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Optimization of Shape of Drilling Tools
L'optimisation de la forme des outils de forage
Optimierung der Konstruktion von Bohrwerkzeugen

L. MISHNAEVSKY JR, Stuttgart, Germany

ABSTRACT: An approach to the optimization of drilling tools which is based on the analysis of dependence of drilling cost on the tool shape is presented. The effect of tool shape on the energy consumption in rotatory drilling and on the lifetime of tool is studied analytically. It is shown that the main part of drilling energy is consumed not for the rock removal, but rather by the microfracture, shearing and crushing of rock in the zone of high hydrostatic pressure under the tool/rock contact surface.

RÉSUMÉR: Une approche a l'optimisation des outils de forage qui est basee sur une analyse de la dependance du forage coute sur la forme d'outil est presentee. L'effet de la forme d'outil sur la consommation d'energie dans le forage rotatoire et la vie de l'outil est etudie analytiquement. On montre que la partie principale d'energie de forage est consommee pas pour le deplacement de roche, mais plutot par la microfissuration, cisaillant et ecrasement de la roche dans la zone de la pression hydrostatique elevee sous la surface de contact.

ZUSAMMENFASSUNG: Die sich auf der Analyse von der Abhängigkeit Kosten des Bohrens von der Konstruktion des Werkzeuges gründete Methode der Bohrwerkzeugsoptimierung, wird dargestellt. Der Einfluss der Werkzeugskonstruktion auf Energieverbrauch beim Drehbohren und auf die Lebensdauer des Werkzeuges wird theoretisch untersucht. Es wird gezeigt, dass das Hauptteil der Energie bei der Bohrung für Sherungen und die Zerkleinerung des Gesteins in der Zone der höchen Dreiaxigkeit unter dem Kontaktoberfläche verbraucht wird.

1 INTRODUCTION

This paper seeks to develop an approach to the improvement of the efficiency of drilling, which takes into account both the efficiency of rock removal and the tool reliability, and is based on the analysis of the dependence of drilling costs of the tool shape.

Costs of drilling are determined to a large extent by the intensity of rock removal (which influences the labor and energy costs in drilling) and lifetime of tool (which determines the tool expenses). The intensity of rock removal depends largely on the efficiency of the use of energy in rock fragmentation, namely, it depends on which part of the applied energy is consumed for the plastic deformation, overcrushing of rock, etc., and which part is consumed just for the detachment of rock from the massif. The rock removal occurs as a result of the growth of large cracks under the rock/tool contact surface.

Therefore, the ratio between the part of applied energy, consumed for the formation of large cracks, and the rest of drilling energy characterizes the efficiency of energy distribution in rock fragmentation. This ratio depends on the tool shape (sharpness), orientation (rake, other angles of cutter), tool material properties, etc. Based on the consideration of the energy distribution in rock fragmentation, and on the analysis of drilling cost, we develop an approach to the improvement of the construction of drilling tools.

2 DRILLING COST PER UNIT VOLUME OF REMOVED ROCK - A CRITERIUM OF OPTIMIZATION OF DRILLING

Cost of drilling consists of three main components: labor, energy and tool costs. Cost of drilling per unit volume of removed rock can be determined by the following formula (Rossmanith et al. 1994, Sveshnikov & Mishnaevsky Jr 1988):

$$C = c_t\, t + c_A\, A + c_v\, t/T \qquad (1)$$

where C - cost of drilling per unit volume of removed rock ($/m^3), c_t - cost of one hour of work of the drilling machine, t - time needed to remove a unit volume of rock, c_A - energy price, A - energy required to remove a unit volume of rock, c_v - tool price, T - lifetime of the tool at given conditions.

The value C presents an evident and natural criterium of optimization of the drilling efficiency.

Consider this formula in detail. One may assume that the values c_t, c_A and c_v are constant. The time t can be determined as follows:

$$t = A/M \qquad (2)$$

where M - the engine power of the drilling machine.

Both the energy consumption A and the lifetime of tool T depend on the construction of tool.

3 ENERGY DISTRIBUTION IN ROCK FRAGMENTATION

3.1 *Mechanism of rock fragmentation under mechanical loading*

Rock fragmentation under mechanical loading includes typically the following stages (Mishnaevsky Jr 1998): surface deformation and then surface destruction of rock; formation of layer of destroyed and then crushed rock between tool and rock; formation of zone of inelastic deformation under contact surface (zone of high hydrostatic pressure, which turns out then into zone of crushed rock) and formation of cone crack; destruction of the rock volume bounded by the cone crack, formation of axial cracks; abrupt change in the direction of cone crack propagation or its branching, which lead finally to the spalling out of some volume of rock; the crushed rock as well as broken rock fly apart and the next cycle begins.

