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STUDY OF DURABILITY IN THE CONNECTION “CONE-TUNGSTEN CARBIDE INSERT” FOR TENSION DEPENDENCE

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Abstract. During and after the technological operation of pressing these factors significantly determine the residual stress states of tungsten carbide inserts, as well as in the areas near the holes of the cones’ crowns of the cone. The stressed state of the inserts and the magnitude of the stress concentration determine their fatigue strength of them and the durability of the inserted carbide rock-blasting equipment of the cones in the area where the inserts the cone.

Dimensional analysis was done for the inserts and holes in the cones of bit and it was established that size errors of component links of dimensional chains are distributed according to laws that are similar to the normal law of distribution of random variables. The test was carried out according to the criteria of Pearson and Kolmogorov.

The influence of various random and systematic factors results to the dispersion of dimensions on the dimensional processing of conjugated surfaces. The amount of tension is a function of the dimensions for mating surfaces during assembly operations. Dispersion of dimensions for the component links of the dimensional chain of a press connection causes the formation of a practical field of dispersion of the closing link.

Accuracy control for the closing link in the dimensional chain is impossible if there are no direct measurements of the constituent links. A mathematical model of the process of assembling “cone-tungsten carbide insert” joints was created. For this, the methods of mathematical statistics were applied in the study.

It was established that the tension values have a greater influence on the force of pressing inserts into the holes of drill steels 14 NiCrMo1, when its hardness value is HRC 59–60 compared to HRC 48-50. This dependence has a linear character within the limits of the studied tension values. The established relationships make it possible to reasonably and most accurately form selective groups of inserts and mark holes for them. This method significantly reduces losses in the production of drilling tools.

Keywords: rock-destroying insert, tension, criteria of Pearson, cone, tricone drill bits, frequency of increment, random distribution.

Introduction

Factors complex influence the hard alloy rock-destructive equipment of roller cone bits life. Design and technological factors note especially among them. During and after the technological operation of pressing these factors significantly determine the residual stress states of tungsten carbide inserts, as well as in the areas near the holes of the cones’ rolling-cutter row. The stressed state of the inserts and the magnitude of the stress concentration determine their fatigue strength of them and the durability of the inserted carbide rock-blasting equipment of the cones in the area where the inserts enter the cone.

The tension state in the body of the rolling-cutter row of the cone also determines the strength of the connection "tungsten carbide inserts – the body of the cone", the initiation of residual plastic deformation or cracks in the body of the cone's rolling-cutter row. Pressing of tungsten carbide inserts should be carried out under the condition of optimal values of design and technological factors.

This makes it possible to reduce the amount of stress concentration and, therefore, will increase the durability of the insertion of hard alloy rock-destructive equipment in the cones. Therefore, it is necessary to study the nature of the influence of these factors in the entire real range of changes in the design and technological parameters of insertion hard alloy rock-blasting equipment for the purpose of optimizing the values of the studied factors.

Aim

The process of forming holes for inserts includes a complex of mechanical cutting operations (drilling, core drilling, reaming), which are performed at various stages of chemical and thermal processing. Tungsten carbide inserts have the final operation of grinding the cylindrical surface of the shank. They are purchased materials, used in the condition of delivery. The influence of various random and systematic factors results in the dispersion of dimensions on the dimensional processing of conjugated surfaces. The amount of tension is a function of the dimensions for mating surfaces during assembly operations. Dispersion of dimensions for the component links of the dimensional chain of a press connection causes the formation of a practical field of dispersion of the closing link.

Accuracy control for the closing link in the dimensional chain is impossible if there are no direct measurements of the constituent links. A mathematical model of the process of assembling "cone-tungsten carbide insert" joints was created. For this, the methods of mathematical statistics were applied in the study.

This makes it possible to determine the distribution parameters of the closing link by samples of the component links. (for example, tension).

