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Investigation of Hardness on the Surface Formed During the Cutting of HARDOX-500 Steel Based on the Planning of the Mathematical Model of Multi-Factor Experiments

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Abstract. The article investigates the variation of hardness on the cut surface of HARDOX-500 chromium-nickel steel, depending on the physical-mechanical properties of the processed metal, particularly its hardness. For this purpose, the hardness formed during the cutting of HARDOX-500 steel has been examined using the mathematical modeling of multi-factor experiments. As a result, a full-factorial mathematical regression equation has been derived based on the dependence on waterjet pressure (P), abrasive particle consumption (Q) and longitudinal feed of the nozzle (S_{long}). The conducted studies revealed that the hardness values on the surface of the cut area can vary significantly during hydro-abrasive cutting of the selected steel workpieces. Specifically, an increase in the longitudinal feed rate of the nozzle, the consumption of abrasive particles, and the pressure of the waterjet leads to an increase in the hardness of the cut surface. Among these factors, the longitudinal feed of the nozzle has the most significant impact on surface hardness. Furthermore, the product of waterjet pressure and longitudinal feed (X_2X_3), as well as the combined effect of all three input parameters ($X_1X_2X_3$), are influential factors contributing to the increase in hardness.

Thus, the study of hardness in hydroabrasive cutting using multi-factor planning is one of the pressing issues in mechanical engineering.

Keywords: HARDOX-500 steel, chromium-nickel, hardness, hydroabrasive cutting, input parameter.

Introduction. During the hydroabrasive cutting of chromium-nickel steels, the hardness of the cut surface varies depending on the physical-mechanical properties of the processed metal, particularly its hardness. The direction and numerical magnitude of these hardness variations influence various physical processes, such as wear resistance, changes in friction intensity, and the degree of corrosion, leading to their intensification [1. p,39], [7, p.28], [9, p.1571].

In European countries, particularly in Germany, special attention has been given to the impact of mechanical processing on the hardness of HARDOX-500 chromium-nickel steel when manufacturing various machine components [11, pp.1-2]. The distinguishing feature of this chromium-nickel steel compared to other similar steels lies in its high resistance to bending, welding, and wear. Due to its nominal hardness of 500 HBW, HARDOX-500 steel exhibits exceptional wear resistance. Consequently, machine components made from this steel not only maintain high load-bearing capacity but also preserve their machinability.

However, studies have shown that during the hydroabrasive cutting of selected steel workpieces, the extreme values of hardness on the cut surface can vary significantly. Therefore, investigating hardness in hydroabrasive cutting using multi-factor planning remains a relevant issue. The requirements for input parameters in multi-factor experimental planning and the corresponding multi-factor solutions have been studied by various researchers [8, p.76], [3, p.59], for other technological processes.

Objective. The objective of this study is to develop a methodology for calculating and evaluating the mathematical relationships between input and output parameters in the technological process of manufacturing complex-profile parts from HARDOX-500 chromium-nickel steel using the hydroabrasive cutting method.

Methodology of the Study. It should be noted that in the hydro-abrasive cutting process, the water-abrasive jet impacts the cut surface, leading to the formation of its geometric parameters through sequential -cutting, erosion, and frequent changes in local stresses. During this process, the abrasive particles directed at the workpiece surface generate significant impact forces under very high speed and pressure, resulting in peening on the hydro-abrasively cut surface. Additionally, chip formation occurs under conditions of high plastic deformation.

Furthermore, due to the large volume of water jet flow over the machined surface during the hydro-abrasive cutting process, the temperature in the contact zone remains low. This means that plastic deformations in chip formation occur in a cold state.

For this reason, in hydro-abrasive cutting, the input parameters studied include the water jet pressure (P, MPa), the hardness of abrasive particles (T, MPa), abrasive consumption (Q, g/l), feed rate (S_{long}, mm/min), and hardness (H_{μ}, kg/mm²). The ranges of these input parameters were determined based on literature sources and industrial experience [2, pp. 60–64], [10, pp. 21590–21594].

Discussion of the results. The planning of experiments for measuring hardness has been carried out using a full-factorial 2^3 design [3, p.76], [2, p.61], with the matrices being organized accordingly. The variation intervals for the limits of the input parameters in hydroabrasive processing are presented in Table 1. Table 1 also shows the coded levels of the factors [2, pp.60-64], [10, pp.21590-21594].