Usually, several (about 5-10) large, penny-shaped cracks are observed in rock (the cone cracks can be considered as a result of joining together the penny-shaped cracks - see Mishnaevsky

Jr 1998). The energy consumed for the formation of the macrocracks can be estimated by a formula:

$$A_m \sim kG\, N_M\, L^2 \qquad (3)$$

where k - the coefficient of brittleness of the rock (which is defined as the energy of the new surface formation divided by the energy of loading, and this value is assumed to be a material constant – Rzhevsky & Novik 1984), $N_M \sim 5...10$ - amount of the macrocracks in rock, G - specific energy of new surface formation, L - average diameter of the penny-shaped macrocracks.

3.2 *Relationship between productive and non-productive parts of drilling energy*

Let us estimate a ratio between the energy required by the formation of large cracks (axial, cone cracks, etc.; this energy is productive, since just large cracks cause the detachment and removal of rock) and the energy of formation of zone of crushed rock (this part of loading energy is unproductive).

Nikiforovsky & Shemyakin (1979) have shown that the crushed zone is formed due to the shearing along slip lines, and it corresponds to the specific (triangular) region of slip line field under the contact surface (see Figure 1). Artsimovich (1985) has shown that the contours of the crushed zone conform to the lines of maximal tangential stress. Since the region of slip line field, which transforms then to the zone of crushed rock, is of triangular shape, one can estimate the volume of this zone by the formula

$$V_{cr} \sim 0.5\, B\, L_{cr}^2$$

where L_{cr} is the linear size of the crushed zone under contact surface.

Assuming that the crushed rock consists of spherical particles of equal diameter, one can determine the energy consumption per unit volume of crushed rock as $p \sim 4.8\; k\; G\; v_o^{-1/3}$ (Rossmanith et al. 1994) and the energy consumed by the formation of crushed zone:

$$A_{cr} = pV_{cr} \sim 4.8\; k\; G\; V_{cr}\; v_o^{-1/3} \qquad (4)$$

where v_o - volume of unit particle of crushed rock. The value 4.8 $v_o^{-1/3}$ is the area of new surface formed in a unit volume of rock as a result of rock crushing (Rossmanith et al. 1994).

Using Equations 3 and 4, one can estimate the ratio of the energy of formation of large cracks to that consumed for the formation of the crushed zone:

$$\nu = A_m/A_{cr} = 0.42\; N_M\; v_o^{1/3}\; B^{-1}\; (L/L_{cr})^2 \qquad (5)$$

The linear sizes of the macrocracks in the rock (axial, cone, spalling cracks, etc.) are varied from 2 (for hard rocks) to 8 (for brittle rocks) sizes of the zone of crushed rock (Mishnaevsky Jr 1998):

$$L \sim (2...8)\; L_{cr} \qquad (6)$$

Substituting approximate values of N_M, L/L_{cr} and B into Equation 5 and assuming that the diameter of particles of crushed rock is about 0.1 mm (Blokhin 1982), one can obtain

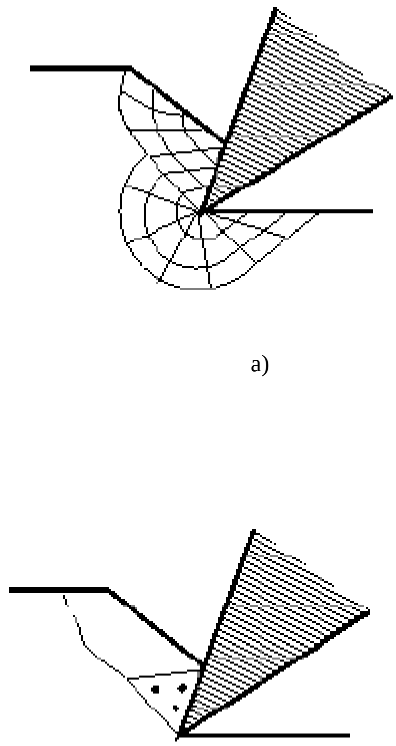
$$\nu = A_m/A_{cr} \sim 0.046 \qquad (7)$$

Thus, only about 5 % of the energy of drilling is consumed for the formation of large cracks, which cause the rock removal. Main part of the loading energy is consumed not to remove rock, but for the formation of the zone of crushed rock under the contact surface.