Review of literature sources

In recent years, many works [1–3] have been devoted to the improvement of the pressing technology of tungsten carbide inserts into cones. The authors were looking for different ways to solve the problem of ensuring the durability of the insertable hard alloy rock-blasting equipment of tricone rock drilling bites. In particular, in [4, 5], the parameters and requirements for the technology of manufacturing cones and developed technologies for assembling the connection "cone-tungsten carbide insert" are established. In the studies [6–8], special attention was spared to the relationship between a complex of technological and design parameters. The effectiveness of the "cone-tungsten carbide insert" connection is being investigated.

The main requirements have been developed regarding the organization and implementation of technological operations for the assembly of rock-destructive equipment on the bite's cone. At the same time, a number of parameters that determine the accuracy of assembling the "cone-tungsten carbide insert" connection need to be studied in detail. For example, the practical provision of dimensional chains for technological pressing operations can be analyzed.

Main Part

Dimensional analysis was done for the inserts and holes in the cones of bit and it was established that size errors of component links of dimensional chains are distributed according to laws that are similar to the normal law of distribution of random variables. The test was carried out according to the criteria of Pearson and Kolmogorov. It is known that the tension in the connection "cone-tungsten carbide insert" is the difference between the shank's diameter of the inserts and the hole in the rolling-cutter row of the cone before assembly. Since this connection is performed with a guaranteed tension fit, the diameter of the shank of the inserts is greater than the diameter of the hole in the rolling-cutter row of the cone, so we have:

$$Z = (Y - X), \tag{1}$$

where X and Y are continuous independent quantities whose probability densities are known (diameters of the hole and shank's diameter of the inserts).

The density of the probability distribution of the tension value:

$$\varphi(Z) = \int_{-\infty}^{+\infty} f_1(X) f_2(X + Z) dX, \tag{2}$$

where $f_1(X)$ is the probability distribution density of hole diameters; $f_2(X+Z)$ is the probability distribution density of insert shank diameters.

If the formulas of the probability distribution laws of the component links of the dimensional chain are substituted into equation (2), then we will have confirmation that the closing link distribution law corresponds to the normal distribution law of random variables. The mathematical model of the assembly operation based on two initial samples of the N fitting diameters of the tooth shank and the same number N of hole diameters creates an array of tensions based N^2 on the main hypothesis. That is, the array includes the voltage values of all possible N^2 component pairs and determines the characteristics of its distribution: expectation value, standard deviation, coefficients of asymmetry, and steepness.

According to recommendations [9], a sample volume of 100 was chosen. The value of the expectation value was estimated by the average value (unbiased estimate)

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i, \tag{3}$$

where N – sample volume (N=100); Xi – sampling effect.

The value of the dispersion and the standard deviation was estimated according to the shifted estimate:

$$s^2 = \frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^2 = \frac{1}{N}\sum_{i=1}^{N} X_i^2 - \overline{X}^2, \tag{4}$$

The value of the deviation is no more than 1 %, given the selected sample volume.

The accuracy of the value M_X was evaluated according to the Student's criterion t_a, when reliability is a =95 %:

$$\xi_{\overline{X}} = t_\alpha \sigma_{\overline{X}} = t_\alpha \frac{s}{\sqrt{N}}, \tag{5}$$

where s_X is the value of sampling variance.

When sample volume N is 100 and a =95 %, the Student's criterion t_a =1,99 [10]:

$$\xi_{\overline{X}} = 1.99\frac{s}{\sqrt{100}} = 0.2s, \quad M_X = \overline{X} \pm 0{,}25s.$$

The value of accuracy evaluation M_X performed according to the Pearson criterion when reliability is a =95 %:

$$\xi_{\bar{s}} = q_s s, \tag{6}$$

where $\xi_{\bar{s}} = q_s s$ – evaluation precision s; q_s – relative evaluation precision s.

