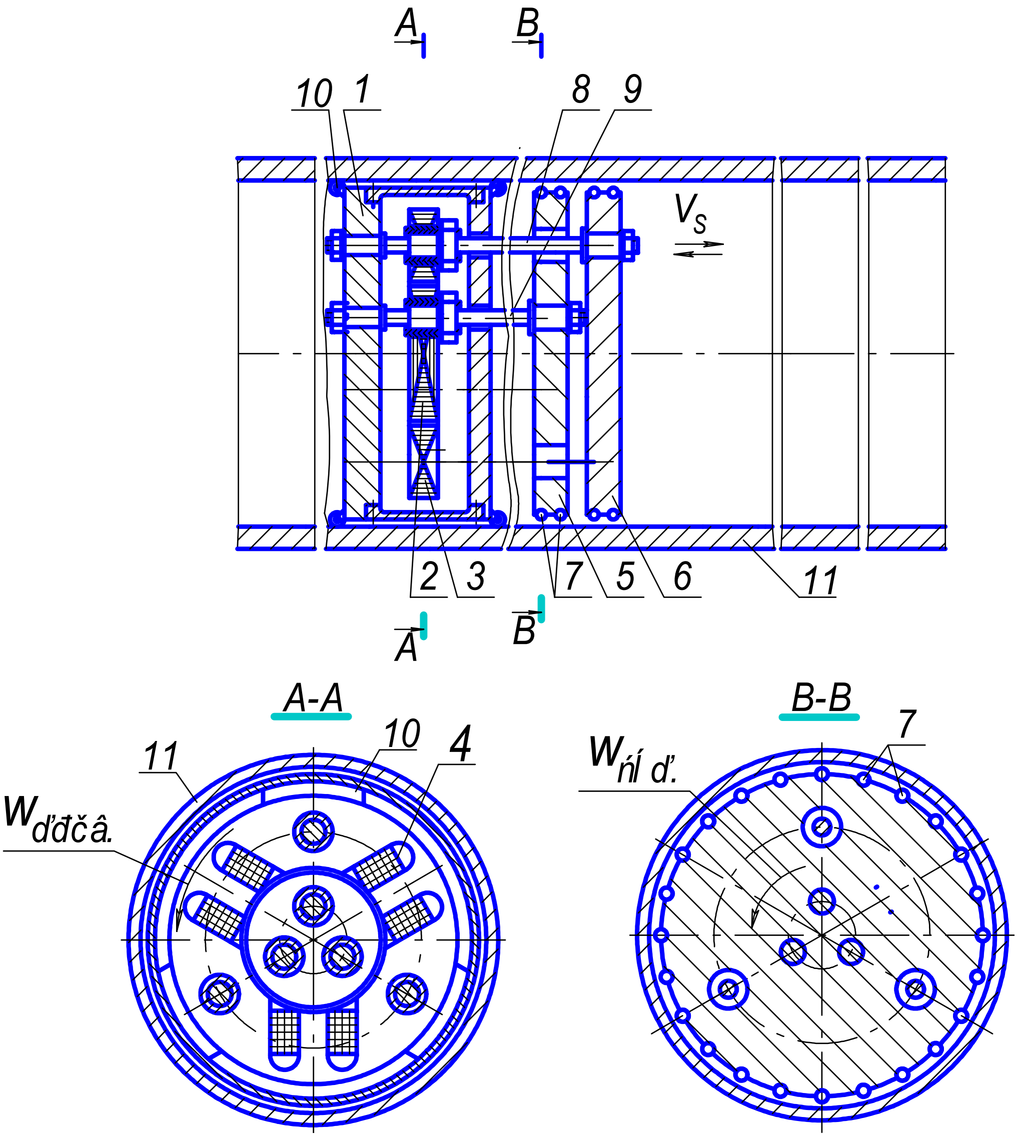


Fig. 1. The conceptual design of the laboratory electromagnetic vibratory-centrifugal hardening device equipped with the drive and the elastic systems

For all round studying of the effect of main technological factors on physico-mechanical parameters of MLSMP surface layer quality (microhardness, depth of hardening layer, level of hardening) it is expediant to use the method of factor planning with applying plane 2^k, where k is the number of variation factors [6, 7]. The process of forming physico-mechanical parameters of MLSMP surface layer quality is due to the influence VCSH main technological conditions: speed of feed Vs, summary rigidity of parts of elastic systems of electromagnetic hardening device c_{sum}, number of passes n, mass of the hardening working body m and current I in the magnet coils determined force of the electromagnetic drive elements attraction.