3.3 *Energy distribution in drilling: discussion*

The value ν characterizes the degree of efficiency of using the energy of loading for the removal of rock. One can see that the main part of the energy of loading is consumed not for the creation of macrocracks, but rather for other processes, which only accompany the rock removal.

This result can be compared with experimental and theoretical results of other authors: Kichigin et al. (1972) have shown that the formation of the crushed zone takes about 85 % of the energy of loading. Artsimovich (1985) has demonstrated that 70 % of the loading energy is consumed by this zone. Although the experimental results obtained by the authors differ from our results quantitatively, these results confirm qualitatively our main conclusion: the main part of energy of rock removal is consumed not for the rock removal, but rather by the microfracture, shearing and crushing in the zone of confining pressure.



a)

b)

Figure 1. Slip line field in rock in front of the cutter (a) and the form of the zone of crushed rock (b).

On the basis of available literature about the crushed zone, one can list the factors which are favouravle for the formation of this zone: accumulation of destroyed rock in contact area when it is not removed (Sulakshin 1964), high ratio between the depth of cut and the width of cutter (Mikhailov & Krapivin 1970), high ratio between tangential and normal cutting forces (Sulakshin 1964), or when the friction between crushed particles exceeds the friction between the particles and the cutter face (Moskalev et al. 1978).

One may suppose that one of possibilities to improve the drilling efficiency is to decrease the volume of this zone. Possibly, the high efficiency of sharp cutters, or that of cutters with cutting face inclined to the cutting vector is caused just by this effect.

3.4 *Volume of crushed rock zone in cutting*

Based on the assumption that the zone of crushed rock under contact surface corresponds to the triangular area of the slip line field (Mishnaevsky Jr 1998), one can obtain the following formula for volume of the zone of crushed rock in cutting:

$$V_{cr} \sim 0.5\ B\ l_s^2/\cos(\alpha + \beta - \pi/2) \qquad (8)$$

where B - cutter width, β - clearance angle of the cutter, l_s - step of chip spalling, which is proportional to the cutting depth (Mishnaevsky Jr 1994). Using Equations 6-8, one can derive the following relationship between the wedge angle of the tool and the energy consumption in rock cutting:

$$A \sim 0.5\ (1 + \nu)\ p\ B\ l_s^2/\cos(\alpha + \beta - \pi/2) \qquad (9)$$

Having plotted the energy A versus the angle α, one can see that the function $A(\alpha)$ has a minimum at $\alpha \sim 70^o$ at $\beta = \pi/10$.

4 EFFECT OF TOOL SHAPE ON THE LIFETIME OF TOOL AND DRILLING COST

4.1 *Lifetime of cutting tool*

Let us consider now a simple wedge-shaped cutter. The lifetime of tool is determined by two main factors: dulling of the tool due to the friction and wear, and the fatigue failure of the tool due to the cyclic interactions with chip elements. The dulling of tool can be modeled with the use of the model of wear based on the control system theory (Mishnaevsky Jr 1995). In the framework of this model, the following formula for the rate of tool wear was obtained:

$$i = (\gamma\ P/S_c)\ \exp\ (P\gamma vt/uS_c) \qquad (10)$$

where i – wear rate, u – surface deformation of the rock on the contact surface, γ - a parameter which depends on the structure of rock and tool material, P – cutting force, $S_c = B\theta$ - contact surface area, θ – length of the flank wear surface, v – velocity of cutting.

Another mechanism which determines the lifetime of tool is the fatigue failure of a cutter due to the cyclic interaction of the cutter with rock at each spalling of chip elements. To determine the number of interactions of the tool with chip elements until tool failure, one can use the Basquin relationship:

$$N = m\Delta\sigma^{\ n} \qquad (11)$$

where $\Delta\sigma$ – the range of the stress variation in the tool during the interaction of tool with the chip elements, m and n - material constants, N - the number of interactions of the tool with chip elements until tool failure.

Assuming that the cutting force is equal to zero, when the chip element is spalled, one can determine the range of the stress variation in the tool $\Delta\sigma$ by the formula:

$$\Delta\sigma = aP/\ f\ (\alpha) \qquad (12)$$

where a - proportionality coefficient (which includes the coordinates of the point of assumed failure initiation in the tool, etc.), α - wedge angle of cutter, $f(\alpha)$ - a function of alpha.