Discussion of the results. The planning of the experiments for hardness measurement was carried out using a full factorial design [3, p. 76], [2, p. 61], whereby the matrices were organized accordingly. The variation intervals for the limits of the input parameters in hydroabrasive machining are shown in Table 1. Table 1 also shows the coded levels of the factors [2, pp. 60-64], [10, pp. 21590-21594]. The experiments are designed to prove that the increase in surface hardness due to hydroabrasive cutting occurs systematically and can be used to improve component properties. This effect has already been described many times in the literature; by way of example, see [12]

Table 1.

Coding of Factors

Names of factors and their corresponding symbols	Variation limits			Variation intervals	Step size of variation
	-1	0	+1		
Waterjet pressure p, MPa	250,0	300,0	350,0	100,0	50,0
Abrasive consumption, Q, g/l.	85	150	215	130	65
Longitudinal feed, S_{long}, mm/min	26,7	53,4	77,4	51,9	25,35

Based on the plan developed, the experiments are conducted according to the 2^3 design. In this case, the number of factors (variables) under investigation is k=3, and the number of levels (upper and lower) p=2, resulting in N=2^3=8 experiments [6, p.13] [5, p.23], [4, p.8]. The number of repetitions for each experiment is set to 3.

The values of the factors influencing hardness and their variation intervals, in coded form, are presented in Table 1 [10, p.2591]. The results of the experiments conducted based on the planned matrix for hardness are shown in Table 2.

Table 2.

Results of experiments based on the planned matrix for hardness

Experiment numbering	*Natural values of the factors*			*Dimensionless values of the factors (coding) in the coordinate system*				*Average results of the experiment*
	p,MPa	*Q,g/l*	*S_{long}, mm/min*	X_0	X_1	X_2	X_3	*y*
	Z_1	Z_2	Z_3					

1	*250*	*85*	*26,7*	*+1*	*-1*	*-1*	*-1*	*529*
2	*350*	*85*	*26,7*	*+1*	*1*	*-1*	*-1*	*531*
3	*250*	*215*	*26,7*	*+1*	*-1*	*+1*	*-1*	*551*
4	*350*	*215*	*26,7*	*+1*	*1*	*+1*	*-1*	*568*
5	*250*	*85*	*77,4*	*+1*	*-1*	*-1*	*+1*	*646*
6	*350*	*85*	*77,4*	*+1*	*1*	*-1*	*+1*	*662*
7	*250*	*215*	*77,4*	*+1*	*-1*	*+1*	*+1*	*670*
8	*350*	*215*	*77,4*	*+1*	*1*	*+1*	*+1*	*696*

Thus, the mathematical expression of the experiments conducted based on the accepted full factorial design matrix in hydroabrasive cutting can be presented as follows:

$$y= b_0+b_1x_1+ b_2x_2+b_3x_3+\ldots+ b_{12}x_1 x_2+ b_{23}x_2 x_3+ b_{123} x_1 x_2 x_3 , \qquad (1)$$

here,

y=Hμ- represents the hardness;

x- values of the input parameter;

b- the regression coefficient of the polynomials.

The coefficients of b_i in equation (1) are determined according to Table 2.

$$bo = \frac{1}{8}\sum_{i=1}^{8} y_i = 606{,}625 ;$$

$$b_1 = \frac{1}{8}\sum_{i=1}^{8} y_i = 7{,}625;$$

$$b_2 = \frac{1}{8}\sum_{i=1}^{8} y_i = 14{,}625;$$

$$b_3 = \frac{1}{8}\sum_{i=1}^{8} y_i = 61{,}875 \qquad (2)$$

$$b_{12} = \frac{1}{8}\sum_{i=1}^{n} x_1 x_2 y_i = 3{,}125;$$

$$b_{13} = \frac{1}{8}\sum_{i=1}^{n} x_1 x_3 y_i = 2{,}875;$$

$$b_{23}=\frac{1}{8}\sum_{i=1}^{n}x_2x_3y_i=-0{,}125;$$

$$b_{123}=\frac{1}{8}\sum_{i=1}^{n}x_1x_2x_3y_i=-0{,}625.$$

The maximum value of the hardness dispersion is calculated using the following expression;

$$S_{max}\frac{\sum_8^8 H_\mu}{8}=\frac{\sum_i^8(y_{max}-y_{\min})}{8}=\frac{167+141+133+117+39+22+4+0}{8}=77{,}875\ . \quad (3)$$

Average value of the hardness distribution dispersion

$$S_{average}=\sum_{i=1}^{\mu}H_{\mu\ dis}=623. \quad (4)$$

The Cochran criterion is calculated as follows:

$$G=\frac{(S_{max})^2}{(\sum_{i=1}^{8}H_{\mu\ dis})^2}=\frac{(77{,}875)^2}{(623)^2}=0{,}016. \quad (5)$$

According to the literature [58, p.77], [70, p.19], the table value of the Cochran coefficient will be as follows:

$$G_{table}=0{,}516$$

The calculated value is close to the table value.

