The effect of combined processing schedules on the value and nature of residual stresses in the surface layer of cylindrical friction pairs

S Fedorov, A Albagachiev, M Isaenkova, A Yakovleva, V Zaripov and R Minushkin

1 Bauman Moscow State Technical University, 5 Second Baumanskaya Street, Moscow, 105005, Russian Federation
2 Mechanical Engineering Research Institute of the Russian Academy of Sciences (IMASH RAN)
3 National Research Nuclear University MEPhI
4 MIREA - Russian Technological University

Email: yakovleva525@mail.ru

Abstract

The purpose of the paper was to study the macroscopic stresses after the combined processing. The combined processing essentially consists in the sequential implementation of electromechanical processing and diamond smoothing. We obtained the formula for calculating the residual stresses arising in the surface layer after the combined processing. For convenience of calculations, a computer program was developed to calculate the parameter for estimating the residual stresses in the language Visual Studio 2017 C#. To determine the residual macrostresses, the standard x-ray method \( \sin^2 \psi \) was used. The study was performed on samples of steel 40X.

Introduction

The operation of machines and mechanisms requires the work of friction pairs, i.e. rods, pistons, plugs, seats, spools, pins, rolls for grinding non-metallic materials. These are parts of engines, pumps, spinning machines including guide rollers, thread guides, tensioning devices, as well as cultivators and other machines, which are used in construction, automotive equipment, agricultural machinery, etc. Most of them are cylindrical [1-3]. Due to the low operational reliability of cylindrical friction pairs, the consumption of spare parts is high [2-7].

The reliability of the machines is directly related to the quality of the surface layer, which is characterized by geometrical and physico-mechanical parameters. The quality of the surface layer is crucial for the operational properties, i.e. wear resistance, corrosion resistance, contact fatigue resistance, etc. [2, 3, 8-12].

In many cases the level of residual stresses is an important parameter that determines the quality of the surface layer of products [4, 6, 13].

In the surface layer of the metal there are always various defects that serve as crack nuclei, therefore, the reliability of parts is determined mainly by the value of crack propagation work [1, 4, 8, 9, 14]. The compressive residual stresses appearing on the surfaces of parts due to various
technological methods prevent the nucleation and propagation of fatigue microcracks, increasing their work. Therefore, for parts operating under conditions of slipping friction, especially in cases of fatigue and abrasive wear during operation, it is important to make a surface layer with compressive residual stresses [4, 5, 9, 10-17].

Description of the Experiment

In view of the foregoing, the technology of combined processing (CP) has been developed. The combined processing essentially consists in the sequential implementation of electromechanical processing and diamond smoothing [5, 12]. Using this technology, it is possible to technologically control the properties of the working surfaces of cylindrical parts and make compressive residual stresses on the surface [1, 4, 6, 12].

To test this assumption, the value of tangential residual stresses was theoretically calculated. In the present CP embodiment, the value of residual stresses will be composed of the following components:

\[ \sigma_{\text{res}} = \sigma_{\text{temp}} + \sigma_{\text{ph}} + \sigma_{\text{mech}} \]  

(1)

where \( \sigma_{\text{temp}} \) is the residual temperature stress, \( \sigma_{\text{ph}} \) is the structural phase residual stress, and \( \sigma_{\text{mech}} \) is the mechanical residual stress.

Examining in detail each component of formula (1), it is possible to derive a general view of the dependence of the tangential residual stress value on the combined processingschedules:

\[ \sigma_{\text{res}} = \alpha \frac{2 \alpha_m (P_g V_p + IL)}{\lambda_2 l_{\text{tool}}^2 \sqrt{\pi}} \sqrt{a e^\left(\frac{z^2}{4at}\right)} - \frac{P_g}{\pi} \left[ \frac{3}{2} \left( \frac{1}{l_{\text{tool}}^2 + z^2} \right) - \frac{1,2}{l_{\text{tool}}^2} \ln \left( \frac{z}{2l_{\text{tool}}} \right) - \frac{3}{10l_{\text{tool}}^2} \right] + E \left( 1 - \frac{P_1}{\sqrt{\rho_2}} \right) \]  

(2)

\( z \) is the current coordinate, \( m; \) \( \alpha_\text{e} \) is the heat sharing ratio (Sharon's heat absorption coefficient); \( P_g \) is the reduced pressure force of the tool during the combined processing, \( H; \) \( V_p \) is the sample rotation speed, \( m / \text{min}; \) \( I \) is the current strength, \( A; \) \( U \) is the voltage, \( B; \) \( \lambda_2 \) is the thermal conductivity of the sample material, \( \text{Wm}^{-1}\text{K}^{-1}; \) \( l_{\text{tool}} \) is the length of the tool contact with the work surface (the width of the roll electrode), \( m; \) \( \alpha_m \) is the thermal conductivity of the sample material, \( m^2/s; \) \( t \) is the contact time, \( s; \) \( \rho_1, \rho_2 \) is the density of the sample material and tool, respectively, \( \text{kg/m}^3; \) \( E \) is the modulus of elasticity of the sample material, \( \text{Pa}. \)

For convenience of calculations, a computer program was developed to calculate the parameter for estimating residual stresses by formula (1) in the language Visual Studio 2017 C#. All data is entered into a table, and at the output we obtain the value of the parameter of residual stresses depending on the combined processing schedules.

