STATISTICAL ANALYSIS OF THE INFLUENCE OF THE MAGNITUDE OF THE INCLUDED ANGLE OF CEMENTED CARBIDE TIP ON STRENGTH WEAR

By

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1. Characteristics of strength wear of cutting edges and the present state of research

Interrupted machining as in face milling, planing and chiselling imposes load conditions on the cutting edges similar to those existing in the case of so-called impacts. In a short time, of the order of some milliseconds, the force acting on the cutting edge may increase to hundreds of kilograms giving a rate of load increase ranging from 150 to 700 tons per sec. [4, 5], after this there follows a complete discharge in an equally short time. Until a conventional degree of blunting is reached, the cutting edges are submitted to hundreds or even thousands of impacts per minute. In such conditions, the ultimate and the fatigue strength of the cutting edge may also influence wear. This is confirmed by observations of wear in cutting edges made of cemented carbides during the process of face milling and planing.

On the basis of statistical data delivered by certain factories and tests conducted by the author for several years, it was stated that the wear of cemented carbide tips caused by fracture and chipping made up 70 to 90% of the total of worn out tips [2, 4, 5, 6]. This fact clearly shows that previous research on the wear of cutting edges for abrasive blunting in the process of interrupted machining does not apply in the majority of cases.

The analysis carried out on wear of cemented carbides indicates that this is, at present, one of the basic problems in manufacturing technology. Research in the field of the strength wear of cutting edges made of cemented carbides are closely connected with the problem of efficient machining, the development of which can be observed in the general development of the technical process, the weak point of which is the tooling problem.

In evaluating the general progress in research in the field of the strength wear of cemented carbides it may be stated that previous research on the ultimate wear is relatively the most advanced [1, 3, 4, 5, 6], while research of the fatigue wear is fragmentary; only test pieces with a rectangular or round cross-section are considered without involving the influence of the shape of the investigated element resembling the cutting edges particularly as to fatigue strength. Attempt is being made to extend results obtained in this way to cover phenomena occurring in interrupted machining [7]. Laboratory model research for the strength wear of cemented carbide cutting edges — according to papers published so far — has not been carried out in a methodical way, especially in the field of fatigue wear. There is a lack of knowledge of relations existing between the geometry of the cutting edges, the magnitude of the area of the acting force and pressure on strength wear.

2. Conditions, test arrangement and apparatus

Laboratory research on strength wear covered cemented carbides of a wolfram-titanium group (P20 according to ISO) is being the most frequently used for cutting edges of machining tools working at varying loads. Tips of carbides originated from one batch from which test specimens were taken at random for the determination of strength properties and structure.

The following physical properties were established experimentally:

$$R_g = 100.3 \pm 2.31\ Kp/\mathrm{mm}^2 \left[0{,}983 \pm 0.0216\ \frac{GN}{\mathrm{m}^2}\right]$$

$$a_n = 0.85 \pm 0.12\ Kpm/\mathrm{cm}^2 \left[0{,}085\ \frac{MNm}{\mathrm{m}^2}\right]$$

$$\text{specific gravity } \gamma = 11.501\ \mathrm{G/cm}^3 \left[11{,}27\ \frac{KN}{\mathrm{m}^2}\right]$$

hardness 90.5 ± 1.35 HRA at the load of 60 Kp.

Metallographic examination of specimen plates showed:

— on a microsection not submitted to etching the normal porosity together with few graphite inclusions,

— on the microsection etched by the tarnish method the following microstructure was stated: on the background of a dark β phase-light crystals mainly of the α_1 phase (very fine) and of the α_2 phase (large).

The fracture of the cemented carbide was light, shining, red in hue, conchoidal. No pores, fissures, inclusions or other defects were stated in the macrostructure.

Surfaces of plates were ground on a grinding machine with an elastic clamp with grinding wheels of hardness H (Norton) and then finished by diamond grinding wheel and submitted to lapping by the polishing paste with B_4C grains.

Testing the influence of stereometry and dimensions of cutting edges at unit pressure was carried out on a pulsator of the author's construction (Patent Polish People's Republic Nr. 55735) fitted with a strain gauge (Fig. 1).