The full factorial mathematical regression equation in natural values with factors for the hydroabrasive cutting of HARDOX-500 steel will be as follows:

$$H\mu=606{,}625+7{,}625X_1+14{,}625X_2+61{,}875X_3+3{,}125X_1X_2+2{,}875X_1X_3-0{,}125X_2X_3-0{,}625X_1X_2X_3 \quad (6)$$

As seen from equation (6), the parameter X_3 (i.e., the value of the longitudinal feed) is the most influential factor on hardness, as its coefficient is 61,875, which is higher than the coefficients of the other factors. After X_3, the factor that most affects hardness is X_2 (i.e., the increase in the abrasive consumption), followed by X_1 (i.e., the effect of the waterjet pressure). Among the interaction factors, X_1X_2, i.e., the change in waterjet pressure and abrasive amount, has an effect.

As seen from equation (6), the coefficients of the interaction terms $X_1X_2X_3, X_1X_2$ and X_1X_3 are positive, while the coefficients of the interaction terms X_2X_3 and $X_1X_2X_3$ are negative.

The calculation of the step size for the factors is carried out as follows [21, pp.59-60], [62, p.61]:

$$Z_1^0 = \frac{Z_1^{max} + Z_1^{min}}{2} = 300;$$
$$Z_2^0 = \frac{Z_2^{max}+Z_2^{min}}{2} = 150; \qquad (7)$$

$$Z_3^0 = \frac{Z_3^{max} + Z_3^{min}}{2} = 52{,}05;$$

$$\Delta Z_1 = \frac{Z_1^{max} - Z_1^{min}}{2} = 50;$$
$$\Delta Z_2 = \frac{Z_2^{max} - Z_2^{min}}{2} = 65;$$
$$\Delta Z_3 = \frac{Z_3^{max}-Z_3^{min}}{2} = 25{,}35;$$

The transition to the new dimensionless coordinate systems X_1, X_2, X_3 is carried out with the help of transformation mappings.

$$X_1 = \frac{P-Z_1^0}{\Delta Z_1} = \frac{P-300}{50};$$

$$X_2 = \frac{Q-Z_2^0}{\Delta Z_2} = \frac{Q-150}{65}; \qquad (8)$$
$$X_3 = \frac{S_{\text{пр}} - Z_3^0}{\Delta Z_3} = \frac{S_{\text{пр}} - 52{,}5}{25{,}35}.$$

The regression equation (6) can be expressed with natural values as follows:

$$H\mu = b_0 + b_1 \cdot \frac{P^{max} - P^0}{\Delta P^0} + b_2 \frac{Q^{max} - Q^0}{\Delta Q^0} - b_3 \frac{S^{max} - S^0}{\Delta S^0} + b_{12} \cdot \frac{P^m - P^0}{\Delta P^0} \cdot \frac{Q^m - Q^0}{\Delta Q^0} + b_{13} \cdot \frac{P^m - P^0}{\Delta P^0} \cdot \frac{S^m - S^0}{\Delta S} + b_{23} \cdot \frac{Q^m - Q^0}{\Delta Q^0} \cdot \frac{S^m - S^0}{\Delta S^0} + b_{123} \cdot \frac{P^m - P^0}{\Delta P^0} \frac{Q^m - Q^0}{\Delta Q^0} \cdot \frac{S^m - S^0}{\Delta S^0} \cdot 1 \quad (9)$$

After the calculations, the dependency equation of HARDOX-500 steel in terms of P, Q, and S will be as follows:

$$H_\mu = 495{,}9440266 - 0{,}169021328 * \mathrm{P} - 0{,}177969924 * \mathrm{Q} + 1{,}430359217 * \mathrm{S} + 0{,}001356 * \mathrm{P} * \mathrm{Q} + 0{,}003406 * \mathrm{P} * \mathrm{S} + 0{,}0022 * \mathrm{Q} * \mathrm{S} - 0{,}000008 * \mathrm{P} * \mathrm{Q} * \mathrm{S}. \quad (10)$$

Let's examine the theoretical calculation of hardness based on the regimes at the maximum values of the factors using the obtained regression equation.

