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RESEARCH ON THE INTERNAL CYLINDRICAL SURFACES ROUGHNESS HEIGHTS PROCESSED BY A TOOL WITH COMBINED EFFECT

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Abstract: *The current article presents the results from conducted experiments on the impact of cutting speed and feedrate on the resulting roughness in the surface layer due of combined cutting and burnishing processing of internal cylindrical surfaces. The double effect processing is carried out using a special designed tool for boring and subsequence surface burnishing based on plastic deformation in the surface layer. Standard workpieces for production of hydraulic cylinders, made of S355 steel are used as test specimens. Stochastic models describing the impact of cutting parameters on the resulting roughness are derived, using the surface response methodology of the design of experiments. The obtained stochastic models and their significance assessment are presented and discussed at the end of the work.*

Key words: burnishing, *plastic deformation, surface roughness, combined boring and burnishing tool*

1. INTRODUCTION

Increasing the efficiency of machining and quality of production appears as the main goals to modern mechanical engineering. The increasingly high demands placed on the production of elements from hydraulic equipment cause the need to develop fundamentally new cutting tools with high operational characteristics.

Machining the holes of hydraulic cylinders is a specific technological operation, for the implementation of which it is necessary to create special tools, devices and equipment. The technology of processing these precise holes has a number of specific features that distinguish it from the technologies in general mechanical engineering.

In the modern production of hydraulic elements in Bulgaria, the main goal is to achieve high productivity, high accuracy of shape and size, and lower roughness of the processed surfaces. For example, according to in-house standards of hydraulic cylinders manufacturers, in machining of the cylinders witch standard cutting tools it is normal to require a roughness height no higher than Ra=0,3 µm (ISO 4287).

There is a direct relationship between the quality parameters of the treated surfaces and their operational characteristics. The functional analysis of the behavior of the surfaces gives the need to obtain reduced roughness height and increased accuracy of the geometric parameters of the holes of hydraulic cylinders. One of the possible ways to achieve increased productivity, along with low heights of the functional surfaces roughness is the application of a tools with a combined effect. They can perform more than one operation at the same time. For example, these operations could be holes boring and subsequent burnishing by plastic deformation of the surface layer.

In the hydraulic cylinders manufacturing usually processing of the inner diameter of the hydrocylinders can be divided into two different operations:

- Material cutting operations, such drilling or hole boring [1,2];
- Surface burnishing that most often associated with deep rolling, ball or slide burnishing operations [3,4].

The final surface treatment or shape improvement is carried out on the basis of two principles:

- Friction during sliding (burnishing) performed in a linear movement of the tool [5,6];
- Friction when rolling along the processed workpiece' hole performed with tools built on the basis of rollers or balls [5,6]. In this case, the processing combine two movements - rotary and rectilinear.

Most often, the operations discussed above are performed by separate complex tools and the deformations in the surface layer of the processed holes are obtained by rollers with a forced tension change [7-9].

The main disadvantage of the tools working simultaneously (cutting and burnishing) is the difference in the force dynamics of the two processes. This requires application of several rows of support elements to both sections - cutting and burnishing. In order to perform the support function, these elements are most often six (evenly distributed around the processed diameter) in two rows, and the last row must be able to adjust their diameter. An additional disadvantage is the limitation in the diameters of the processed holes, because from this.

Diamond burnishing inserts are also employed in surface burnishing processes, but the main disadvantages of their usage in combined tools are their inappropriate shape and higher cost, which lead to the final product overall cost increase.

Another reason for studying these burnishing schemes with combined tools is the lack of enough research results reported, although they have great potential for development and application, according to the authors [10-13].

The present paper aims to investigate the influence of machining regime parameters (cutting speed S [m/min] and feedrate f [mm^{-1}] of a simultaneous cutting and burnishing operation, on the resulting roughness height of the hydraulic cylinders' inner surfaces, processed by a tool with combined effect: hole boring, followed by slide burnishing.

2. MATERIALS AND METHODS

An experimental model of a combined tool (Fig. 1) [14,15] was created to conduct the experimental studies. It allows changing both the parameters of the cutting part of the tool and the angle of mutual arrangement of the support & burnishing inserts, using interchangeable modules (which is the essential contribution of the presented tool to reduce the roughness and increase the hardness in the surface layer of the machined surface). Support & burnishing inserts guide the tool and perform burnishing operation after boring by sliding friction as they work with a certain tension in the machined hole.