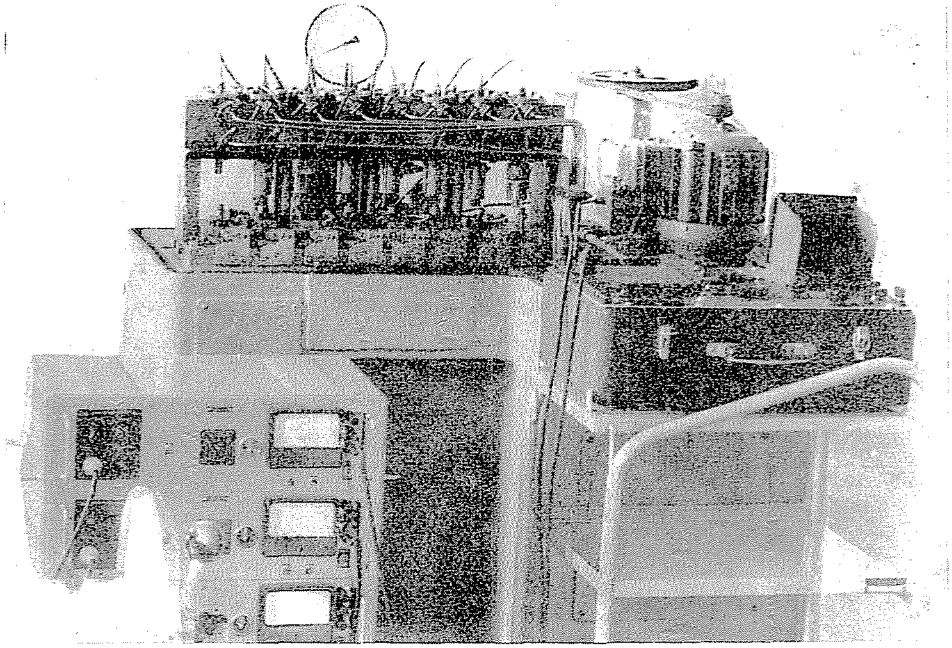

Fig. 1. Stand with the measuring apparatus for fatigue tests of cemented carbide plate[5]

Self-adjusting fastening of the end to the piston rod of a pulsator created such conditions that the force of the pressure was perpendicular to the surface of the cutting edges and was uniformly distributed over the surface.

3. Motivation of the methodology of analysis of results

The influence of the cutting edge angle (wedge) β and of the magnitude of the surface exposed to the force causing the strength wear may be treated as a complex of main causes. Cemented carbides belong to the brittle and heterogeneous materials which create a number of random causes influencing strength properties.

In connection with this, cemented carbides are especially suitable for research applying mathematical statistics methods.

The condition of applicability of this method in research on mass phenomena is to show that the examined magnitudes have the features of random variables which, in the case of cemented carbide cutting edges, are as follows:

a) Strength quantities are the random function of space edges in the defined volume of material. There is no reproducibility of the results in these measurements as cemented carbides are a heterogeneous material containing stronger and weaker elements (various sizes of grains and pores, various shapes of pores, various inclusions and so on). The grain boundaries may be oriented unfavourably from the point of view of stress distribution;

b) The applied methods of measurement of strength wear in many cases do not exclude random influences acting during measurement on the value of the measured coefficients, e.g. the accuracy of placing the specimens, accuracy of the adherence of the pulsator element pressing on to the surface of the specimen wedge and so on.

The random character of fatigue strength of cemented carbide cutting edges is also justified by the following additional causes:

— The process of the dislocation formation at producing a fatigue fracture is of random character as a rule [8];

— The small volume of the cutting edge wedge and small dimensions of the surface area exposed to pulsating force determine in particular the influence of the scale effect according to W. WEIBULL [9].

To express mathematically the influence of examined parameters forming the set of main causes of the strength wear of the cutting edges when marginal causes exist, statistical methods were applied to estimate the components of a mass process.

4. Results and analysis of tests on strength wear of cemented carbide cutting edges

Specimens were characterized by a varying angle β of the cutting edge (Fig. 2); the thickness of tips (plates) was constant and was 14 mm. The magnitude of the area of the force acting on the cutting edge was established for a given dimension b and angle β of a plate by increasing width a. The plate was mechanically fixed to the surface of the pulsator table and adjusted using a micrometer screw.

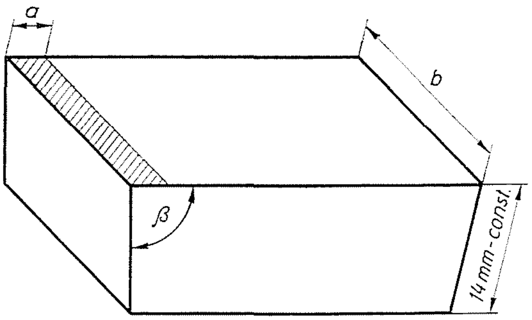

Fig. 2. Characteristic measures of a model-plate of the tested cutting edge on the strength wear

4.1. *Ultimate wear of the cutting edge*

On account of the possibility of observation it was assumed (according to other authors [4]), that ultimate wear of the cutting edge will be taken to be the chipping of the cutting edge occurring during the first five changes in pressure ($I = 1 - 5$).