$P^{max} = 350\ Mpa;$

$Q^{max} = 215 \frac{g}{l};$

$S^{max} = 77{,}4\ mm/min;$

$$H_{\mu\ theoretical} = 693{,}5557 \quad (11)$$

The calculations show that the theoretical value obtained is 693,5557, and the experimental hardness values differ by 2,4442 units, or 0,35%, from the value of 696.

By rounding the theoretical hardness values, a smaller difference can be obtained, which is written as follows:

$$H_\mu = 495{,}944 - 0{,}169*P$$
$$0{,}178*Q + 1{,}43*S + 0{,}0014*P*Q + 0{,}0034*P*S + 0{,}0022*Q*S - 0{,}000008*P*Q*S$$

Thus, the calculations show that the theoretical value obtained is 696,6774, and the experimental hardness values differ by -0,6774 units, or 0,10%.

Based on the specified equation (6), automatic calculations of hardness have been performed using the Excel program, depending on the regime parameters of the hydroabrasive finishing process, and the results are presented in Table 3 and Figures 1, 2, and 3.

Table 3.

Construction of the table for the automatic determination of Y

		26.7	31.77	36.84	41.91	46.98	52.05	57.12	62.19	67.26	72.33	77.4
		-1	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8	1
		85	98	111	124	137	150	163	176	189	202	215
-1	250.0	529.0000	542.9200	556.8800	570.8800	584.9200	599.0000	613.1200	627.2800	641.4800	655.7200	670.0000
-0.8	260.0	529.2000	543.4050	557.6400	571.9050	586.2000	600.5250	614.8800	629.2650	643.6800	658.1250	672.6000
-0.6	270.0	529.4000	543.8900	558.4000	572.9300	587.4800	602.0500	616.6400	631.2500	645.8800	660.5300	675.2000
-0.4	280.0	529.6000	544.3750	559.1600	573.9550	588.7600	603.5750	618.4000	633.2350	648.0800	662.9350	677.8000
-0.2	290.0	529.8000	544.8600	559.9200	574.9800	590.0400	605.1000	620.1600	635.2200	650.2800	665.3400	680.4000
0	300.0	530.0000	545.3450	560.6800	576.0050	591.3200	606.6250	621.9200	637.2050	652.4800	667.7450	683.0000
0.2	310.0	530.2000	545.8300	561.4400	577.0300	592.6000	608.1500	623.6800	639.1900	654.6800	670.1500	685.6000
0.4	320.0	530.4000	546.3150	562.2000	578.0550	593.8800	609.6750	625.4400	641.1750	656.8800	672.5550	688.2000
0.6	330.0	530.6000	546.8000	562.9600	579.0800	595.1600	611.2000	627.2000	643.1600	659.0800	674.9600	690.8000
0.8	340.0	530.8000	547.2850	563.7200	580.1050	596.4400	612.7250	628.9600	645.1450	661.2800	677.3650	693.4000
1	350.0	531.0000	547.7700	564.4800	581.1300	597.7200	614.2500	630.7200	647.1300	663.4800	679.7700	696.0000

