Optimization of Nanostructuring Burnishing Technological Parameters by Taguchi Method

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Abstract. On the basis of application of Taguchi optimization method, an approach for researching influence of nanostructuring burnishing technological parameters, considering the surface layer microhardness criterion, is developed. Optimal values of burnishing force, feed and number of tool passes for hardened steel AISI 420 hardening treatment are defined.

1. Introduction

The perspective finishing hardening technology of surface layer processing at multi-purpose treatment of high-precision parts from constructional steel is nanostructuring burnishing. The technology is based on severe plastic deformation development due to repeated frictional loading of elementary volumes of the surface layer material [1, 2]. Nanostructuring burnishing ensures a significant increase of surface layer hardness and a level of compression residual stresses due to grain structure refinement up to a nanoscale state. At this, high plasticity of deformable material as well as dimensional workpiece accuracy remain, and microprofile roughness height decreases several-fold times [1-3].

So far the problem of controlling the nanostructuring burnishing process has not been solved fully because the achievement of the required physical and mechanical properties of the surface layer depends on a significant number of factors: burnishing force and speed, feed and number of tool passes, friction coefficient in the contact area of the indenter and workpiece. The objective of this research aims at optimizing parameters of normal force, feed and number of tool passes at the established magnitudes of the friction coefficient and AISI 420 steel nanostructuring burnishing speed for maximizing surface layer microhardness.

The problem solution was carried out applying Taguchi method, which provides a simple and effective approach to the experiment performance having minimum costs for specimen processing. These particular advantages have caused wide application of Taguchi method for optimizing parameters of various technological processes, including cutting, polishing and burnishing [4-6]. However, till present time, Taguchi method has been applied for optimizing burnishing parameters according to the criterion of improvement of the surface roughness, while nanostructuring burnishing is directed at microhardness increase and structural surface layer modification.

2. Experimental procedure and equipment

Experimental studies were conducted on AISI 420 steel specimens of commercial alloy production containing 0.22 C; 13.06 Cr; 0.17 Ni; 0.28 Mn; 0.30 Si; 0.057 Cu; 0.020 P; 0.008 S, in % wt.; the rest

is Fe. The specimens were disk-shaped with the diameter of 75 mm and the thickness of 10 mm. Preliminarily, the specimens underwent quenching and low-tempering at 150°C. The maximum hardness after heat treatment reached 460 HB, the surface layer had a structure of low-tempered lath martensite.

Specimen processing by nanostructuring burnishing was carried out on a multipurpose machining centre Multus B300-W by an indenter with a synthesized diamond in the environment of cooling liquid (Rhenus company, Germany) that provided a friction coefficient in the contact area of the indenter and workpiece surface µ=0.12 [1]. Burnishing speed v_b=25 m/min remained constant in all the experiments.

Surface microhardness after nanostructuring burnishing was measured by means of the ecoHARD XM1270C microhardness tester with load on the indenter of 0.25 N. For each experiment, three values of surface layer microhardness HV were measured and an average value was calculated. The scanning microscopy was carried out with magnification of x2500 by means of a Zeiss CrossBeam AURIGA microscope.

3. Results and discussion

Figure 1 represents the parameters of controlled nanostructuring burnishing. Burnishing force F_b, feed f_b and the number of tool passes n_p were accepted as the variable (input) factors of the process. Surface microhardness *HV* was as a surface layer response to an input action. Burnishing speed v_b and friction coefficient μ in the contact area of the indenter and a workpiece within the frames of this experiment were considered as constant magnitudes.
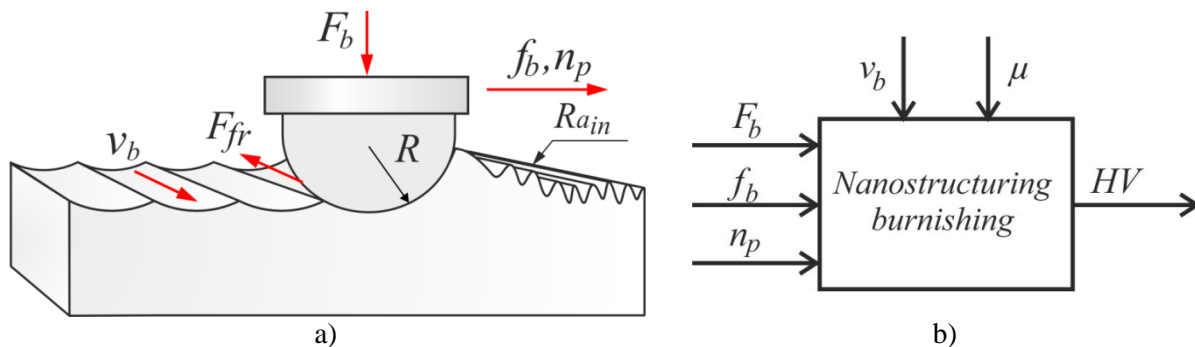