When $k = N$ =100, a =95 %, q_s=0,15 [10]:

$$\sigma = s \pm 0.15s \tag{7}$$

Let's determine the asymmetry parameter *a* and coefficient of steepness *t* [10], if we take into account the accepted hypothesis about the normal distribution of values characterized by the sample:

$$\alpha = \frac{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^3}{Ns^3}, \tag{8}$$

$$\tau = \frac{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^4}{Ns^4}. \tag{9}$$

Testing of the hypothesis about the normal distribution of values, which is characterized by the sample, was performed according to the Pearson criterion:

$$\chi^2 = \sum_{i=1}^{m}\frac{\left(f_i - f_i'\right)}{f_i}. \tag{10}$$

where *m* – amount of measurement increments; *fi'* – theoretical frequency of increment; *fi* – empirical frequency of increment.

According to the distribution table of the Pearson criterion [9], for $k = m$-3 (m – the number of division intervals), the probability density function for the confidence coefficient was determined $P = 0.05$.

The analysis of the correlated relation of the parameters *X* and *Y* was performed according to the polynomial:

$$Y = r_{X,Y}X + r_{X,Y}\frac{\sigma_Y}{\sigma_X}, \tag{11}$$

where $r_{X,Y}$ – correlation coefficient $r_{X,Y} = \frac{C_{X,Y}}{\sigma_X \sigma_Y}$,

where covariation is $C_{X,Y} = \frac{\sum_{i=1}^{N}\left(X_i \sum_{i=1}^{N} n_{X,Y} Y_i\right)}{N} - \overline{X}\cdot\overline{Y}$,

where $n_{X,Y}$ – recurrence frequency of initial parameter value *X* when we know parameter value *Y* and correlation deviation [10]:

$$\eta_Y = \frac{\sigma_{\overline{Y}_X}}{\sigma_Y},$$

where s_Y – standard deviation of *Y* for measurement average $\overline{Y}$; $\sigma_{\overline{Y}_X}$ – standard deviation value of frequency average (when *X* is fixed value) and $\overline{Y}$ is overall mean value [10]:

$$\sigma_{\overline{Y}_X} = \sqrt{\frac{\sum_{i=1}^{N}\left(\overline{Y}_X - \overline{Y}\right)^2}{N}}.$$

Research results and their discussion

Holes were measured (table 1) in the peripheral rolling-cutter row of the cone for fitting insert cutter and the diameters of the shanks of the lot (100 pcs.) of insert cutter (Table 2) for the implementation of research.

The maximum and minimum values of tension:

$$Z_{min} = 0.024\ mm,\ Z_{max} = 0.137\ mm.$$

Root mean square deviation of tension values: $s^2 = 0.017236$.

The results of statistical calculations are presented in the Table 3.

Table 1

Manifold of hole measurements in the peripheral rolling-cutter rows of the bits for fit insert cutters (mm)

12.044	12.042	12.048	12.039	12.052	12.039	12.045	12.045	12.053	12.049
12.043	12.055	12.077	12.043	12.045	12.044	12.049	12.044	12.043	12.045
12.031	12.031	12.037	12.027	12.023	12.024	12.029	12.025	12.027	12.035
12.024	12.033	12.025	12.037	12.037	12.026	12.031	12.030	12.030	12.035
12.035	12.035	12.036	12.035	12.047	12.039	12.037	12.045	12.027	12.030
12.061	12.060	12.060	12.064	12.065	12.059	12.062	12.043	12.071	12.070
12.037	12.028	12.035	12.024	12.037	12.033	12.036	12.056	12.043	12.027
12.005	12.053	12.053	12.050	12.005	12.048	12.028	12.017	12.017	12.001
12.014	12.012	12.011	12.012	12.010	12.016	12.022	12.040	12.042	12.039
12.030	12.040	12.028	12.027	12.033	12.020	12.037	12.050	12.052	12.050

Table 2

Manifold of diameter measurements for the shanks of insert cutters (mm)