The aim of investigations was to establish the destructive pressure p, depending on the cutting edge angle and on the width of area of the acting force.

Analyzing the influence of the angle β of a cutting edge (wedge) — Fig. 3 — it may be stated that with the increase of the angle the magnitude of the pressure destructing the cutting edge increases as well as the field of the scatter of results, which is in agreement with W. Weibull's theory.

The influence of the angle β on the mean value of the pressure destructing the cutting edge may be expressed by the following formula:

$$p = A \cdot \beta^x \tag{1}$$

Values of the coefficient x, dependent on the range of the angle β and the width of the area a, exposed to a destructing force are shown in Table I.

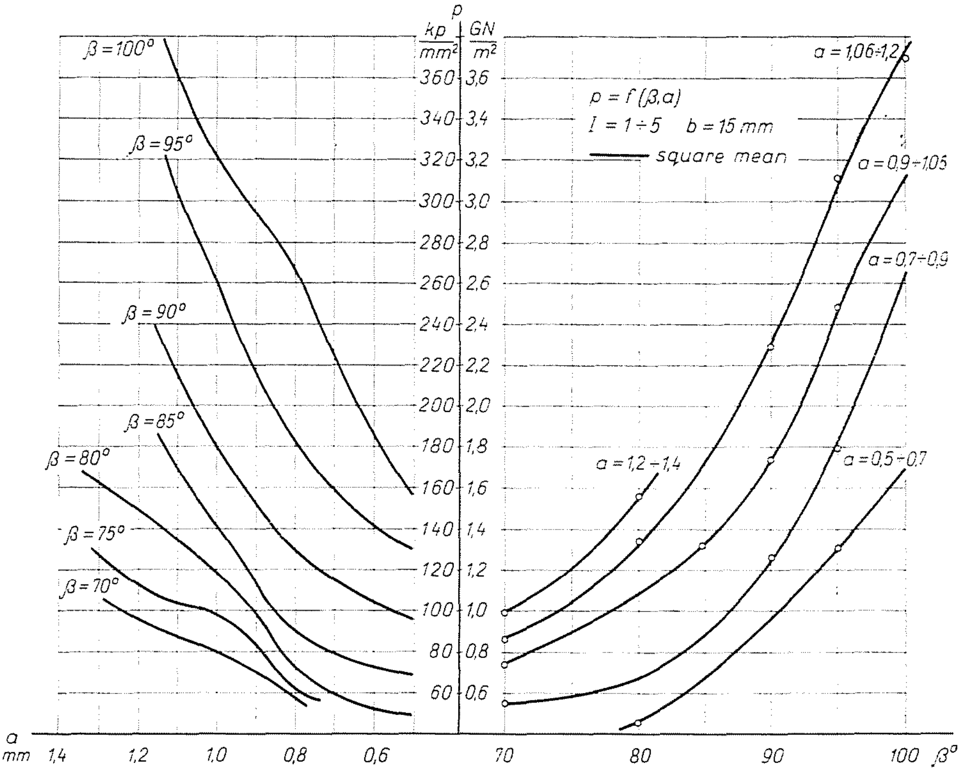

Fig. 3. The influence of cutting edge angle β and the width of the area of the acting force on the magnitude of the pressure p chipping cutting edge

Table I

The value of exponent x of the influence of the cutting edge angle β on the magnitude of distructive pressure

a [mm]	Cutting edge angle β						
	70	75	80	85	90	95	100
0.5 – 0.7	—	—	←		5.0–5.5		→
0.71–0.9	←	1.04	→ ←		5.0–5.5		→
0.91–1.05	←	2.9–3.1		→ ←	5.2–5.5		→
1.06–1.2	←	2.9–3.1		→ ←	5.2–5.5		→
1.21–1.4	←	2.9–3.1		→	—	—	—

4.2. *The fatigue wear of a cutting edge*

The research carried out by the author showed that the measured parameters: p, β, a — influence the number of cycles up to fatigue wear of the cutting edge.