Figures 1 a) and b) shows respectively: a general view of the tool and a view of the face of the tool. As can be seen the design of the tool consists of a body (1), which ensures the stability of the whole tool. The front end has a tail of a thin-walled part (2) consist of the longitudinal grooves (1a) for feeding the cutting fluid, a front seal (3), a cutting unit (6), carrying the triangular shaped carbide cutting insert (8) and fixing screw (9). The support and burnishing inserts are stationary (10) and movable (5) one, which are fixed with screws (4) and counterbody (7). The stationary support (10) is act as counterbody of the cutting unit (6).

The angle of arrangement of the guide-burnishing elements (5) and (10) can be changed within 40º, and after their adjustment they are fixed by the screws (4) and counterbody (7). The available angles are predetermined by the analytical studies and they are adjusted with an optical protractor with an accuracy of 30'.

Grooves are formed in the body (1) and covered with a thin-walled casing (2) for feeding the cutting fluid. Their arrangement along the entire cylindrical surface of the body allows not only cooling of the cutting area, but also lubricate the friction area of the guide-burnishing elements.

The guide elements are made of steel and they have three strips of P10 hard alloy welded to them. The rest of the elements are made of 41Cr4 steel, the nut is made of S235JR steel, and the gasket is made of rubber.

When using friction (guiding) elements (5) and (10) with different heights and a cutting unit (6) with a different displacement of the cutting plate, relative to the axis of the tool, holes of different diameters can be machined. The tip of the cutting insert (8) is located at the same diameter as the guides (5) and (10).

