

## MACHINE BUILDING AND MACHINE SCIENCE



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### Development of design methodology of technological process of ball-rod hardening with account for formation of compressive residual stresses



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*Introduction.* The study results on the multicontact shock-vibrating machining using a ball-rod hardener are presented. Methods of surface plastic deformation processing, their advantages are described. The tool circuit diagram is given. Features, technological advantages, and the application area of the ball-rod hardening are specified.

*Materials and Methods.* When conducting theoretical studies on the processing, factors, which affect the quality of the surface layer of the machined parts, were established. Dependences are given for calculating the surface roughness, the hardened layer depth, and the deformation ratio under ball-rod hardening. While studying the generation of residual stresses, the dependence for calculating the residual stresses generated in the surface layer of the machined part was specified.

*Results.* The experimental findings of the processing requisite for verification of the adequacy of the theoretical models, as well as the routine of the experiments, are presented. A table and graphs clearly confirming good convergence of the theoretical and experimental data are given (the difference does not exceed 20%). Residual stresses in the surface layer are compressive which enables to predict high performance properties of the machined parts. The value of residual stresses on the workpiece surface is in the range of  $130 \div 200$  MPa. The depth of compressive residual stresses is in the range of 0.9–1 mm. The fatigue characteristic variation, the ultimate stresses of the cycle in depth, which affects the endurance limit, is calculated. It has been established that the processing of workpieces by a ball-rod hardener provides increasing the ultimate cycle stress under repeated loading by 27–35%.

*Discussions and Conclusions.* The design methodology of technological process of ball-rod hardening can be used under the development of production at the machine-building enterprises. In accordance with the recommendations, the limits of the required quality parameters of the workpiece surface layer are set; the parameters of the ball-rod hardener, the interference fit and the radius of rod sharpening are selected. Quality parameters of the surface layer are calculated. Correction of the selected modes and re-calculation of the parameters of the machined surface are carried out until all the specified characteristics are located within the required limits.

**Keywords:** ball-rod hardening, surface roughness, hardened layer depth, deformation ratio, residual stresses.

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**Introduction.** The quality of parts depends on many different parameters, one way or another manifested in the process of their manufacture and affecting their life cycle. A special role in the formation of surface quality is played by finishing processing methods, the use of which provide improving the basic operational properties of machine parts, such as contact stiffness, wear resistance, fatigue strength and durability, etc.

Surface plastic deformation (SPD) processing methods allow solving the problems of increasing the product life cycle for parts from various materials of any configuration. In addition, such methods provide localized processing, which can significantly reduce production costs. The characteristic surfaces of the parts processed through the local SPD hardening are stress concentration zones (holes, slots, bevels, sampling, screwthreads, fillets, grooves, etc.); unreinforced areas of the surface of parts that have undergone general hardening in vibration, shotblasting and others installations (under clamps, in pockets, holes and other difficult-to-access areas for the processing environment); places for mechanical refinement of parts, etc.

Methods of processing SPD, including local ones, can significantly reduce the surface roughness of the workpiece and increase its physical and mechanical properties. In addition, the SPD methods make it possible to remove residual stresses generated by various defects in a part, which have a significant effect on the physicomechanical properties of the material from which the part is made. It is known that tensile residual stresses can significantly reduce the strength characteristics of a part, and vice versa, compressive ones can improve them.

To carry out the process of local processing of SPD parts of simple and complex configurations, including those having a small vertical difference in height, a special device, a ball-rod hardener (BRH), was invented at the Engineering Technology Department, Don State Technical University, under the guidance of Prof. Babichev A.P. BRH is a multi-contact vibro-impact tool, the processing of which is based on the surface-plastic deformation. This processing method has several advantages, such as the ability to handle stress concentrators of large-sized products, products of irregular shape, low-rigid products. The method combines the technological capabilities of vibratory finishing and hardening processing and embossing.

A pneumatic hammer, on which the hardener body is fixed, is used as a power drive. The striker of the power drive 1 hammers with a frequency of about 42 Hz on several layers of steel balls 4, which are transmitted to the set of round rods 2 installed in the collet clamp 6 (Fig. 1). Several layers of balls allow rods with a spherical sharpening of the working surface to copy the shaped profile of the workpiece 5.