12.130	12.129	12.128	12.135	12.131	12.031	12.126	12.132	12.124	12.130
12.125	12.127	12.127	12.117	12.132	12.030	12.135	12.122	12.136	12.121
12.126	12.129	12.130	12.120	12.128	12.026	12.122	12.123	12.123	12.122
12.130	12.130	12.131	12.138	12.122	12.035	12.129	12.132	12.130	12.132
12.123	12.133	12.131	12.108	12.123	12.020	12.124	12.119	12.129	12.125
12.127	12.130	12.121	12.121	12.130	12.020	12.131	12.129	12.126	12.119
12.134	12.128	12.118	12.122	12.119	12.020	12.101	12.105	12.115	12.129
12.124	12.132	12.105	12.134	12.118	12.029	12.120	12.128	12.113	12.131
12.127	12.128	12.119	12.129	12.130	12.019	12.115	12.131	12.128	12.121
12.130	12.129	12.129	12.126	12.123	12.028	12.128	12.128	12.122	12.123

Table 3

Frequency distribution of the empirical tension array

No.	Tension (mm)	Frequency distribution	No.	Tension (mm)	Frequency distribution
1	0.024	1	21	0.084	666
2	0.027	2	22	0.087	800
3	0.030	3	23	0.090	705
4	0.033	2	24	0.093	790
5	0.036	7	25	0.096	753
6	0.039	10	26	0.099	567
7	0.042	22	27	0.102	504
8	0.045	36	28	0.105	444
9	0.048	46	29	0.108	270
10	0.051	78	30	0.111	199
11	0.054	108	31	0.114	188
12	0.057	150	32	0.117	177
13	0.060	202	33	0.120	178
14	0.063	213	34	0.123	102
15	0.066	292	35	0.126	100
16	0.069	410	36	0.129	76
17	0.072	373	37	0.132	29
18	0.075	475	38	0.135	12
19	0.078	580	39	0.138	2
20	0.081	410			

According to statistical calculations, the theoretical curve of the random distribution of tension values was obtained during the pressing of the "cone-tungsten carbide insert" joint (Fig. 1).

