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INFLUENCE OF THE CUTTING WEDGE ON THE FORMATION OF MATERIAL REACTION TO THE CUTTING TOOL

WPŁYW GEOMETRII OSTRZA NA KSZTAŁTOWANIE SIĘ REAKCJI MATERIAŁU NA SKRAWAJĄCE NARZĘDZIE

The article presents results of studies on the influence of the cutting wedge geometry on the parameters of the work material and the value of the coefficient of friction between the cutting wedge and work material on the formation of material reaction to the cutting wedge. The studies were carried out by means of FEA analysis with the application of the ALGOR system that was extended to cover the problems of the contact zone. As a result of the analyses carried out, it was found out that the radius of the cutting edge rounding, coefficient of friction of the cutting wedge against the work material, value of the rake angle and size of the cutting wedge wear band have a decisive influence on the level of material reaction to the cutting wedge. The value of F_p/F_c ratio, i.e. the ratio between the force of material reaction to the cutting wedge (F_p) to the force exciting wedge movement (F_c) in the case of sharp cutting wedges (r_n = 0.01 mm, $\alpha_0 = \beta_0 = 5°$) ranged at the level of 0.3. Direction of reaction was such that the wedge was "pulled out" of the holder. An increase in the radius of the cutting edge rounding (r_n) to 1.5 mm caused a rapid decrease in the analysed ratio up to about 0.03 (or lower, depending on the coefficient of friction). Similarly, a decrease in the rake angle of the cutting wedge ($\gamma_0 = -7.5$) caused a decrease in the studied ratio up to the level of 0.1. Also the direction of the F_p reaction changed. The wedge was pushed out from the work zone. The tendencies observed by the present authors agree with the other results (Ingraffea et al., eds.).

Key words: rock cutting, modelling, reaction

W artykule przedstawiono wyniki badań nad wpływem geometrii ostrza, parametrów skrawanego materiału oraz wielkości współczynnika tarcia ostrza o skrawany materiał na kształtowanie się reakcji materiału na ostrze. Jak wykazują badania (np. Jonak 1994), wartość proporcji składowych całkowitej siły skrawania, tj. stycznej (F_c) do odporowej (F_p), w przypadku skrawania naturalnych materiałów kruchych (skał) waha się w przedziale 0,3–0,6, zależnie od geometrii ostrza czy właściwości skrawanego materiału. W niektórych przypadkach może ona osiągać znacznie większe wartości (1,0–3,5),

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np. dla stępionych ostrzy stożkowych, w trakcie skrawania np. piaskowców czerwonych, charakteryzujących się dużym współczynnikiem tarcia. Dla stali proporcja ta często waha się na poziomie 1,0–1,25 [3], zależnie od warunków skrawania i właściwości skrawanego materiału. Podobnie w procesie skrawania ceramiki technicznej, w szerokim zakresie parametrów skrawania, rodzaju i stanu ostrza oraz środowiska skrawania, występuje zależność $F_p > F_c$ (Kawalec i in. 2000).

Prezentowane badania prowadzono na drodze analiz MES, z wykorzystaniem systemu ALGOR, którego możliwości rozszerzono o zagadnienia kontaktowe. Analizę prowadzono dla płaskiego stanu odkształcenia, zakładając nieskończoną szerokość ostrza i pomijając wpływ oddziaływań bocznych powierzchni ostrza i skały. Przyjęto skrawany ośrodek skalny jako materiał dwuwarstwowy (pomiędzy ostrze a litą skałę wprowadzono warstwę pośrednią, symulującą zachowanie się warstwy miału, jaka powstaje pomiędzy ostrzem a skałą w rzeczywistym procesie skrawania). Analizę przeprowadzono dla różnych kombinacji stałych materiałowych charakteryzujących te warstwy oraz dla liniowej i nieliniowej charakterystyki materiału. W przypadku modelu nieliniowego przyjęto model ciała sprężysto-idealnieplastycznego Drackera-Pragera. W wyniku analizy stwierdzono, że na wartość reakcji materiału na ostrze, spośród jego parametrów geometrycznych, decydujące znaczenie ma promień zaokrąglenia krawędzi skrawającej, wartość kąta natarcia oraz wartość pasma zużycia ostrza. Ponadto, wartość tej proporcji zależy od parametrów charakteryzujących skałę, a w tym współczynnika tarcia ostrza o skrawany materiał, proporcji ich parametrów wytrzymałościowych (f_c/f_f), założonej sztywności warstw oraz ich liczby Poisssona. Wartość proporcji (F_p/F_c), tj. proporcji siły reakcji materiału na ostrze (F_p) do siły wymuszającej ruch ostrza (F_c), dla ostrza ostrego (r_n = 0,01 mm, $\alpha_0 = \beta_0 = 5°$) wahała się na poziomie 0,3. Kierunek reakcji był taki, że nóż był „wyciągany" z uchwytu. Wzrost promienia zaokrąglenia krawędzi skrawającej (r_n) do 1,5 mm powodował gwałtowne zmniejszenie się rozpatrywanej proporcji do wartości około 0,03 (i poniżej, zależnie od współczynnika tarcia). Podobnie, zmniejszanie kąta natarcia ostrza ($\gamma_0 = -7{,}5°$), powodowało zmniejszenie się rozpatrywanej proporcji do poziomu 0,1. Zmienił się też kierunek reakcji (F_p). Ostrze było „wypychane" ze strefy skrawania. Zaobserwowane tendencje są zgodne z wynikami innych badań (np. Ingraffea i in., w druku), niemniej niezbędne jest prowadzenie dalszych badań, celem doskonalenia proponowanej metody, zwłaszcza pod kątem opracowania procedur ułatwiających automatyzację niektórych czynności, zwiększenia precyzji obliczeń itd. Oczekuje się, że proponowana metoda stanie się wygodnym narzędziem projektowo-badawczym służącym do szybszego i bardziej efektywnego doboru narzędzi do skrawania określonych formacji skalnych itd.