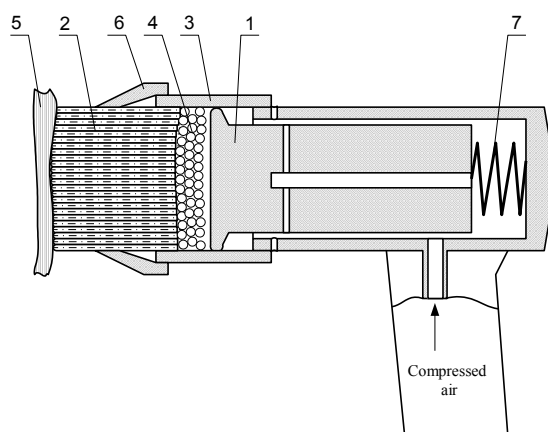


Fig. 1. Diagram of multi-contact vibro-impact tool (BRH):

1 - power drive, 2 - set of round rods, 3 - hardener body,  
4 - steel balls, 5 - workpiece, 6 - collet clamp, 7 - elastic element

### Main Part

The processing method under consideration is studied by a fairly large number of authors [1–10]. When studying the technological capabilities of the BRH processing, it was found that the impact energy of the drive, the diameter of the sharpening of the rods, the number of rods in the set, and the advance of the device along the working surface, have the greatest impact on the quality of the workpiece surface layer [1, 2]. In the work of Shcherba L.M. [1], a methodology for designing the process of treatment by a ball-rod hardener is developed.

Dependences are presented for determining the quality parameters of the surface layer: roughness of the treated surface, the degree of deformation, and the depth of the hardened layer. In the work of Isaev A.G. [2, 5], these dependences are refined and described below.

The surface roughness is determined by the formula

$$Rz = 0.03 \sqrt{\frac{E_y \cdot \eta}{D \cdot N \cdot HB^{1,12}}}, \quad (1)$$

where  $E_y$  is indenter impact energy;  $N$  is the number of rods in the set;  $HB$  is hardness of the work material according to Brinell;  $\eta$  is the device efficiency depending on a number of factors (interference during processing, the number of layers of balls, etc.),  $D$  is the diameter of the spherical sharpening of the hardener rod (indenter).

The deformation ratio is presented as:

$$\varepsilon = 1.13^4 \sqrt{\frac{E_y \cdot \eta}{D^3 \cdot N \cdot HB^{1,12}}}. \quad (2)$$

The depth of the hardened layer is determined from the following relationship:

$$h_n = \sqrt[8]{\frac{\left(\frac{E_y \cdot \eta}{D \cdot N \cdot HB^{1,12}}\right)^3}{D}}. \quad (3)$$

In the study of Yu.R. Kopylov [3], the dependence of the determination of residual stresses for vibration finishing and hardening treatment is given. It seems possible to apply a similar technique to determine the residual stresses under the BRH processing through introducing the coefficient  $k_u$  that considers the features of the generation of internal stresses under the BRH processing. The coefficient  $k_u$  is determined during experimental studies. After transformations, the dependence will take the following form:

$$\sigma_0 = k_u k_\sigma \left( \frac{E_y}{\left( \frac{Dd}{2(D+d)} \right)^3} \right)^{\frac{1}{5}} \cdot \left( \frac{1-v_\delta^2}{E_\delta} + \frac{1-v_{uu}^2}{E_{uu}} \right)^{\left( \frac{-4}{5} \right)}, \quad (4)$$

where  $k_u$  is the coefficient that considers features of the generation of internal stresses during the BRH processing (determined experimentally);  $k_\sigma$  is the coefficient that takes into account the ability of the material to hardening;  $E_y$  is indenter impact energy;  $D$  and  $d$  are the diameters of the rod sharpening and the indent on the workpiece, respectively;  $v_\delta$  and  $v_{uu}$  are Poisson's ratios for the workpiece and the rod;  $E_\delta$  and  $E_{uu}$  are elasticity moduli for the workpiece and the rod, respectively.

To verify the adequacy of dependence (4), experimental studies on the generation of residual stresses under the BRH were carried out. Residual stresses were measured according to the standard method used by the factory laboratory, Rostvertol, Russian Helicopters JSC, using an automated test bench for residual stresses ASCON-3-KI on samples of B95 aluminum alloy. The rectangular samples 200×100×20 mm were processed under various modes with a tightness of 1.5 mm and 4.5 mm. Sets of rods with a radius of spherical sharpening of 4 mm and 8 mm were used. The residual stresses were determined according to the Davidenkov method through etching surface layers from plate samples cut from rectangular work samples. The measured values were compared to the theoretical values calculated from the formula (4). The calculation results are presented in Table 1.