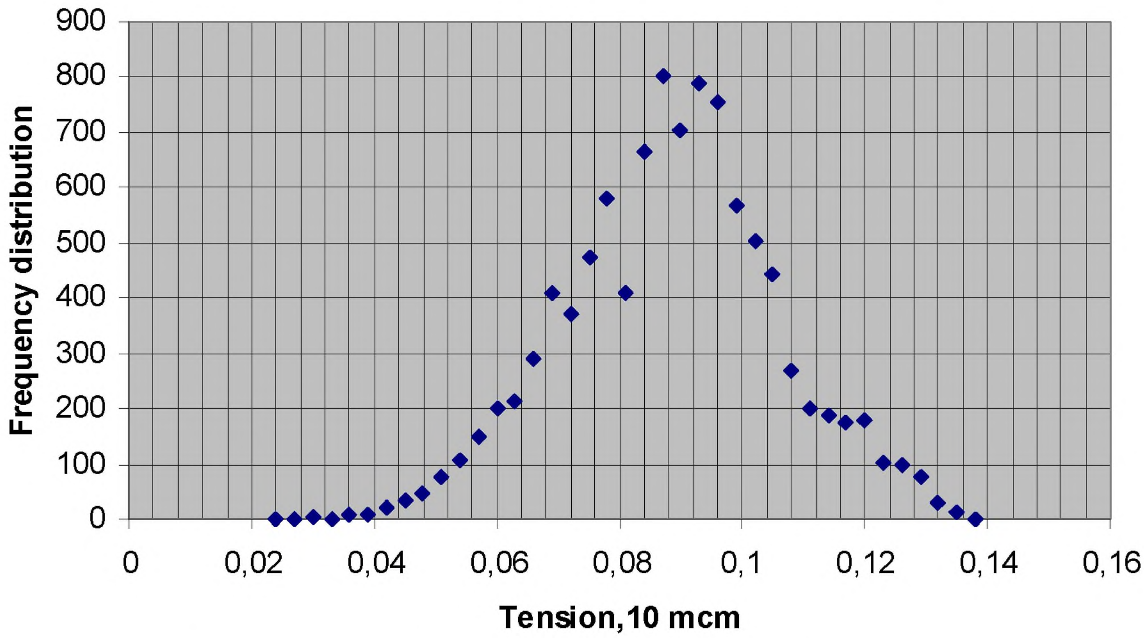

Fig. 1. Calculated curve of random distribution for tension values during pressing joint "cone-tungsten carbide insert cutter"

The accuracy of assembling the "cone-tungsten carbide insert" connection is carried out with tension.

It is determined by the stray field of the actual values of the diameters of the shanks of the inserts and the corresponding holes for their fitting. For this purpose, the nature of the influence of the tension value was investigated. It characterizes the accuracy of assembly on the strength of the "cone-tungsten carbide insert" connection. It is customary to estimate the strength by the values of the inserts pressing forces.

The character of the influence was established for the values of the tension on the pressing force and the hard alloy pressing inserts in the "cone-tungsten carbide insert" connection using the method developed in [4].

The extreme character of the relationship during extrusion (Fig. 2) of carbide inserts can be represented by an approximate function in absolute force values (kg)^

$$P_B = 70Z - 0.28Z^2. \tag{12}$$

The increase in pressing force with an extension in tension is explained by the increase in elastic deformation both in the cemented layer and in the core layers of the rolling-cutter rows. This can be illustrated by the stress model in the connection. The distribution of deformation increases in volume with extended tension. This causes a decrease in the expansion gradient of the pressing force. The extreme part of the relationship corresponds to tensions of 118–125 μm. This is explained by the characteristics of the strength and plasticity of the hardened drill steel. It is necessary to take the circumstances into account special attention to the chemical composition of the drill steel, the quality of the chemical-thermal treatment technology, etc.

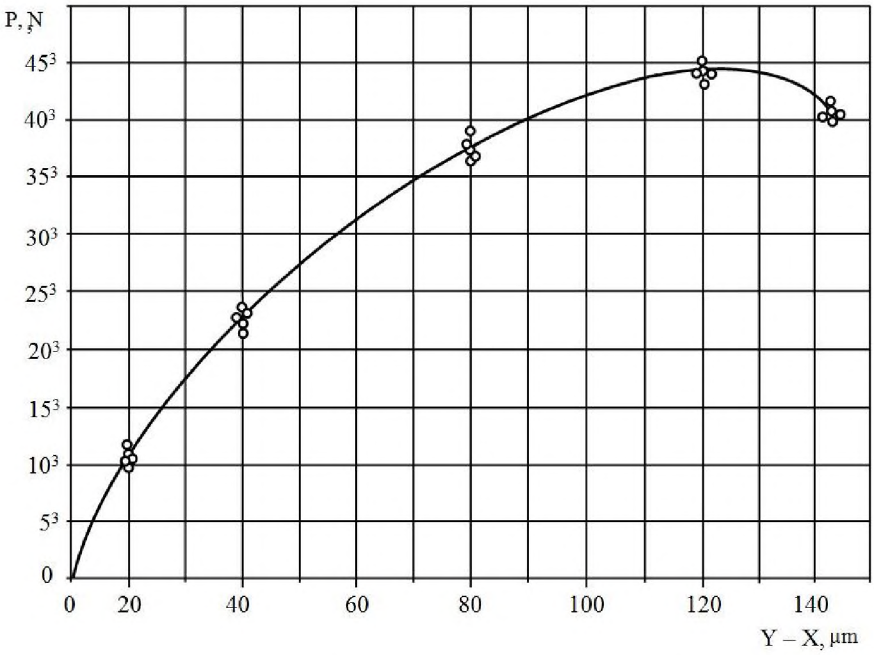

Fig. 2. The perceptual pattern tension values on the force of pressing insert cutter HG40 alloy way out holes of cone's steel 14 NiCrMo1 for HRC 59-60

Excessive tensions with an exceeded value of the extreme point cause the occurrence of unfavorable plastic deformation or destruction of the layers of the cone (which are conjugated along the height of the shank of the insert cutter). Irrational stresses arise in the body of a hard alloy insert cutter.