Słowa kluczowe: skrawanie skał, modelowanie, reakcja

1. Introduction

Information on the cutting wedge loading during cutting is important for the correct selection of geometrical parameters of the tool holder or cutting wedge already at the stage of tool design. Analysis of the work zone, understanding of the process mechanics allows to choose the best possible material configuration of the cutting wedge — machined material and determine the most profitable values of the geometrical parameters of the cutting wedge or exploitation parameters of the process possible, already at an early stage. The methods of analysing conditions of material effort in the machined zone and in the cutting wedge of the tool based on the theoretical models are far more convenient than experimental methods and allow for a broad, preliminary analysis of various process variants. One of the more popular methods of analysis of these problems is the Method of Finite Elements which on more than one occasion was proved useful and has become one of the basic tools for the mechanical engineer, for example for the calculations of resistance. The most popular FEA systems are: ABAQUS, MECHANICA, NASTRAN, ANSYS, COSMOS, ADINA or ALGOR. Not all of them are suitable for the analysis of problems related to cutting brittle materials due to the fact that the calculation moduli offered are based on the criteria of the so-called border conditions that are adequate only for metals (plastic materials).

The Method of Finite Elements consists in substituting a continuos structure by a discreet (non-continuous) model that if further called "structure" (Zienkiewicz, Taylor 1979). Division of this structure into elements is called discretization. The following elements are subjected to digitisation: the inside of the structure, continuous loading, border conditions. Continuous loading are substituted by a static equivalent system of concentrated forces fixed in the nodes. Reaction between the elements appears through the nodes. Continuity of dislocations and angles of turning in the nodes is secured. The name of the method comes from the fact that the elements are small but have finite dimensions contrary to the indefinitely small dimensions applied in the theories of elasticity.

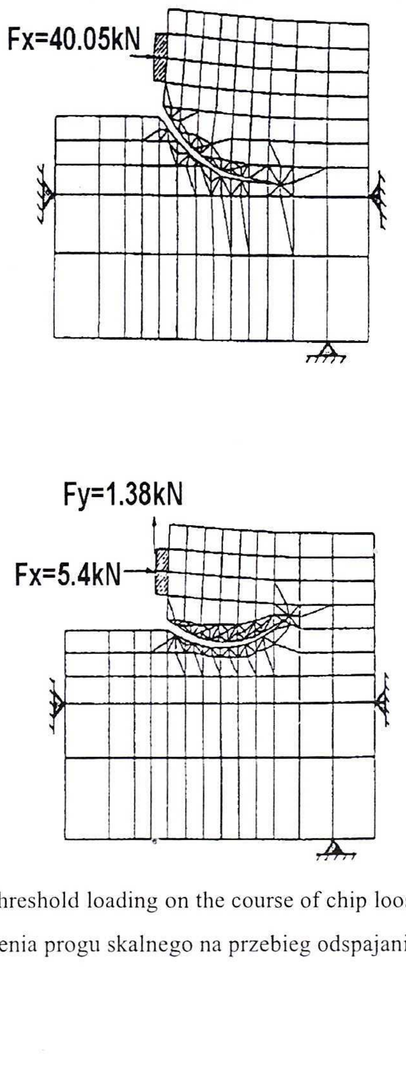


Fig. 1. Influence of the rock threshold loading on the course of chip loosening (Ingraffea et al., eds.)