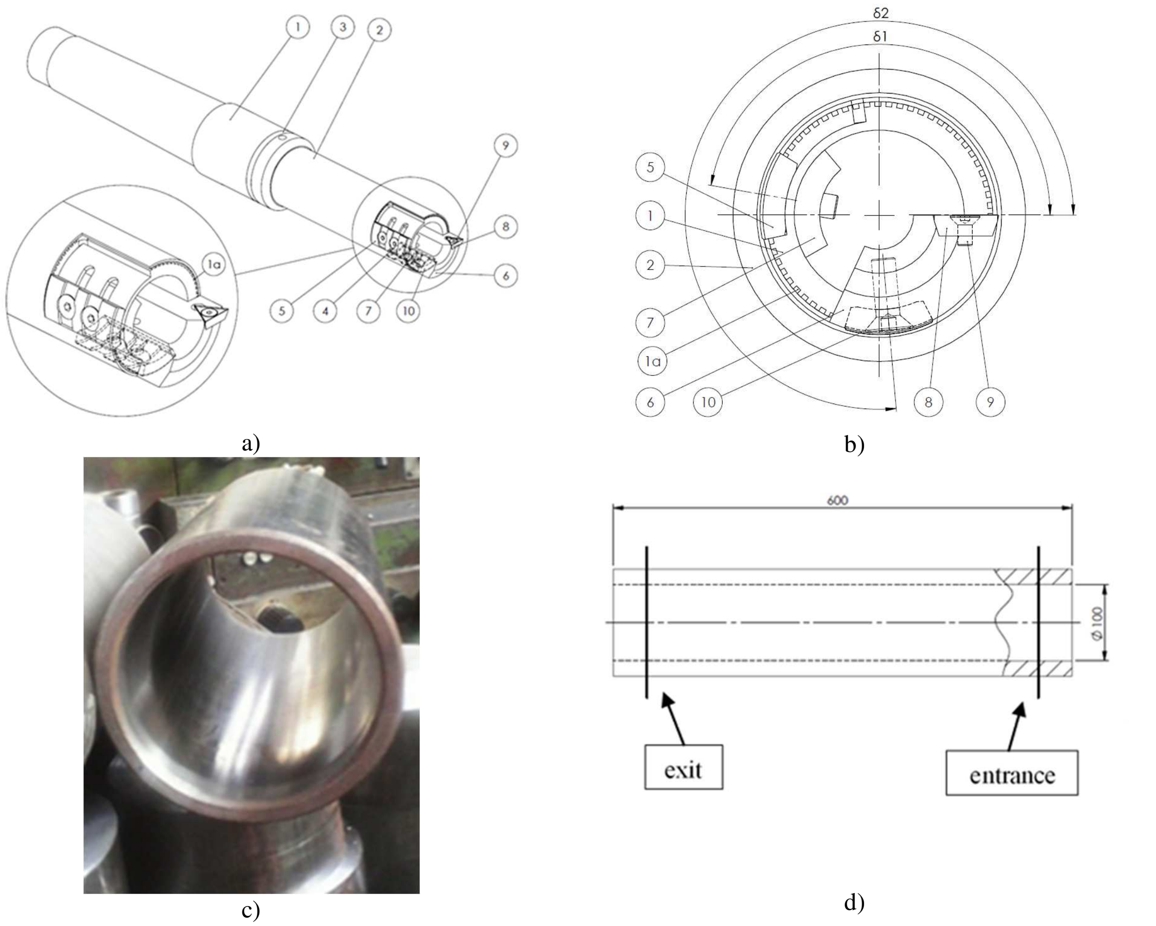


Fig. 1. a) Scheme of the combined tool's working part; b) Front view of the tool; (c) Internal cylindrical surface machined by the combined tool; d) Roughness measurement scheme.

In the current study, a cutting module (6) and guide-burnishing elements (5) and (10) are mounted to the body (1). On the basis of preliminary theoretical and experimental studies [16], the range of variation of the angles δ_1 and δ_2 (Fig. 1. b)) was determined, expressed in an angle between them equal to the difference (δ_2 - δ_1), since element (10) is movable. Moving the guide-burnishing elements at certain angles (δ_1 and δ_2) allows to adjust the forces F1 and F2 in the guides (pressing forces) and to change the values of the resistance coefficients S_1 and S_2 for each of the two guide-burnishing elements [16], which affect the roughness of the processed inner surfaces of the holes (Fig. 1. c).

Moving the guide-burnishing elements at angles δ_1 and δ_2 allows to find the optimal options for the forces F_1 and F_2, where $F_1 \approx F_2$ and their value is such that it ensures plastic deformation under normally applied load, but without scuffing effects and the resistance coefficients S_1 and S_2, which must be equal to (or greater) than 1. In the present work these two angles are fixed to be $\delta_1 = 170°$ and $\delta_2 = 275°$.

In the conducted experimental studies, the test specimens have tubular shape and made of S355 steel, with inner diameter Ø100 mm and length 600 mm (see Fig. 1. c)).

For the processing of the specimens a CNC lathe machine, model SP586 is used. Its operational characteristics allows adjustment of the speed between 50 - 2500 min^{-1} and feedrates between 0.01 - 40.9 mm^{-1}. The current regime parameters values in the experimental investigation are according to the experimental design, shown in the table 1. A nominal value of the deforming force, applied to both guiding inserts is $F_1 = F_2 = 2500$ N [16].

3. A STUDY THE INFLUENCE OF MACHINING REGIME PARAMETERS ON ROUGHNESS HEIGHTS

The influence of the regime parameters on the obtained roughness in the surface layer was studied by conducting two rotatable surface response experiments [17,18] of type 2^2. As a result, stochastic regression equations R_a=f(S, f) were derived and assessed about their statistical significance.

Due to the difference in dynamics process when the tool enters the machined hole and exits it (when the tool enters, there is initial cutting and subsequent burnishing, and when the tool exits the hole, the final treatment is burnishing), the roughness is examined at the entrance and the exit of the experimental specimens (see Fig. 1. d)). Due to the design of the tool, the burnishing part continues to contact the machined surface when the cutting part is already outside of the hole. This will lead to changes in the tool's operating mode, so it is important to check to what extent these changes are at different values of the machining regime parameters. These changes in the operating mode affect the resulting roughness at the input and output of the part. For this reason, the roughness at the entrance and exit of the test specimen is investigated.