To find curves fitted to points scattered in the coordinate system created many difficulties. It is known that the method of least squares gives fitting which fulfils the following conditions:

$$\Sigma(x_2 - \bar{x}_2) = 0 \tag{2}$$

$$\Sigma(x_2 - \bar{x}_2)^2 = \min \tag{3}$$

where $\bar{x}_2$ is obtained from the found function.

It has been stated, for the majority of tests, that e.g. the second-degree curve of parabolic shape fulfils the above conditions, which means that there is no other better suited parabola of second degree. This does not mean, however, that this parabola is the most suitable, as it would be possible to find another curve better suited that would give a less sum of squares of deviation than the sum of squares of the former curve. Thus the method of least squares does not solve the problem equivalently in spite of giving in regression the essential result which cannot be rejected. The statement of correlation does not always give the right to draw the conclusion that the obtained curve defined by a general equation $\bar{x}_2 = f(x_1)$ is the estimation of the unknown theoretical curve $\mu_2 = f(x_1)$ expressing the dependence between the random variables x_1 and x_2.

In searching for a curve of a shape best approximating the problem, various shapes were analyzed using a computer "Odra 1013" produced in Poland.

The curves best approximating the obtained results, took the form, according to a system of normal equations

$$\frac{\Sigma \ln x_2}{n} = \ln C + g \frac{\Sigma \ln x_1}{n} \tag{4}$$

$$\frac{\Sigma x_1 \ln x_2}{n} = \ln C \frac{\Sigma x_1}{n} + g \frac{\Sigma x_1 \ln x_1}{n} \tag{5}$$

where: n — the number of tests carried out.

After transformation we obtain:

$$\bar{x}_2 = e^{\ln C + g \ln x_1}. \tag{6}$$

Using the formula:

$$s^2_{x2} = \frac{\Sigma(x_2 - \bar{x}_x)^2}{n} \tag{7}$$

$$\sigma^2_{x2} = \frac{\Sigma(x_2 - \bar{x}_2)^2}{n} \tag{8}$$

where: $\bar{x}_2 = \frac{\Sigma x_2}{n}$.

The observed value of a coefficient of hyperbolical regression was calculated:

$$\varrho = \sqrt{1 - \frac{S^2_{x_2}}{\sigma^2_{x_2}}}. \tag{9}$$

Assuming that the random variable (x_1, x_2) has a normal distribution, the hypothesis H_0 $(\varrho_0 = 0)$ was put forward.

To verify the assumed hypothesis H_0 the quantity expressed by the formula was used:

$$\frac{\varrho}{\sqrt{1 - \varrho^2}} \cdot \sqrt{n - 2} \tag{10}$$

which has t-Student's distribution with $(n - 2)$ degress of freedom. The verification according to hypothesis H_0 served as a basis for the statement of an essential correlation between variables x_1 and x_2 and the established equation of a curve was recognized as an estimation of the function $\mu_2 = f(x_1)$ expressing the correctness occurring in the investigated population. The above function expresses an absolute regularity which would exist when only the complex of main causes acted on mass phenomena, but Equation (6) determines the mean value $\bar{x}_2$ of the random variable x_2 when the variable x_1 assumes various