Conclusion

A mathematical model of the assembling process of "cone-tungsten carbide insert" joints have been created. It makes it possible to determine the parameters of the distribution of the closing link – tension by samples of the component links. The character of the random allocation of tension values was established during the pressing of the "cone-tungsten carbide insert" connection. For example, the tension of $Ø12^{+0,05}$mm holes for tungsten carbide inserts Ø12 mm was studied. Frequency distributions of the tension array are obtained where the dimension errors of the constituent links of the dimensional chains are distributed according to laws that are similar to the normal law of the distribution of random variables. It was established that the tension values have a greater influence on the force of pressing inserts into the holes of drill steels 14 NiCrMo1, when its hardness value is HRC 59–60 compared to HRC 48–50. This dependence has a linear character within the limits of the studied tension values. The more the tension, the more the requirements for steel strength indicators. The extreme nature of the relationship of the pressing force on the amount of tension for the connection "cone-tungsten carbide insert" has been established. This function can be used to design technological pressing operations for drill steels with different strength indicators. It is a characteristic of the strength of the connection. In our example, the rational tension limits are between 100–125 µm for pressing inserts into cemented and hardened rolling-cutter row of the cone.

The established relationships make it possible to reasonably and most accurately form selective groups of inserts and mark holes for them. This method significantly reduces losses in the production of drilling tools.

References

[1] A. Slipchuk, R. Jakym, J. Novitskyi, "Improvement in the Construction of the "Tungsten Carbide Insert Cutter–Cone" Joint for Tricone Drill Bits", *Ukrainian Journal of Mechanical Engineering and Materials Science*, vol. 8, No. 3, pp. 25–35, 2022.

[2] V. I. Bolobov, G. A. Iusupov, "Possible ways to expand range of rock strength, destroyed by cutter bit, *IOP Conference Series: Earth and Environmental Science*, vol. 87, No. 2, 2017.

[3] B. Ratov, B. Fedorov, A. Sudakov, I. Taibergenova, S. Kozbakarova, "Specific features of drilling mode with extendable working elements", *E3S Web of Conferences*, vol. 230, 2021.

[4] Y. Deng, M. Chen, Y. Jin, Y. Zhang, D. Zou, Y. Lu, "Theoretical and experimental study on the penetration rate for roller cone bits based on the rock dynamic strength and drilling parameters", *Journal of natural gas science and engineering,* vol. 36, pp. 117–123, 2016.

[5] V. K. Rohatgi, A. K. Ehsanes Saleh, "*An Introduction to Probability and Statistics*", John Wiley & Sons, 2015.

[6] Y. Yang, D. Song, H. Chen, X. Chen, L. Chen, "The research on the fixation strength of tapered cone bit teeth", *Engineering Failure Analysis,* vol. 124:105318, 2021.

[7] H. Zhiqiang, G. Li, "Optimization of cone bit bearing seal based on failure analysis", *Advances in Mechanical Engineering*, vol. 10, No. 3, 2018.

[8] E. Lukacs, "*Probability and Mathematical Statistics*". Academic Press: NY, 2014.

[9] R. Dieter, D. Schott, "*Mathematical statistics",* John Wiley & Sons: NY, 2018.

[10] M. Ramachandran Kandethody, C. P. Tsokos, "*Mathematical statistics with applications"* Academic Press: NY, 2020.