Experimental Result

An x-ray evaluation method was used to verify the theoretical values obtained.

A BRUKER D8 Discover X-ray diffractometer (Fig. 1) using chromium K-radiation was used to study the phase composition of the sample material and to measure the residual macrostress. Data processing was carried out using the software DIFRAC.EVA and DIFRAC.LEPTOS.

For this purpose, steel 40X samples were made with a diameter of 40 mm, a length of 200 mm and treated with a combined processing in the following schedules.

Electromechanical processing: current \( I = 2000 \text{ A}; \) voltage \( U = 4 \text{ V}; \) contact roller pressure \( P_1 = 300 \text{ N}; \) part rotation speed is \( 2.0 \text{ m / min}; \) feed \( S_1 = 1.2 \text{ mm / rev}. \) Diamond smoothing: the pressure of the diamond smoother \( P_2 = 300 \text{ N}, \) feed \( S_2 = 0.02 \text{ mm / rev}, \) the radius of the diamond smoother is 1 mm.
In accordance with GOST 16865-79 and with ASTM E2860-12, the most accurately residual macrostresses are measured in the precision X-ray spectrum area, i.e. the lines located at large angles of 2Θ, which also allow the use of large angles of rotation of the samples. To determine the residual macrostresses, the standard x-ray method sin²ψ was used [18, 19]. The location of the investigated surface areas on the samples in which the measurement of stress was performed is schematically shown in Fig. 2. The size of the investigated area is determined by the size of the collimator and is ~ 5 mm².

In this case, to determine the value of the residual stresses, a line (211) (2Θ = 156.084 °) was recorded at different angles of rotation (Fig. 3, 4). To approximate and calculate the obtained lines, the Pearson VII function was used.
Fig. 3. X-ray diffraction spectrum of the rod (the material of the anode of the x-ray tube is Cr)

Fig. 4. X-ray line (211) for different angles of sample rotation

The interplanar distances, as well as the degree of deformations, are calculated from the angular positions of the X-ray lines, using the Wulff-Bragg formula. Further on, we plotted a graph of the dependence of the degree of deformations ($\varepsilon$) on $\sin^2\psi$ (where $\psi$ is the angle of sample rotation). In the general case, the dependence graph has a linear character ($\varepsilon=a\sin^2\psi+b$), from the slope coefficient of which the value of the residual macrostress is calculated (Fig. 5). The error in the determination of macrostress is the deviation of the values obtained from the linear dependence [20, 21].
During the study, the following results were obtained: according to the obtained phase analysis data, the material of the studied samples is α-phase (bcc-structure) of iron.

The stresses at the sample control points (Fig. 2) are presented in the table.

| Stresses at sample control points |
|----------------------------------|
| Stress, MPa                      |
| Axial                            |
| Point 1  | -1901,2±87,7                  |
| Point 1.1 | -1774,2±91,5                  |
| Point 2  | -1738,7±129,1                 |
| Point 2.1 | -2019,8±172,5                 |
| Point 3  | -760,5±14,6                   |
| Point 3.1 | -806,1±43,4                   |
| Tangential                        |
| -866,9±21,5                      |
| -1409,1±44,1                     |
| -1420,0±186,3                    |
| -1127,5±114,9                    |
| -975,6±41,3                      |
| -455,7±17,8                      |

This method allows us to determine the numerical value of axial and tangential residual stresses.

Conclusions

In this research, macrostresses have been studied, as they appear to be the most significant from the point of view of practical application.

Comparing the results of theoretical and practical research, we arrive at a conclusion that the combined processing creates favorable compressive residual stresses on the surface of the samples under study. This is evidenced by the sign “-” before the numerical values of the axial and tangential stresses of the experimental studies and the tangential residual stresses in the theoretical study. The convergence of the results is 89%.

Furthermore, a positive feature of the combined processing is the fact that the value and nature of residual stresses obtained in previous operations do not affect the formation of the value and sign of residual stresses in the CP process, and the method presented may be a barrier to technological heredity.

Reference list

[1] L. Fedorova, S. Fedorov, A. Sadovnikov, Y. Ivanova, M. Voronina Abrasive wear of Hilong Bo TN hardfacings VII International conference on mechanical engineering and applied composite materials. Hong Kong, China, November 23-24, 2017.