Figure 1. Process diagram (a) and controlling parameters (b) of nanostructuring burnishing: *R* – indenter radius, Ra_{in} – initial surface roughness, F_{fr} – friction force in the contact area of the indenter and a workpiece

The experiment design according to Taguchi method was carried out on the basis of the orthogonal array, the choice of which was defined by the number of assumed variable parameters and assumed levels for each parameter. Thus, for example, for three variable parameters A, B, C, each of which can assume three discrete values (conditionally let us denote them 1, 2, 3), a standard orthogonal array L9 is used, which structure in simple terms is given in Table 1.

Consequently, according to Taguchi method, it is enough to make only 9 experiments to establish the degree of impact of each of three variable parameters on the output characteristic of the process.

The assumed discrete values (levels) of the parameters of controlling nanostructuring burnishing being modified within the frames of the experiment are given in Table 2.

The variation range of nanostructuring burnishing parameters was chosen on the basis of the experimental and theoretical studies having been carried out earlier [1-3]. The minimum force value of burnishing was fixed on condition of full smoothing of the initial roughness, the maximum value was fixed according to the criterion of the material losing shear stability and of essential deterioration of surface layer roughness up to further destruction [3].

Table 1. Standard array L9.

Experiment No.	Parameter values		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 2. Assumed levels of variable parameters

Levels	Variable parameters					
	F_b, N		f_b, mm/rev		n_p	
1	A1	530	B1	0,025	C1	1
2	A2	610	B2	0,04	C2	2
3	A3	690	B3	0,08	C3	3

The resultant orthogonal array considering the assumed values of nanostructuring burnishing variable parameters is given in Table 3.

Table 3. Taguchi orthogonal matrix for carrying out experiments on optimization of nanostructuring burnishing parameters

Experiment No.	Variable parameters		
	A (F_b, N)	B (f_b, mm/rev)	C (n_p)
1	530	0.025	1
2	530	0.040	2
3	530	0.080	3
4	610	0.025	2
5	610	0.040	3
6	610	0.080	1
7	690	0.025	3
8	690	0.040	1
9	690	0.080	2

To define the extent of influence of variable technological parameters on the output characteristic of the process HV, for each experiment, a signal to noise ratio SN_i was calculated. Since by experiment condition the output characteristic of the process has to be maximized, the calculation of a signal to noise ratio was carried out according to the formula:

$$SN_i = -10\log\left[\frac{1}{N_i}\sum_{u=1}^{N_i}\frac{1}{y_u^2}\right], \tag{1}$$

where y is an output characteristic of the process, i is the number of the experiment, u is the number of a measurement in the experiment, N_i is the number of measurements in the i-th experiment.

The calculations were carried out by means of the software for processing statistics, Minitab 15. The results are given in Table 4.

On the basis of the obtained data, the average values of signal to noise ratio for all three levels of each variable parameter of the process are calculated, the difference Δ between maximum and minimum values SN is determined and parameters ranking is carried out. The results are shown in Table 5. The data from Tables 6 are graphically represented in Figure 2. The parameters which are characterized by the greatest value SN are to provide the maximum surface layer microhardness: burnishing force F_b =690 N, feed f_b =0.025 mm/rev, number of tool passes $n_p = 3$.

Table 4. Calculation results of signal to noise ratio

Experiment No.	Microhardness, HV				Signal to noise ratio, SN_i
	Mes. 1	Mes. 2	Mes. 3	Mean	
1	897	932	922	917	59.24
2	851	874	862	862.33	58.71
3	788	808	798	798	58.04
4	840	840	862	847.33	58.56
5	862	874	897	877.67	58.86
6	840	862	851	851	58.6
7	1031	1031	1046	1036	60.31
8	909	909	934	917.33	59.25
9	874	897	885	885.33	58.94

The analysis shows that feed f_b and burnishing force F_b have the maximum statistically significant effect of nanostructuring burnishing variable parameters on the surface layer microhardness HV. The number of tool passes has considerably smaller effect on the output characteristic of the process.