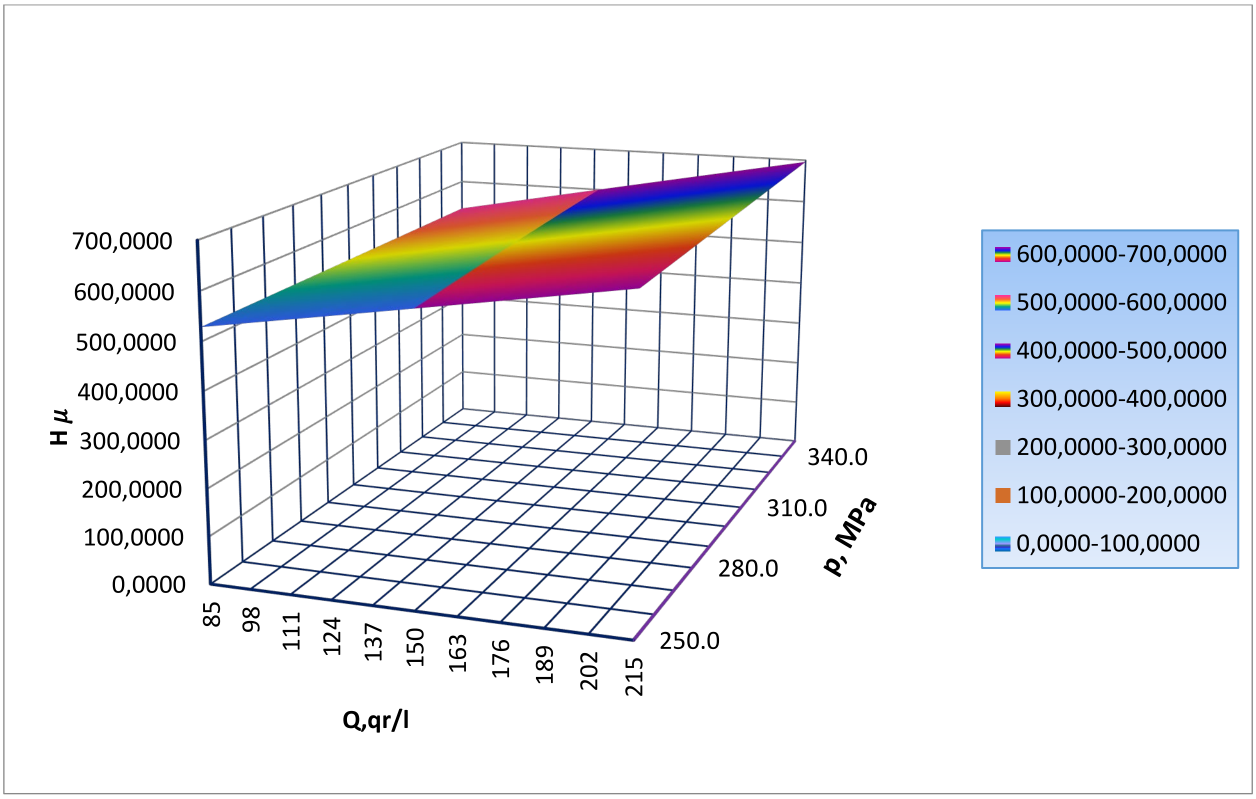

Figure 1. The surface view of hardness across the mass

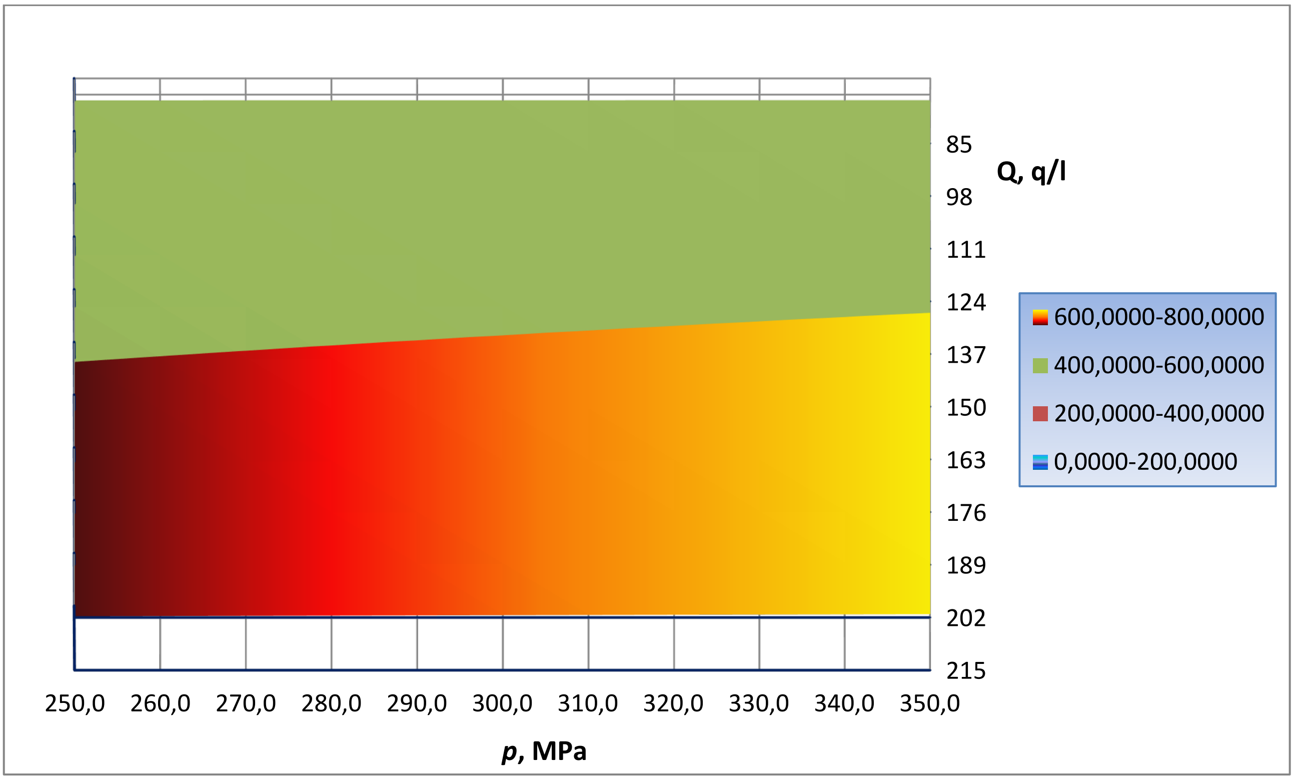

Figure 2. Top view of the hardness surface across the mass

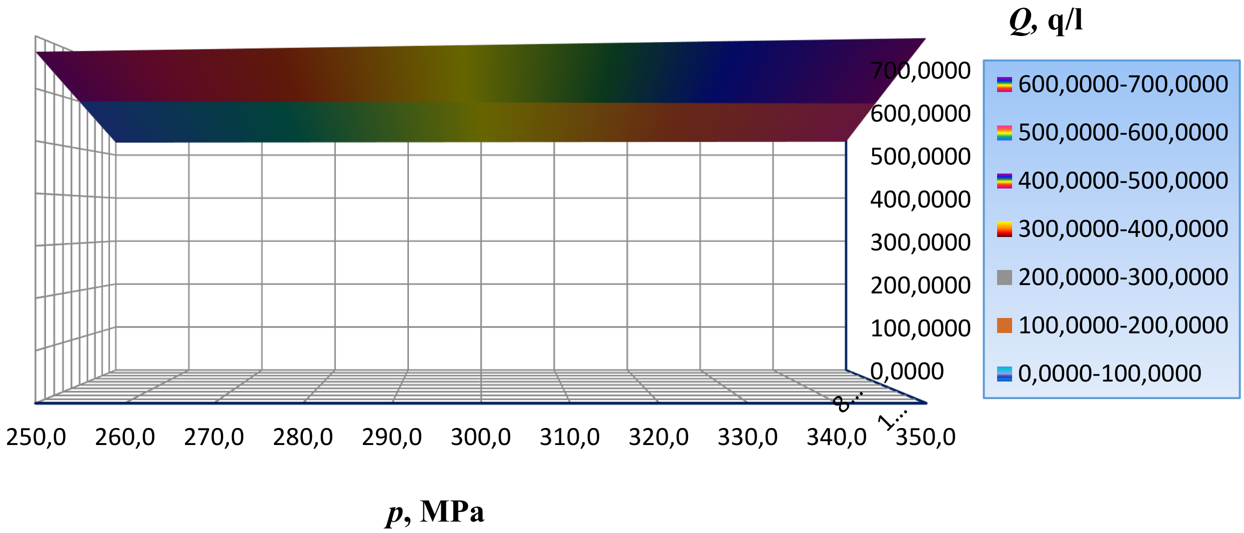

Figure 3. Horizontal (frontal) view of the hardness surface across the mass

Results.

1. One of the quality parameters of machine parts is the hardness of the machined surface that develops during the operation. Research has shown that in the hydroabrasive cutting of HARDOX-500 grade chromium-nickel steels, regardless of the cutting regime parameters, the hardness of the machined surface increases by 10 to 18%, which occurs due to plastic deformation created by the abrasive particles striking the surface with high impacts during the cutting process.
2. It has been determined that the increase in hardness of HARDOX-500 grade chromium-nickel steels cut by hydroabrasive machining results in improved wear resistance of the produced parts.
3. Thus, the calculations show that the experimental value of the surface hardness is 696, while the theoretical value is 696.6774, resulting in a difference of -0.6774 units, or 0.10%.

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