Summary rigidity of elastic systems parts is expressed as:

$$c_{sum.} = c_{\mathrm{i}} \cdot \frac{m_{drive}}{m} \tag{2}$$

where m_{drive} is mass of the drive element (rotor or stator);
c_i is rigidity of i^{th} part of elastic system determined by Formula [8]:

$$c_i = \frac{12 \cdot E \cdot J \cdot n}{\ell_i^3} \tag{3}$$

where:

E is modulus of elasticity of the material of torsion rods, Pa;
l_i is length of the torsion rod working part, m;
n is number of the torsion rods;
J is moment of inertia of the torsion rod cross-section relative to central axes, m^4.
($J = \frac{\pi \cdot d_i^4}{64}$, where d_i is diameter of the torsion rod, m).

Thus:

$$c_{звед.} = \frac{3 \cdot \pi \cdot E \cdot d_i^4 \cdot n}{16 \cdot \ell_i^3} \cdot \frac{m_{drive}}{m}.$$

4. The effect of technological parameters of VCSH on the forming of physico-mechanical parameters of surface quality of MLSP made of alloyed steels

When treating specimens made of 40XH2MA steel by means of electromagnetic vibratory-centrifugal hardening device, we controlled physico-mechanical parameters of MLSD – specimen surface quality: the maximum value of microhardness HM, the depth of hardened surface layer a, and the degree of hardening ε under different treating conditions. In order to cut down expenses of labor, experimental researches were conducted applying matrix plans of fractional factor experiment 2^{5-2}. The ranges of the factors are determined on the basis of trial passes during VCSH treating.

The processing of results are carried out according to the technique proposed in [6, 7]. After checking the uniformity of reproducibility variances in experiments according to Kohren's criterion, ofther checking the significance of regression rates according to Student's criterion and the adequacy of mathematical models according to Fisher's criterion, mathematical relations for determination physico-mechanical parameters of surface quality (presented in code variables) are the following:

$$Y_{H\mu} = 7{,}892 - 0{,}0316 \cdot X_1 + 0{,}0101 \cdot X_2 + 0{,}0334 \cdot X_3 + \\ + 0{,}0167 \cdot X_4 + 0{,}0145 \cdot X_5 - 0{,}0132 \cdot X_1 \cdot X_2 + 0{,}0223 \cdot X_1 \cdot X_5 \quad (5)$$

$$Y_a = -1{,}6475 - 0{,}2315 \cdot X_1 + 0{,}2503 \cdot X_2 + 0{,}3619 \cdot X_3 + \\ + 0{,}0849 \cdot X_4 + 0{,}1496 \cdot X_5 - 0{,}0997 \cdot X_1 \cdot X_2 + 0{,}0649 \cdot X_1 \cdot X_5 \quad (6)$$

$$Y_\varepsilon = 3{,}0107 - 0{,}2207 \cdot X_1 + 0{,}2253 \cdot X_3 + 0{,}1495 \cdot X_4 + \\ + 0{,}1268 \cdot X_5 - 0{,}1105 \cdot X_1 \cdot X_2 + 0{,}1572 \cdot X_1 \cdot X_5 \quad (7)$$

From the obtained relations (5) – (7) it follows:

- parameters essentially affecting the parameter of microhardness Hμ of the articles made of 40XH2MA steel are the following (given in descending order as to there effects):
  - the number of passes (factor X_3),
  - the speed of feed (factor X_1),
  - interaction between factor X_1 and factor X_5,
  - the mass of the working body of the hardener (factor X_4),
  - the value of current in the magnet coils (factor X_5),
  - interaction between factor X_1 and factor X_2;
- parameters essentially affecting the depth a of a treated layer of an MLSMP made of 40XH2MA steel are the following (given in descending order):
  - the number of passes (factor X_3),
  - summary rigidity of the parts of the elastic systems (factor X_2),
  - the speed of feed (factor X_1),
  - the value of current in the magnet coils (factor X_5);
- parameters essentially affecting the level of hardening of a treated layer of an MLSMP made of 40XH2MA steel are the following (given in descending order):
  - the number of passes (factor X_3),
  - speed of feed (factor X_1),
  - interaction between factor X_1 and factor X_5,
  - the mass of the working body of the hardening device (factor X_4),
  - the value of current in the magnet coils (factor X_5),
  - interaction between X_1 and X_2.