Table 5. Parameters ranking

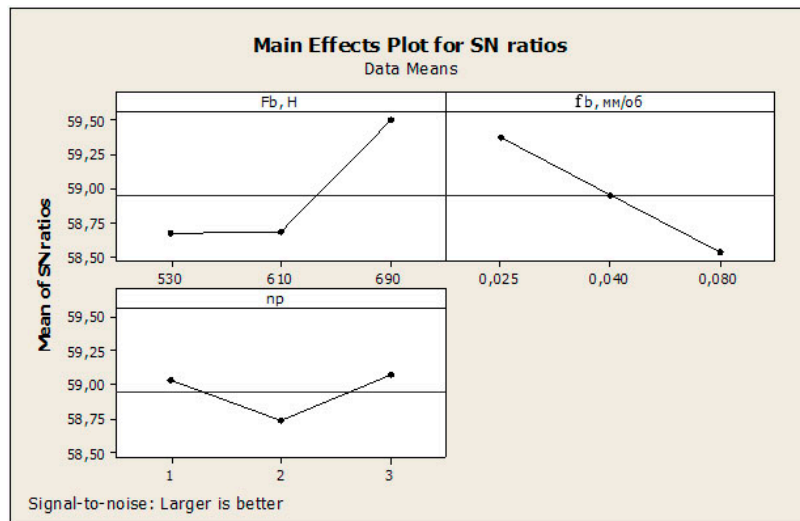| Level	SN		
	F_b	f_b	n_p
1	58,6633	59,37	59,03
2	58,6733	58,94	58,73667
3	59,5	58,526667	59,07
Δ	0,83667	0,8433333	0,333333
rank	**2**	**1**	**3**

Figure 2. Mean values of signal to noise ratio *SN* for three levels of variable parameters of the process: burnishing force F_b; feed f_b, number of tool passes n_p.

It is established that the surface layer thickness, which underwent shear strain in severe plastic deformation, reaches 10…12 μm (Figure 3).
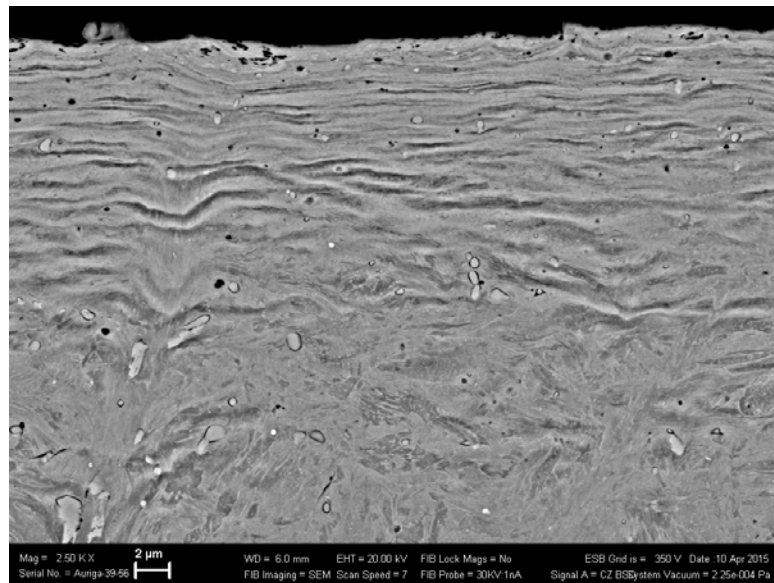

Figure 3. Scanning microscopy of a surface layer of thermostrengthened AISI 420 steel processed by nanostructuring burnishing at optimum parameters F_b =690 N, f_b =0,025 mm/rev and $n_p = 3$

4. Conclusion

The simplicity and ease of processing outcome results are the advantages of Taguchi method from the point of view of experiment design. The method allows for optimizing nanostructuring burnishing parameters without carrying out an expensive full-factorial experiment. It is established that feed f_b and burnishing force F_b have the greatest effect on surface layer microhardness, and number of tool passes have a lesser influence on hardening. The maximum surface layer microhardness after nanostructuring burnishing with optimum parameter values equals 1036 $HV_{0.025}$.

References

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