The coefficient value  $k_u$  is determined from the results of preliminary experimental studies through comparing the magnitude of the residual stresses calculated by the dependence (4) and obtained experimentally. It varies in the range of 1.5–1.7. For calculations, the value of 1.6 is taken

Table 1

Comparison of the results of theoretical and experimental studies

Initial data		Theoretical values, MPa	Experimental data, MPa	Difference of theoretical data from experimental data, %
Rod sharpening radius	Interference			
4	4.5	141.6	168	15.7
4	1.5	137.3	135	1.7
8	4.5	124.1	130	4.5
8	1.5	118.74	126	5.6

Fig. 2 and 3 show graphs of the dependences of the residual stresses on the interference under processing. The solid line shows the theoretical curve. The squares indicate the results of experimental studies.

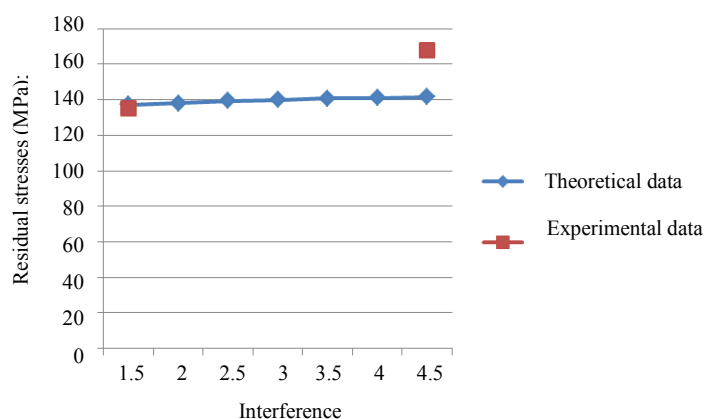


Fig. 2. Dependence of residual stresses on interference under processing.

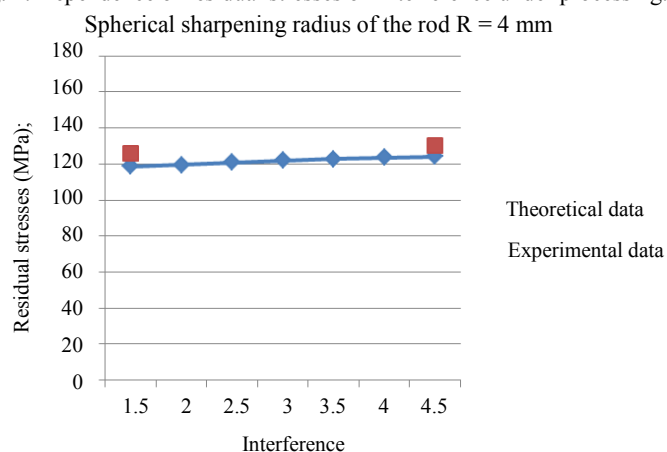


Fig. 3. Dependence of residual stresses on interference under processing.

Spherical sharpening radius of the rod  $R = 8$  mm

For the values of residual stresses obtained as a result of studies, the changes in the fatigue characteristic, the ultimate stresses of the cycle in depth, were calculated using the formula given in [1]. It is known that the endurance limit value is affected by the value of the average stress of the cycle, which largely depends on the level of residual stresses of the surface layer.

The graphs are presented in Fig. 4–7. The solid line shows the ultimate stresses of the cycle, the dotted line shows the distribution of residual stresses.

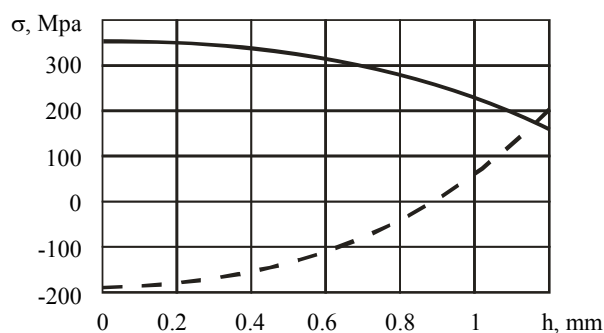


Fig. 4. Change in limiting stresses value of the cycle along the workpiece depth after BRH processing:  $R = 4$  mm, interference is 4.5 mm

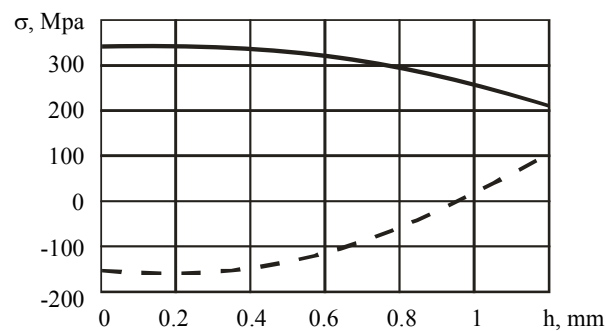


Fig. 5. Change in limiting stresses value of the cycle along the workpiece depth after BRH processing:  $R = 4$  mm, interference is 1.5 mm