4. EXPERIMENTALLY OBTAINED RESULTS

The coefficients of the factors of the regression models were determined using Minitab 19 statistical software [19]. They describe the relationship between the studied mode parameters and the height of the resulting roughness during processing with the combined tool in the case of its entry into the hole of the test specimen (1) and when exiting (2) from it. They have the following form:

$$R_a(S,f) = 0.0757 - 0.00181 \cdot S + 4.068 \cdot f + 0.000022 \cdot S^2 - 9.06 \cdot f^2 - 0.02542 \cdot S \cdot f \quad (1)$$

$$R_a(S,f) = -0.1051 - 0.000658 \cdot S + 5.030 \cdot f + 0.000010 \cdot S^2 - 8.22 \cdot f^2 - 0.03417 \cdot S \cdot f \quad (2)$$

Table 1 shows the data of the response surface experimental study when the combined tool enters and exits the machined hole. Statistical tests for the adequacy of models (1) and (2) was performed at the 95% confidence level, which is shown in table 2.

Table 1

Experimental design and results for the entry and exit of the machined specimens by combined tool.

№ of trial	Coded factors		Factors in natural values		Measured roughness values		Calculated from the regression models	
					Entry	Exit	Entry	Exit
	X1	X2	S (m/min)	f (mm^{-1})	R_a (μm)	R_a (μm)	R_a (μm)	R_a (μm)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	-1	-1	80.00	0.04	0.130	0.090	0.135	0.091
2	1	-1	120.00	0.04	0.198	0.145	0.194	0.145
3	-1	1	80.00	0.10	0.176	0.161	0.181	0.160
4	1	1	120.00	0.10	0.183	0.134	0.179	0.132
5	-1.414	0	71.72	0.07	0.176	0.136	0.169	0.135
6	1.414	0	128.28	0.07	0.203	0.152	0.209	0.152
7	0	-1.414	100.00	0.03	0.145	0.103	0.145	0.101
8	0	1.414	100.00	0.11	0.167	0.139	0.166	0.140
9	0	0	100.00	0.07	0.172	0.136	0.172	0.135
10	0	0	100.00	0.07	0.171	0.136	0.172	0.135
11	0	0	100.00	0.07	0.168	0.130	0.172	0.135
12	0	0	100.00	0.07	0.175	0.141	0.172	0.135
13	0	0	100.00	0.07	0.173	0.136	0.172	0.135

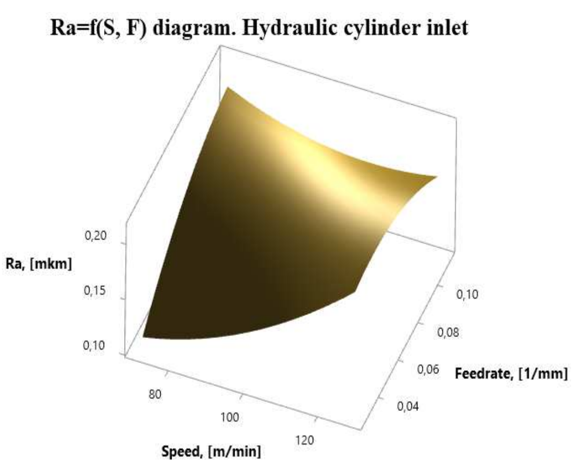
Table 2

Statistical tests results for adequacy of the regression equations.

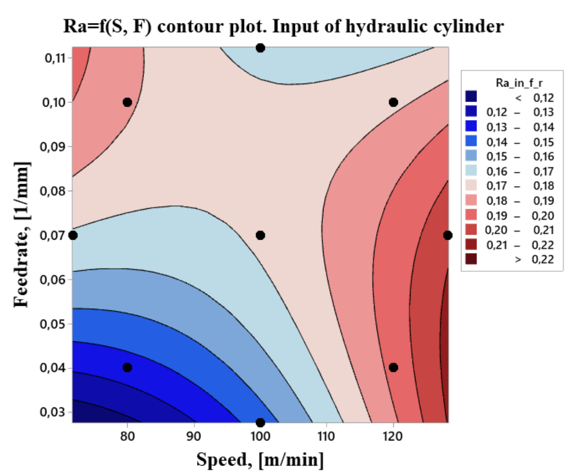
Entering the hole					**Exiting the hole**				
Term	**Coeff.**	**T-Value**	**P-Value**	**VIF**	**Term**	**Coeff.**	**T-Value**	**P-Value**	**VIF**
Constant	0.17180	72.19	0.000	-	Constant	0.13580	92.93	0.000	-
S	0.01415	7.52	0.000	1.00	S	0.00633	5.48	0.001	1.00
f	0.00776	4.13	0.004	1.00	f	0.01386	12.00	0.000	1.00
S*S	0.00860	4.26	0.004	1.02	S*S	0.00410	3.31	0.013	1.02
f*f	-0.00815	-4.04	0.005	1.02	f*f	-0.00740	-5.97	0.001	1.02
S*f	-0.01525	-5.73	0.001	1.00	S*f	-0.02050	-12.55	0.000	1.00
Model Summary					**Model Summary**				
S		**R-sq**		**R-sq(adj)**	**S**		**R-sq**		**R-sq(adj)**
0.0053215		95.43%		92.16%	0.0032674		98.21%		96.93%