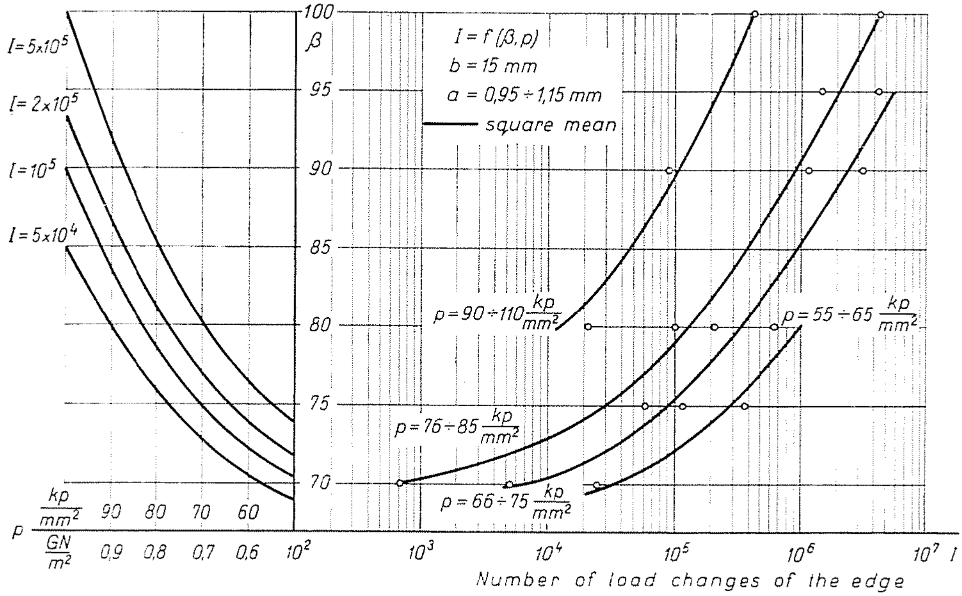

Fig. 4. The influence of the magnitude of the angle β on the number of changes of the cutting edge load J up to the appearance of fatigue wear with various magnitudes of the pressure p and with a ranging from $a = 0.95$ to 1.15 mm: $J = f(\beta, p)$

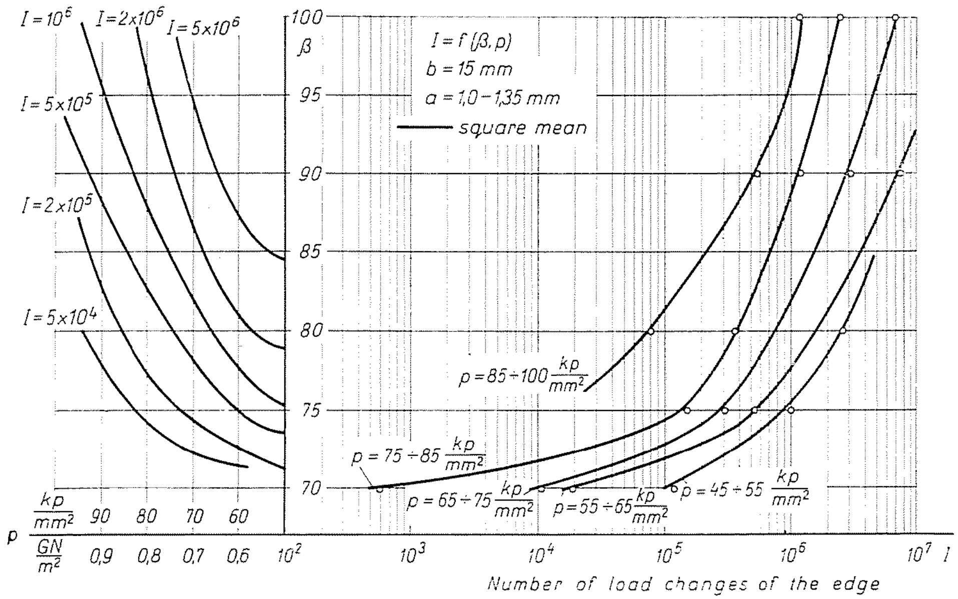

Fig. 5. The influence of the magnitude of cutting edge angle β on the number of load changes of cutting edge J up to the appearance of fatigue wear with various values of pressure p and with a ranging from $a = 1.0$ to 1.35 mm

values. Since the curve given in (6) is the approximation of absolute regularity, hence the mean values $\bar{x}_2$ are estimates of expected values μ_2, what permits the formulation

$$\bar{x}_2 \approx \mu_2 \tag{11}$$

4.2.1. The correlation between the cutting edge angle β and the number of changes of its load J up to reaching the fatigue strength with constants b and in certain periods a and p. The above correlation is illustrated by Figs 4 and 5 and examples of fractures are illustrated by photos in Fig. 6.

With the increase of angle β the number of changes of cutting edge load J increases until its chipping in an inverse ratio begins.

Between the number of load changes J and the value of the angle β — as shown in Table II — there is a strong curvilinear correlation in series of tests Nr. 128 and 131 and a slightly weaker correlation in series of tests 129 (for the range $75^\circ \leq \beta \leq 100^\circ$). Verification of the hypothesis H_0 ($\varrho_0 = 0$) on the level of essentiality $\alpha = 0.05$ permits its rejection in series of tests 128, 131 and 129. In these tests the values of the coefficient are essential.

In series of tests Nr. 130 the hypothesis H_0 cannot be rejected. The obtained equations of the hyperbolas of the type

$$\bar{x}_2 = e^{\ln C + g \ln (x_1 - k)} \tag{12}$$

are an evaluation for the test series 128, 129, 131 (approximation) of unknown functions $\mu_2 = f(x_1)$.