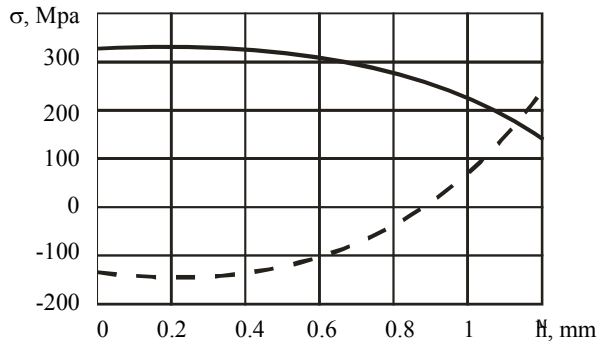


Fig. 6. Change in limiting stresses value of the cycle along the workpiece depth after BRH processing:  $R = 8$  mm, interference is 1.5 mm

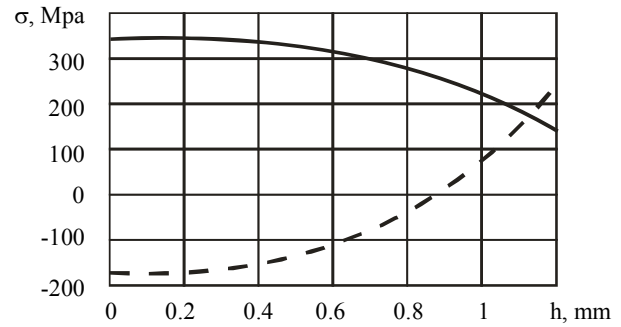


Fig. 7. Change in limiting stresses value of the cycle along the workpiece depth after BRH processing:  $R = 8$  mm, interference is 4.5 mm

### Conclusion

Based on the results of the research, the following conclusions can be drawn.

1. The residual stresses in the surface layer are compressive, which enables to predict high performance properties of the finished workpieces.
2. The magnitude of the residual stresses on the workpiece surface is in the range of 130–200 MPa, which, according to the data of Rostvertol PJSC, approximately corresponds to the magnitude of the residual stresses after the vibration hardening treatment.
3. The depth of the compressive residual stresses is in the range of 0.9–1 mm, which, according to the data of Rostvertol PJSC, is approximately two times greater than during the vibration hardening treatment.
4. BRH processing of workpieces provides increasing the ultimate stress of the cycle during cyclic loading of the workpiece by 27–35%.
5. Processing modes have a slight impact on the magnitude and depth of the residual stresses.
6. It is established that the difference between the results of theoretical and experimental studies does not exceed 20%, which indicates the adequacy of the obtained theoretical dependence for calculating the residual stresses under processing by a ball-rod hardener.

Studies on residual stresses with BRH are presented in the works of A. Shvedova [4, 6–9]. In [4], computer simulation of the process was performed using the Ansys software package. The obtained values of residual stresses correlate with the results of the above experiments.

Based on the research results, the following methodology for designing a ball-rod hardener treatment is proposed.

1. The limits of the required quality parameters of the workpiece surface layer are set.
2. A pneumatic hammer is selected. Then, a nozzle is selected considering those at the tooling engineer's disposal. For processing small areas, nozzles with a small number of rods are recommended; for processing areas of a large area – with a large number of rods. The number of layers of balls is selected depending on the height of the drops or the radius of curvature of the work surface.
3. Interference during processing and the radius of sharpening of the rod are selected. For harder materials, higher machining interferences and smaller sharpening radii are selected.
4. We assign a processing time of 10–15 seconds for the area of the bundle of rods. Considering the feed value recommended above, the number of tool passes along the workpiece surface is selected, and in most cases it is desirable to use single-pass machining. If there are several options for combinations of processing modes that enable to obtain the specified characteristics of the surface layer, the one, whose total processing time for a particular workpiece is shorter, is selected.
5. Then, the arithmetic average deviation of the surface roughness, the depth of the hardened layer, the deformation ratio, and the residual stresses are calculated according to formulas 1–4.

6. Based on the calculation results, the selected processing modes are adjusted. Then, the parameters of the machined surface are calculated again, and so on, until all the specified characteristics are located within the necessary limits.

The above technique can be used under the production design of the BRH treatment.

The above engineering recommendations were used in the implementation of the BRH treatment at Rostvertol PJSC.

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*All authors have read and approved the final manuscript.*