It can be seen that the coefficients of the regression models obtained are statistically significant as seen by the calculated T-values (Student criterion). The calculated probabilities regarding the risk of wrongly rejecting the null hypothesis are small (P-values < 0.05), which is a reason to consider that the coefficients in the regression equations are significant. The overall assessment of the regression models (1) and (2) Model Summary from table 2 shows that the dispersion of the differences between the measured and calculated values for Ra when the tool enters the hole (R-sq = 95.43%) is greater than when it exits (R-sq =98.21%). Therefore, it can be concluded that the tool works more stable when it is exiting the hole than when it is entering it.

Checking the correlation of the coefficients before the regression equations factors using the VIF (Variance Inflation Factor) parameter shows values close to 1.00, which is an indication that they are uncorrelated with each other. In addition, an analysis of variance (ANOVA) was performed on the regression equations (1) and (2), after which the obtained values of the F-criterion (Fisher) for the significance of the coefficients repeated the results of the calculated probabilities (P-values) shown in table 2. Therefore, it can be considered that the obtained models (1) and (2) describe the relationship between the resulting roughness Ra and the mode parameters S and f sufficiently adequately (95% confidence level).

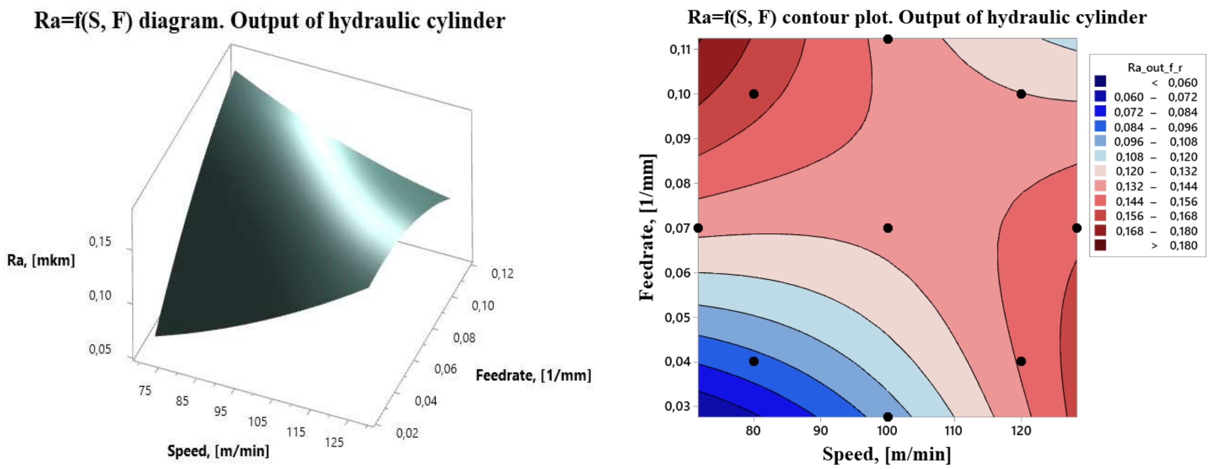


a)



b)

Fig.2. Graphical representation of the influence of the cutting parameters on the resulting roughness heights (Ra) after application of the combined machining when the tool enters the hole:
a) 3D response surface diagram; b) contour diagram



a) b)

Fig.3. Graphical representation of the influence of the cutting parameters on the resulting roughness heights (Ra) after application of the combined machining when the tool exits the hole:
a) 3D response surface diagram; b) contour diagram

A graphical representation of the conducted experiments results, when the combined tool enters the hole is shown in the figure 2., and when it leaves the hole in the figure 3. respectively.