Rys. 1. Wpływ sposobu obciążenia progu skalnego na przebieg odspajania wióra (Ingraffea et al., eds.)

As has been shown in some of the research works (Jonak 1996), the size of the ratio between the components of total machining force, i.e. the tangent F_c to the back (thrust) force F_p in the case of cutting natural brittle materials such as rocks, ranges from 0.3 to 0.6 depending on the geometry of the cutting wedge or the properties of the machined material. In some cases, it can reach markedly higher values (1.0–3.5), e.g. in the case of blunt conical wedges when materials such as red sandstone characterised by a high coefficient of friction are cut. In the case of steel, this ratio often ranges from 1.0 to 1.25 (Zębala, Gawlik 1996) depending on the conditions cutting and material properties. Similarly, in the process of machining technological ceramics, in the broad range of cutting parameters, type and conditions of the cutting wedge and the environment of cutting, the relation $F_p > F_c$ (Kawalec et. al. 2000) is true.

As has been shown in other studies (Ingraffea et al., eds.), in the case of cutting brittle materials, the value of the F_p/F_c ratio exerts a significant influence on the extend of the primary crack that generates the main chip element (Fig. 1) (Ingraffea et al., eds.). It is an important problem from the point of view of efficiency and energy consumption of the process of rock cutting with multi-tool heads. Due to the fact that propagation of the a.m. cracks itself requires the minimum energy input, conditions for the biggest possible extend of the cracks generated in front of the cutting wedge must be ensured. Then the volume of the loosened material in the basic machining cycle will also be the highest.

As can be seen from Fig. 1, the biggest loosening appears when the back (thrust) component (F_p) is close to zero. In-depth crack penetration, and hence chip volume, decreases when the ratio of the analysed force components increases. For the ratio that is equal to 0.254, it exceeds the level of the work surface only slightly.

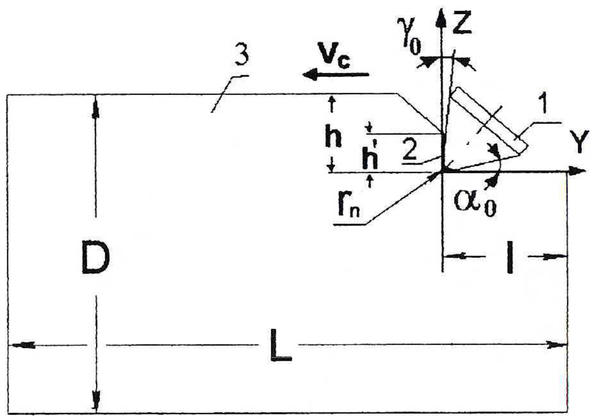
2. Analytical model of the machined zone

An analytical model of free machining presented in Fig. 2a was worked out for the analysis of the problems of formation of rock reaction to the cutting wedge in relation to its geometry and conditions of friction. Digitisation of the model together with the method of fixing its border nodes is presented in Fig. 2b.

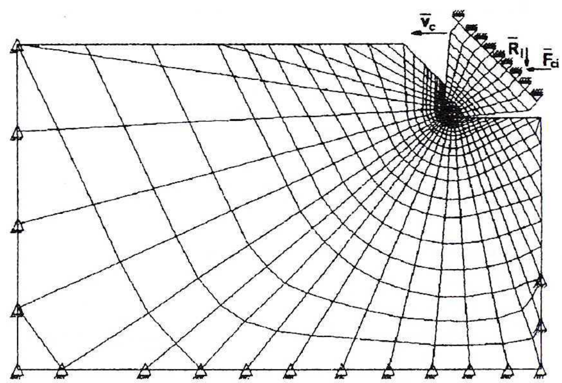
Geometry of the cutting wedge at the assumed stage of its wear is presented in Fig. 3.

The above problem was analysed for various geometrical variants of the cutting wedge that have been presented in Table 1.