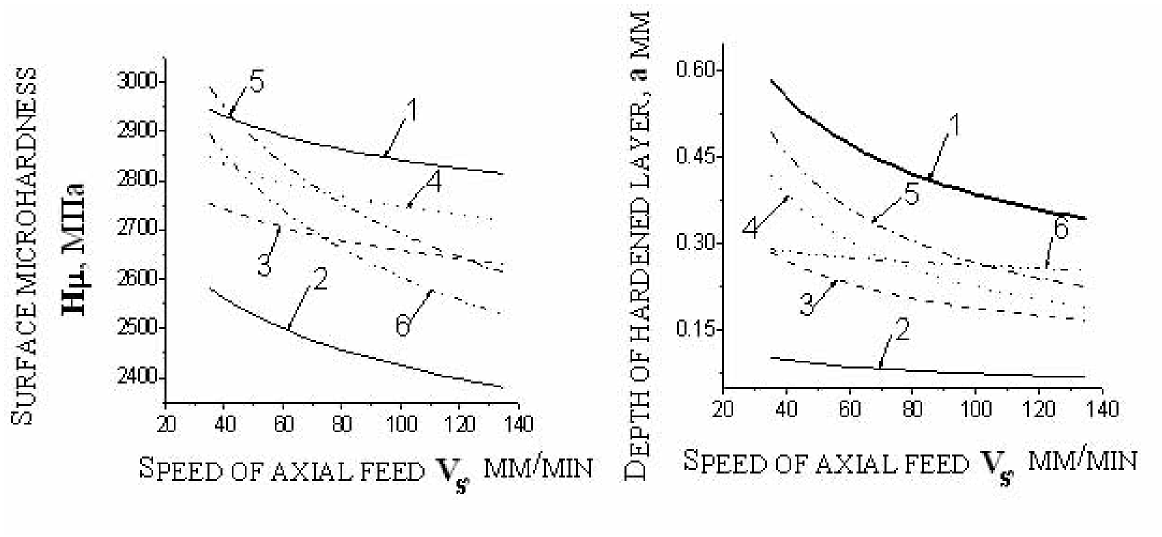
When only significant coefficients of regression, as a function of main technological parameters, are taken into account mathematical formulas for determining physico-mechanical parameters of the quality of surfaces VCSH treated by means of an electromagnetic vibrohardenin device with elastic systems are the following.

$$H\mu = e^{4{,}9865} \cdot (V_S)^{0{,}5893 - 0{,}0482 \cdot \ell n(c_{звед.}) + 0{,}1293 \cdot \ell n(I)} \cdot (c_{звед.})^{0{,}2286} \times \\ \times (n)^{0{,}0608} \cdot (m_{2(4)})^{0{,}0654} \cdot (I)^{-0{,}4902} \quad (8)$$

$$a = e^{-29{,}146} \cdot (V_S)^{4{,}4416 - 0{,}3638 \cdot \ell n(c_{звед.}) + 0{,}3763 \cdot \ell n(I)} \cdot (c_{звед.})^{2{,}1554} \times \\ \times (n)^{0{,}6586} \cdot (m_{2(4)})^{0{,}3323} \cdot (I)^{-1{,}0063} \quad (9)$$

$$\varepsilon = e^{-18{,}796} \cdot (V_S)^{4{,}992 - 0{,}4032 \cdot \ell n(c_{звед.}) + 0{,}9115 \cdot \ell n(I)} \cdot (c_{звед.})^{1{,}7056} \cdot (n)^{0{,}41} \cdot (m_{2(4)})^{0{,}571} \cdot (I)^{-3{,}36} \quad (10)$$