5. RESULTS DISCUSSION

The effects obtained from the regression equation (1) is shown in the contour diagram from the figure 2. b). They describes the influence of the regime parameters on the obtained roughness height (Ra) after the application of combined processing at the entrance of the specimens. It can be seen that when the tool entering the hole, the value of the roughness criterion Ra is increased, at high values of the cutting speed and the feed rate. The construction of the tool (the cutting part followed by the burnishing part) and the accuracy of the shape of the hole are the main reasons for this. When the cutting insert enters, the impact of cutting forces causes a large load on the cutting part, which leads to the instability behavior of the tool. That instability results in a concentration of the load mainly in one of the guide burnishing inserts. As result, the one of the guide and burnishing inserts work properly, while the other one has minimal contact with the surface of the hole. This is not only because to the instability of the tool, but also is due to the cylindricity deviations of the experimental specimen's inner surface. The combined tool reaches the optimal working temperature, after a certain time of operation that leads to the shape correction of the hole, and that is why the roughness heights start to reducing again.

The contour diagram shown in figure 3. b), shows the effect of cutting speed and feed on the resulting roughness heights after applying the machining by the combined tool, described by the regression equation (2). It can be seen that when the tool exit from the hole, the similar phenomenon is observed again. The roughness heights are increased at the high values of the cutting speed and the feedrate. The reason for such effect is the design of the tool again, namely when the tool exits from the hole, it only works with its burnishing part. The other reason is that the degree of the plastic deformation is affected from the feedrate magnitude, and as it is known, the roughness heights also is affected from that regime parameter. At high feedrate magnitude and low values of the cutting speed, the tool becomes unstable in the exit of the hole because its burnishing part is not working in an optimal condition. This is because the resistance coefficients and burnishing forces in the tool' guides are not perfectly uniform: one of the guide & burnishing inserts stop to contact properly with the processed surface, and this results to plastic deformation decrease, which affects the resulting roughness heights, respectively.

6. CONCLUSION

The results from the current research reveals the influence of the main regime parameters: speed and feedrate over cylindrical inner surfaces roughness heights that are processed by the combined boring and burnishing tool. Some positive effects of the combined operation for cutting and burnishing of the investigated specimens are established, due to the roughness height reducing. As can be seen the reduction is between 1.86 and 3.33 times (see Table 1), in comparison to the permissible roughness height values according to the factory norms observed in the specialized enterprises producing hydraulic equipment. At the same time, it is clear that there is a difference between the height of the roughness at the entrance and at the exit of the cylinder, which are about 22.3%. They due to the higher resistance when combined tool is working at the exit of the hole. Therefore, it is necessary to find ways to increase the stability of the combined tool machining scheme. The obtained results of the study will be used for future improvement of the design of double-acting tools. The team's future work will be focused on identifying approaches for their application in combined processing of functional surfaces of parts with the possibility of forming more specific textures on them, than only decreasing the roughness heights.

7. ACKNOWLEDGEMENTS

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CERCETĂRI PRIVIND RUGOZITATEA SUPRAFEȚELOR CILINDRICE INTERIOARE PRELUCRATE PRIN UTILIZAREA UNUI DISPOZITIV CU EFECT COMBINAT

Articolul prezintă rezultatele experimentale ale unor încercări experimentale cu privire la influența vitezei de așchiere și a avansului de lucru asupra rugozității suprafeței cilindrice interioare rezultate prin utilizarea unui proces hibrid de așchiere și de deformare plastică superficială. Procesul de prelucrare cu efect dublu se realizează cu ajutorul unui dispozitiv special conceput pentru prelucrarea găurilor prin așchiere, urmată de o netezire a stratului superficial prin deformare plastică. În calitate de epruvete, se folosesc bucșe standard din oțel S355, utilizate la fabricarea cilindrilor hidraulici. Aplicând metoda suprafeței de răspuns din programarea experimentelor, au fost obținute modele stohastice, care descriu influența valorilor parametrilor de așchiere asupra rugozității suprafeței rezultate. În partea finală a lucrării, sunt prezentate și discutate modelele stohastice obținute, evaluându-se semnificația acestora.

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