In the variants I, IV, V and VI, very small, fictitious values of the angle of inner friction and stiffness were assumed for the contact layer. Similarly, in the II, III, IV and VI variants lower values of the Poisson's number were assumed (close to the values characteristic of plastic materials). On the one hand, it follows from the fact that compressed rock dust that appears in the real conditions of cutting, shows parameters comparable to condensed soil. On the other hand, the need for the maximum limitation of the chip element friction against the cutting wedge (aim of the analysis) was taken into



a)



b)

Fig. 2. Geometry (a) and border conditions of the model (b)
1 — cutting wedge, 2 — contact layer, 3 — machined material, D, L — dimensions of the machined zone, l — distance between the machined edge and the edge of the sample, h — thickness of the machined layer, h' — length of the contact zone between the face rake and machined material, r_n — radius of the cutting edge rounding, v_c — machining velocity, α_0, γ_0 — angles of rake and clearance of the cutting wedge, F_{ci} — machining force applied at the i-th node of the wedge mesh, R_i — force of reaction in the i-th supporting node of the cutting wedge mesh (F_{pi})

Rys. 2. Geometria (a) i warunki brzegowe modelu (b)
1 — ostrze, 2 — warstwa kontaktowa, 3 — skrawany materiał, D, L — wymiary strefy skrawania, l — odległość krawędzi skrawającej od brzegu próbki, h — grubość warstwy skrawanej, h' — długość strefy kontaktu powierzchni natarcia ze skrawanym materiałem, r_n — promień zaokrąglenia krawędzi skrawającej, v_c — prędkość skrawania, α_0, γ_0 — kąty przyłożenia i natarcia ostrza, F_{ci} — siła skrawania przyłożona w i-tym węźle siatki ostrza, R_i — siła reakcji w i-tym węźle podporowym siatki ostrza (F_{pi}).

consideration in order to ensure the widest possible range of position change for the element in relation to the cutting wedge. In the variants II and VI, the values of cohesion and inner friction assumed resulted from the Drucker-Prager's theory (for rocks, for

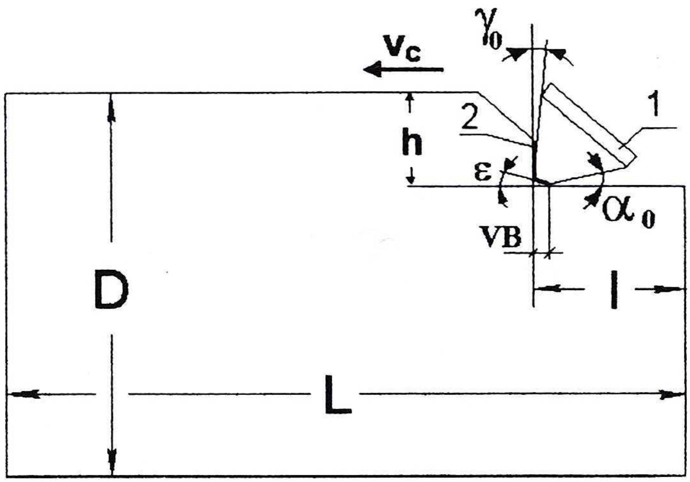


Fig. 3. Geometry of the cutting wedge model at the assumed stage of its wear
ε — angle of clearance in the blunt zone, *VB* — width of the band of wear

Rys. 3. Geometria modelu ostrza, w założonym stadium zużycia
ε — kąt przyłożenia w strefie stępienia, *VB* — szerokość pasma zużycia

TABLE 1

Parameters of the cutting wedge according to the assumed geometrical models

TABLICA 1

Parametry ostrza według przyjętych modeli geometrycznych

No of the geometrical model of the cutting wedge	1	2	3	4	5
Rake angle (γ_0)	5°	5°	5°	5°	–7.5°
Clearance angle (α_0)	5°	5°	5°	5°	2.5°
Radius of the cutting edge rounding — r_n [mm]	0.01	0.1	1.5	—	1.5
Width of the band of wear (VB) [mm]	—	—	—	0.4	—
Clearance angle in the zone of wear — ε				–7°	

f_c = 40 MPa and f_f = 2 MPa). In the remaining cases, fictitious values from the range characteristic of sand rock, were assumed.

3. Results of analysis

The values of the F_p/F_c ratio that were obtained in the present analysis, i.e. the ratio between the resultant of the material reaction (F_p) and the level of the force exciting the movement of the cutting wedge (F_c) in relation to the conditions of modelling, have been presented in Table 3.

TABLE 2

Parameters of the machined material and the contact layer (acc. to variants)

TABLICA 2

Parametry materiału skrawanego i warstwy kontaktowej (wg wariantów).