On the basis of Formulas (8) – (10), a series of graphic charts of the effect of main technological parameters of VCSH method on physico-mechanical parameters of surface quality (microhardness, depth of hardened layer, and level of strengtening) under the application of hardening devices equipped with electromagnetic drive can be plotted. The most important effects of V_S on microhardness and on the depth of hardening layer under constant values of c_{sum}, n, m_{drive}, and I are graphically show in Fig.2.



a) b)

Fig. 2. Surface microhardness $H\mu$ (a) and depth of hardened layer *a* (b) as functions of speed of axial feed of hardening device V_S obtained for articles made of 40XH2MA steel. The values of constants are the following:
1 - $c_{sum} = 7.471 \cdot 10^5$ *N/m*, n = 3 *passes*, $m_{2(4)} = 3.0$ *kg*, I = 1.25 *A*;
2 - $c_{sum} = 3.317 \cdot 10^5$ *N/m*, n = 1 *pass*, $m_{2(4)} = 1.8$ *kg*, I = 0.75 *A*;
3 - $c_{sum} = 7.471 \cdot 10^5$ *N/m*, n = 1 *pass*, $m_{2(4)} = 3.0$ *kg*, I = 1.25 *A*;
4 - $c_{sum} = 7.471 \cdot 10^5$ *N/m*, n = 3 *passes*, $m_{2(4)} = 1.8$ *kg*, I = 1.25 *A*;
5 - $c_{sum} = 7.471 \cdot 10^5$ *N/m*, n = 3 *passes*, $m_{2(4)} = 3.0$ *kg*, I = 0.75 *A*;
6 - $c_{sum} = 3.317 \cdot 10^5$ *N/m*, n = 3 *passes*, $m_{2(4)} = 3.0$ *kg*, I = 0.75 *A*.

The following conclusions can be drawn from analyzing experimental results, regression relations (8) – (10), and graphs (Fig. 2b):

- When the purpose of treatment is improvement to improve wear resistance of MLSMP made of alloyed steels, especially 40XH2MA steel, through the increase in microhardness HM and in the level strengtening ε, the optimal technological parameters are: $V_S = 35$ mm/min, $c_{sum} = 7.471 \cdot 10^5$ N/m, $n = 3$ passes, $m_{2(4)} = 3.0$ kg, $I = 0.75$ A.
- When it is necessary to maximally increase fatigue strength, i.e. to ensure maximum values of the depth of the layer strengthened *a* in the surface layer of MLSMP, the following optimal parameters are recommended for VCSH treatment when an electromagnetic vibrostrengtening device is used: $V_S = 35$ mm/min, $c_{sum} = 7.471 \cdot 10^5$ N/m, $n = 3$ passes, $m_{2(4)} = 3.0$ kg, $I = 1.25$ A.
- When it is necessary to ensure maximal labor productivity in a technological strengthening operation, the improvement of performance of MLSP (increasing HM, *a* and ε) being retained, and when the number of passes of the hardening device with elastic systems is equal to three, the following parameters should be used for treatment: $V_S = 135$ mm/min, $c_{sum} = 7.471 \cdot 10^5$ N/m, $m_{2(4)} = 3.0$ kg, $I = 1.25$ A.
- When the number of passes is equal to one, the maximal labor productivity during the treatment of MLSD by means of the hardening device with elastic systems (desirable physico-mechanical parameters of surface quality of being ensured) can be obtained under the following technological parameters: $V_S = 135$ mm/min, $c_{sum} = 7.471 \cdot 10^5$ N/m, $m_{2(4)} = 3.0$ kg, $I = 1.25$ A.

5. General conclusions

The effect of technological parameters of VCSH and that of constructional dimensions of the hardening device equipped with electromagnetic drive and elastic system parameters of MLSMP surface hardening qualities is ambiguous.

The number of passes, summary rigidity of elastic systems parts, speed of axial feed are the determinants of the achievement of the required hardened layer depth.

Surface microhardness and the level of hardening are, mainly, determined by the number of passes, speed of axial feed of the hardening device, and the correlation between the speed of feed and the value of current in magnet coils.

The obtained empiric relations (8) – (10) enable us to predict the values of physico-mechanical parameters of MLSMP made of alloyed steels (especially of 40XH2MA steel) depending technological parameters of VCSH, the parameters being within their ranges.

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