[2] A.S. Vasilev Controlled Forming of Machine Components Operating Characteristics. Procedia Engineering, 2016, no. 150, pp. 975–979. DOI: 10.1016/j.proeng.2016.07.073
[3] A.I. Kondakov. Productivity as Measure of Multiproduct Metal Processing Production Efficiency. *Procedia Engineering*, 2016, Vol. 150, pp. 987–991. DOI: 10.1016/j.proeng.2016.07.151.

[4] L.V. Fedorova, S.K. Fedorov, Y.S. Ivanova, M.V. Voronina Increase of Wear Resistance of the Drill Pipe Thread Connection by Electromechanical Surface Hardening *International Journal of Applied Engineering Research* ISSN 0973-4562, Vol. 12, no 18 (2017) pp. 7485-7489 © Research India Publications.

[5] A.P. Yakovleva Improving the Durability of Machine Parts Using a Combined Method. *Materials Science Forum*, 2019, Vol. 946, pp 37-41. DOI:10.4028/www.scientific.net/MSF.946.37.

[6] N.N. Zubkov, I.V. Bezin, M.Y. Oshchepkov Surface reinforcement of carbon composites with microstructural metal materials *Polymer Science - Series D*, 2016, 9(1), c. 91-95.

[7] N.N. Zubkov, Yu. L. Bityutskaya Simulation of the Deformational Cutting and the Geometric Parameters of Pin Structures to Analyze the Thermohydraulic Characteristics of Heat-Removal Plates. *Russian Metallurgy (Metally)*, 2018, no. 13.- p.1202-1207. DOI:10.1134/S003602951813027X (Scopus, WoS).

[8] N.N. Zubkov, A.I. Ovchinnikov, S.G. Vasil’ev Tool–workpiece interaction in deformational cutting. *Russian Engineering Research*, 2016, no. 36(3), c. 209-212.

[9] Yu.G. Shneyder Ekspluatatsionnyesvoystvadetaley s regulyarnymikrorel’yefom [Performance characteristics of parts with regular microrelief]. Moscow, Mashinostroenie, 1982, 245 p. (in Russian).

[10] N.N. Zubkov, V. Poptsov, S. Vasiliev, A. Batako Steel Case Hardening Using Deformational Cutting. *Journal of Manufacturing Science and Engineering*, 2018, vol. 140, no. 6, art. 061013. DOI: 10.1115/1.4039382.

[11] N. Zubkov, V. Poptsov., S. Vasiliev Surface Hardening by Turning without Chip Formation. *Jordan Journal of Mechanical and Industrial Engineering*, 2017, vol. 11, no. 1, pp. 13–19.

[12] A.P. Yakovleva Strengthening of coarse pitch gears. *Aviatsionnayapromyshlennost* [Aviation Industry], 2014, no. 2, pp. 31–33. (in Russian).

[13] A.G. Suslov Kachestvopoverkhnostnogosloyadetaleymashin [Property of machine parts surface layer]. Moscow, Mashinostroenie, 2000, 320 p. (in Russian).

[14] P.H. Mayrhofer, C. Mitterer, J. Musil Structure-property relationships in single- and dual-phase nanocrystalline hard coatings. *Surface and Coatings Technology*, 2003, Vol. 174-175, pp. 725–731. DOI: 10.1016/S0257-8972(03)00576-0.

[15] A. Leyland, A. Matthews Design criteria for wear-resistant nanostructured and glassy-metal coatings. *Surface and Coatings Technology*, 2004, Vol. 177-178, pp. 317–324. DOI: 10.1016/j.surfcoat.2003.09.011.

[16] N.N. Zubkov, I.V. BezinSurface modification by deformational cutting for improving the bonding strength of polymers and polymer composite materials with metals and with each other* IOP Conference Series: Materials Science and Engineering* 2017, Vol. 213(1),012010.

[17] O. Fanidi, A.V. Shchedrin, A.A. Kostryukov, N.Yu. Chihacheva Improving Efficiency of the Surface Plastic Covering Deformation of Billets from Aluminum Alloys // Tribology in Industry , 2019, Vol. 41, No. 1. Pp, 50-55. DOI: 10.24874/ti.2019.41.01.06

[18] Perlovich Yu., Bunge H.J., Isaenkova M.G. The fullest description of the structure of textured metal materials with generalized pole figures: The example of rolled Zr alloys // *Materials Science Forum*, vols. 378-381, 2001, pp.180-185.

[19] Isaenkova M., Perlovich Yu., Fesenko V. Use of generalized pole figures in the X-raystudy of textured metal materials // *Z. Kristallographie*, 2007, suppl. 26, s. 327–332.

[20] Perlovich Yu., Isaenkova M. and Fesenko V. General Principles of Substructure Inhomogeneity, Arising in Metal Materials under Plastic Deformation // *Mat. Sci. Forum*, 2007, v. 550, p. 253–258.

[21] Perlovich Yu., Isaenkova M. and Fesenko V. Principles of microstress equilibrium in textured metal materials // *Advances in X-ray Analysis*, 2009, 53, December, pp. 125-140.