If the length of cutter/rock contact surface is much smaller than the depth of cutting, and assuming that the tangential component of cutting force is much greater than the normal component, one can determine the function $f(\alpha)$ as follows (Timoshenko & Goodier 1970):

$$f(\alpha) = (\alpha + 0.5 \sin \alpha)$$

Substituting Equation 12 into 11, one derives:

$$N = m\ [a\ P/\ f\ (\alpha)]^{\ n} \qquad (13)$$

If the lifetime of tool is controlled by the fatigue failure mechanism only, it can be calculated as follows:

$$T = N\ (l_s/v) \sim\ m\ (l_s/v)\ [a\ P\ /\ f\ (\alpha)]^{\ n} \qquad (14)$$

If the cutter does not fail, but is worn and should be replaced when the length of the flank wear surface reaches some critical value θ_{cr}, the lifetime of tool can be calculated by the formula:

$$T = (v\ \gamma\ P/S_c)^{-1} \log\ [(\theta_{cr}\ v/u)\ [\tan(\pi/2-\beta)+\tan(\alpha-\pi/2+\beta)]] \qquad (15)$$

4.2 *Dependence of drilling cost of tool shape: an example*

Equations 4-15 relate all the terms of Equation 1 with the shape of drilling tool. Substituting these Equations into Equation 1, one derives a simplified relationship between the drilling cost and the shape of tool:

$$C = [c_1 + c_2/\ f^{\ n}\ (\alpha)]\ V_{cr} \qquad (16)$$

where
$c_1 = (c_t\ M + c_A)\ (1 + \nu)\ p$,
$c_2 = (1 + \nu)\ p\ (c_v/M)\ m\ (l_s/v)\ [a\ P]^n$.

Equation 16 corresponds to the case when the lifetime of tool is determined by the fatigue failure mechanism.

It can be seen from Equation 16 that the cost of drilling increases with increasing the ratio ν.

Determining the minimum of the function $C(\alpha)$, one obtains the optimal wedge angle of wedge-shaped cutter. This method can be used also for the optimization of drilling regimes.

Figure 2 shows the dependence of the drilling cost of the wedge angle of the tool. In calculations, the following values have been used: $c_1 = c_2$, n = 2, $\beta = \pi/10$, $Bl_s^2 = 2$. Wedge angles of the tool α are plotted on the horizontal axis. The ordinate is the normalized drilling cost C/c_1. The normalized drilling cost C/c_1 is a value which is more or less independent of the purely economic factors, like energy price or worker salary.

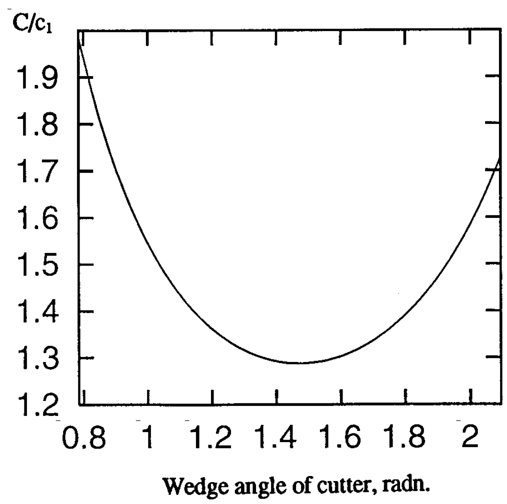


Figure 2. Normalized drilling cost plotted versus the wedge angle of cutter.

One can see from Figure 2 that the function $C(\alpha)$ has a minimum at $\alpha = 80...90^o$ (1.4...1.6 radn.). One should note that the wedge angle of cutter which ensures the minimum of drilling cost appeared to be greater that the angle which ensures the minimum energy consumption in drilling. Actually, this result was to be expected: in limiting case, the minimum energy of drilling is achieved if the tool is extremely sharp and the wedge angle is extremely small, whereas the maximum strength and lifetime of tool can be achieved (in limiting case as well) if the wedge angle of tool is maximum. So, taking into account the requirements of both high strength of tool and high intensity of rock fragmentation should give greater values of the optimal wedge angle than the solution based only on the consideration of the efficiency of rock fragmentation.

5 CONCLUSIONS

The method of optimization of drilling tool shape based on the minimization of drilling costs is presented. The possibility of practical application of the method is demonstrated for the case of optimization of wedge angle. This approach allows to optimize the tool shape taking into account both the effect of tool shape on the energy consumption in rock and the dependence of the lifetime of tool of the tool shape. It is shown that the main part of the drilling energy is consumed not for the formation of macrocracks which cause the detachment of rock, but rather by the rock crushing in the zone of confined pressure under contact surface.

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