Variant	Material	E [MPa]	v	ϕ [°]	c [MPa]
I	contact layer	500	0.2	1	0.1
	machined material	10^4	0.2	30	2
II	contact layer	10^3	0.4	30	0.1
	machined material	10^4	0.2	69	3.7
III	contact layer	10^3	0.4	30	0.1
	machined material	10^4	0.2	30	2
IV	contact layer	10^3	0.4	1	0.1
	machined material	10^4	0.2	30	2
V	contact layer	10^3	0.2	1	0.1
	machined material	10^4	0.2	30	2
VI	contact layer	10^3	0.4	1	0.1
	machined material	10^4	0.2	69	3.7

TABLE 3

Form of the F_p/F_c ratio for the analysed geometrical models of the cutting wedge and material variants

TABLICA 3

Kształtowanie się proporcji F_p/F_c dla analizowanych modeli geometrycznych ostrza oraz wariantów materiałowych

No. of the geometrical model of the cutting wedge	Material variant					
	I	II	III	IV	V	VI
1	0.313	0.313	0.042	0.3	0.31	0.229
2	0.297	0.297	0.041	0.28	0.29	0.269
3	0.03	0.03	0.014(–)	0.007(–)	0.011	0.024(–)
4	0.256	0.256	0.025	0.213	0.237	0.125
5	0.104(–)	0.104(–)	0.046(–)	0.104(–)	0.106(–)	0.117(–)

Analysing the results obtained, it can be noticed that there are certain noticeable trends. For example, an increase in the radius of the cutting edge rounding is manifested as a significant decrease of the resultant reaction in the supporting nodal points of the cutting wedge. In the case of the cutting wedge model No.1 (r_n = 0.01mm) the reaction is directed according to the *O–Z* axis of the assumed co-ordinate system. Ratio between the forces of reaction and excitement is the highest in this case at the level of 0,3 (except the II and III material variant). The sense of the resultant reaction consistent with the *O–Z* axis shows that the cutting wedge No.1 is in a way "supported" by the supports before its flank gets deep into the work surface of the cut material at the thrust of the chip element on the cutting wedge rake surface. In this situation, in a way, there is no support for the cutting wedge from the flank surface which is explained by the assumed model of cutting. In the real conditions of cutting, there will be a tendency for pulling out the tool off its holder (such an effect was observed in the studies in industrial conditions but only when the angle of the cutting wedge rake was at the level of 25°).

For the cutting wedge model No.3, the value of the discussed ratio ranges at the level of 0.01. It is probable that due to the cutting wedge geometry, chip thrust onto the cutting wedge rake (in the direction of the *O–Z* axis) is balanced by the reaction of the material pressed under the cutting wedge. Hence it is possible, that the resultant of the components of the forced of friction and work material reaction to the cutting wedge (that is counterbalanced by the resultant reaction of the F_p support) in the rake face zone and rounding of the cutting edge located below the above mentioned D point, can take on values close to zero.

When the symptoms of the cutting wedge wear appear, the value of the F_p/F_c ratio is also lower. For the VB band width of 0.4 mm (cutting wedge model No. 4), the value of this ratio ranges at the level of 0.21–0.25. It is lower than for the cutting wedge model No. 1 and considerably higher than for the model No. 3. As it seems, the effect of cutting wedge "support" at the wear land side is weaker than in the case of the cutting wedge with rounded cutting edge (r_n = 1.5 mm).

The influence of the cutting wedge with a negative rake angle (model No. 5) is characterised by the change in the "sense" of the resultant reaction (the "–" sign in Table 3). Then the tendency to "push out" the cutting wedge from the work zone is predominant. The tool has to be pressed by the holder to the work surface to make machining possible. The value of the F_p/F_c ratio is not very high in this case, either.

As has already been mentioned, in the case of cutting natural brittle materials, the mean values of the F_p/F_c ratio determined from the temporal courses of these forces obtained with the application of the tensiometric dynamometers range from 0.25 to 0.32 for the sharp cutting wedges, 0.6 to 1.0 for the sharp conical cutting wedges and reach the value of up to 1.5 to 3.5 for blunt / worn cutting wedges (depending on the properties of the machined material). It should be stressed that these are mean values. As it is well known, cutting such materials is characterised by a certain cycle of the cutting wedge loading related to the periodical character of the process of chip formation. When a big chip element is being loosened, it forms only a small part of the cutting cycle. In longer time intervals, cutting takes place with a relatively small thickness of the work layer comparable to the size of the radius of rounding of the cutting edge. At the same time, the value of the a.m. ratio can be very far from the mean value. However, there are no more detailed data on the above subject in literature.

4. Conclusions

The present studies showed that the level of reaction of the work material on the cutting wedge is influenced by its geometrical parameters such as: radius of the cutting edge rounding or the rake angle. Equally important is the value of the coefficient of friction of the work material on the cutting wedge in the machined zone including both the rake face of the rounded cutting edge and the flank where the effect of elastic return of the machined surface and increased friction of the cutting wedge against the work material are observed.

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