At some values of the angle $\beta < 75^\circ$ a rapid decrease of a number of changes of cutting edge load J follows up to the appearance of fatigue chipping in the examined ranges of pressures. The established hyperbolic regression does not involve the values of the angle $\beta < 75^\circ$.

4.2.2. The influence of the magnitude of pressure p on the amount of changes of load J up to reaching the fatigue strength for various values of angle β for ranges $a_1 = 1.06 - 1.2$ and $a_2 = 1.2 - 1.4$ mm (Figs 7 and 8).

The results of investigations are shown in Tables III and IV. Positive results are obtained when analyzing the series of tests No. 3, 1, 36, 37, 49, 51, 55.

In the remaining series of tests there is no value of coefficient of hyperbolic regression ϱ, or the value ϱ is small and for the high magnitude P the hypothesis H_0 cannot be rejected.

In positive results the curvilinear — hyperbolic correlation $0.475 < \varrho < 0.952$ appears between the quantity of changes of load J and the pressure p on the cutting edge. In connection with this it is possible to accept the established equations as the approximations of the function $\mu_2 = f(x_1)$ expressing the regularity occurring in the examined population.

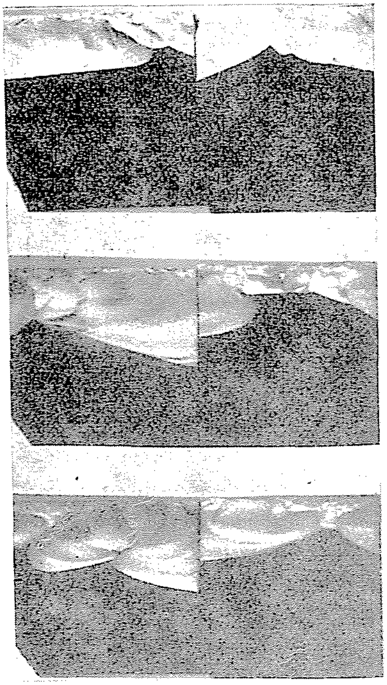

Fig. 6a. $\beta = 70^\circ$

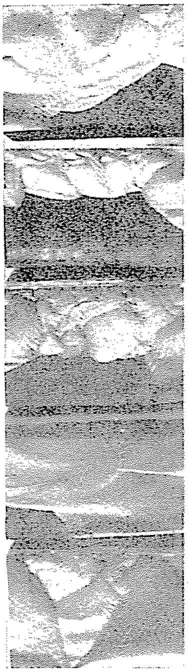

Fig. 6b. $\beta = 80^\circ$

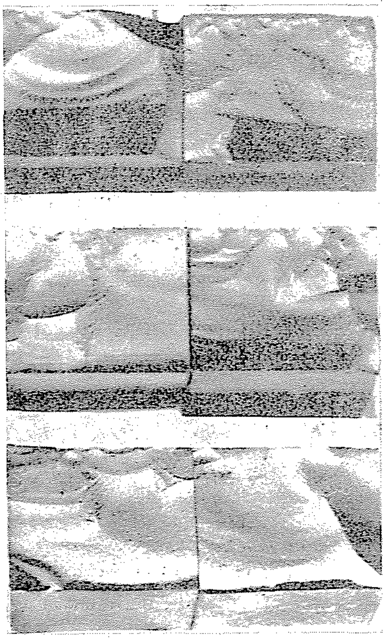

Fig. 6c. $\beta = 75^\circ$

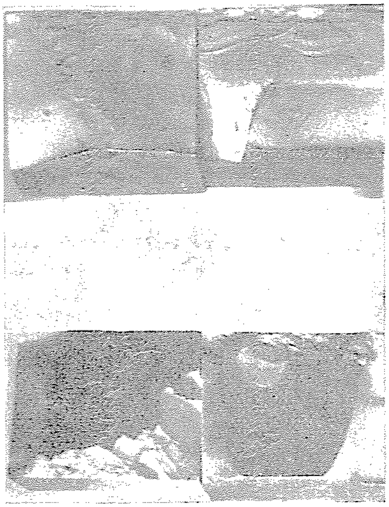

Fig. 6d. $\beta = 90^\circ$

Fig. 6. The influence of cutting edge angle β on the range and the appearance of the fatigue fracture of cemented carbide S20 cutting edges (P20 according to ISO)

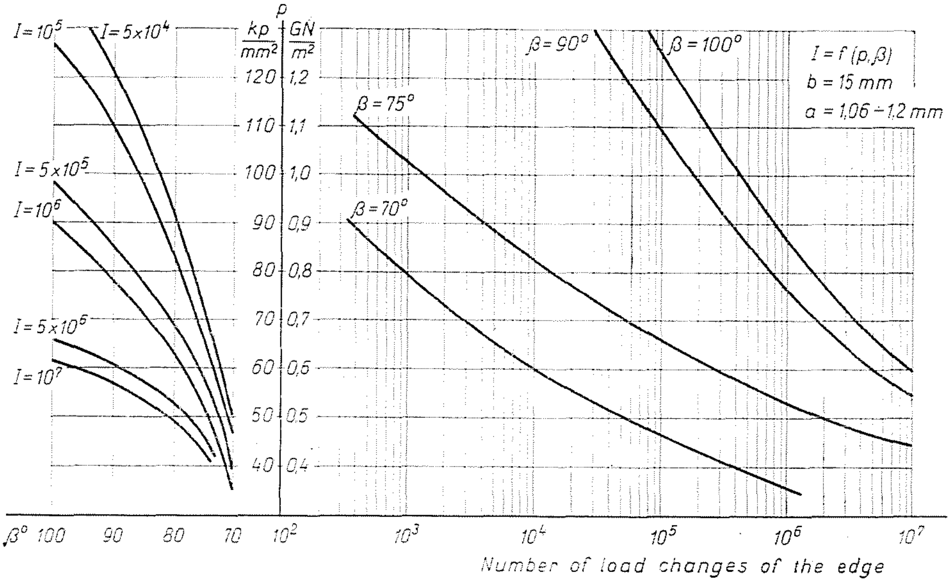

Fig. 7. The influence of the value of the pressure p on the amount of load cutting edge changes up to the appearance of fatigue wear with the changes in cutting edge angles β and with a ranging from $a = 1.05$ to 1.20; $J = f(p, \beta)$

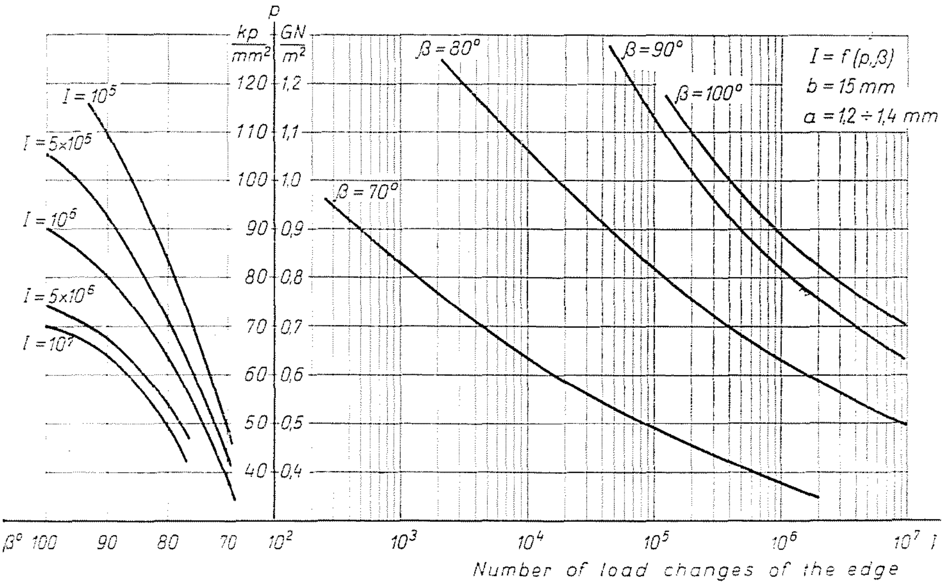

Fig. 8. The influence of value of pressure p on the number of changes in the load of cutting edge till the appearance of fatigue wear with changing cutting edge angle β and with a ranging from $a = 1.2$ to 1.4 mm

Table II

Results of analysis $J = f(\beta)$ the range $75° \leq \beta \leq 100°$ for various values of the width a of the area of action of the pulsating force

No of test series	Constants in test series			Number of specimens n	ϱ	t	$P(\|t_i\| \geq t)$	$H_0(\varrho_0 = 0)$	$\bar{x}_2 = f(x_1)$ $J = f(\beta)$
	b mm	a mm	p Kp/mm²						
130	15	0.95—1.15	65—75	33	0.264	1.535	$P = 0.1363$	cannot be rejected	$J = e^{-8,766+4,666 \ \ln(\beta° - 60)}$
128	15	0.95—1.15	76—85	36	0.753	6.680	$P > 0.00$	reject	$J = e^{-10,552+5,028 \ln(\beta° - 60)}$
131	15	1.00—1.35	65—75	38	0.590	4.386	$P > 0.00$	reject	$J = e^{-11,140+5,045 \ln(\beta° - 60)}$
129	15	1.00—1.35	76—85	42	0.423	2.905	$P = 0.0037$	reject	$J = e^{-9,216+4,590 \ \ln(\beta° - 60)}$

Table III

Results of analysis $J = f(p)$ for the range of angles $70° \leq \beta \leq 100°$ with $a = 1.06$ to 1.2 mm

No of test series	Constants in test series			Number of specimens n	ϱ	t	$P(\|t_i\| = t)$	$H_0(\varrho_0 = 0)$	$\bar{x}_2 = f(x_1)$ $J = f(p)$
	b mm	$\beta°$	a mm						
51	15	70	1.06—1.20	24	0.794	6.100	$P > 0.00$	reject	$J = e^{38,343-8,781 \ \ln p}$
55	15	75	1.06—1.20	24	0.533	2.964	$P = 0.037$	reject	$J = e^{57,967-12,356 \ \ln p}$
3	15	90	1.06—1.20	23	0.720	4.760	$P > 0.00$	reject	$J = e^{35,663-6,610 \ \ln p}$
1	15	100	1.06—1.20	17	0.952	12.121	$P > 0.00$	reject	$J = e^{34,438-6,151 \ \ln p}$

Table IV

Results of the analysis $J = f(p)$ for the range of angles $70° \leq \beta \leq 100°$ with $a = 1.2$ to 1.4 mm

No of test series	Constants in test series			Number of specimens n	ϱ	t	$P(\|t_i\| \geq t)$	$H_0(\varrho_0 = 0)$	$\bar{x}_2 = f(x_1)$ $J = f(p)$
	b mm	$\beta°$	a mm						
49	15	70	1.20—1.40	20	0.475	2.291	$P = 0.038$	reject	$J = e^{39,030-8,930 \ \ln p}$
46	15	75	1.20—1.40	19	has no value $S^2 = \sigma^2$	—	—	—	$J = e^{47,439-9,928 \ \ln p}$
42	15	80	1.20—1.40	18	0.277	1.154	$P = 0.250$	cannot be rejected	$J = e^{40,425-8,171 \ \ln p}$
37	15	90	1.20—1.40	19	0.882	4.952	$P < 0.002$	reject	$J = e^{38,727-7,191 \ \ln p}$
36	15	100	1.20—1.40	21	0.676	2.755	$P = 0.024$	reject	$J = e^{50,626-9,730 \ \ln p}$

For the remained test series — Nr. 42 and 46 the established functions approximate the theoretical model unsufficiently to the function of hyperbolic shape. From these test series with a changing range a and with the changing angle β it can be concluded an essential change of the main causes acting on these mass phenomena or else that the results of experiments contain an error of not random character.

5. Conclusions

The investigations carried out and their analysis permit the following conclusions.

1. With the increase of the cutting edge angle β its influence on the magnitude of destructing force and on the number of load changes decreases up to the appearance of fatigue wear. It was possible to state that there exists a range of the value of the angle β for which its influence on the wear of the cutting edge dictinctly changes. This range for the tested P20 plates (tips) — according to ISO — was:

— when establishing the force destructing the cutting edge: 75°—85°;

— when testing the fatigue strength of the cutting edge: 76°—80°.

2. As a result of analysis and by the use of the methods of mathematical statistics it was possible to establish for the range of laboratory research the dependence between the cutting edge angle β and the number of changes in its load J in order to obtain the fatigue strength in the form of a hyperbolic equation for various widths of the pressure field:

$$\mathrm{J} = e^{\ln C_1 + g_1 \ln p}\, e^{\ln C_2 + g_2 \ln \beta}\, e^{\ln C_3 + g_3 \ln \alpha} \tag{13}$$

or

$$\mathrm{J} = e^{\sum_{i=1}^{i=3} \ln C_i + G \ln p + \ln \beta + \ln a} \tag{13a}$$

where

$$G = \frac{\sum_{i=1}^{i=3} g_i}{3}\,.$$

Summary

This report presents research results for the influence of sintered carbide tips wedge angle on the fatigue wear.

From the experimental investigations and statistical analysis performed mathematical formulae have been established for the influence of the above mentioned angle on the number of changes of the tool point loads.

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