MARIAN DOLIPSKI*, PIOTR CHELUSZKA*, PIOTR SOBOTA*

THE RELEVANCE OF THE ROTATIONAL SPEED OF ROADHEADER CUTTING HEADS ACCORDING TO THE ENERGY CONSUMPTION OF THE CUTTING PROCESS

ZNACZENIE PRĘDKOŚCI OBROTOWEJ GŁOWIC URABIAJĄCYCH KOMBAJNU CHODNIKOWEGO ZE WZGLĘDU NA ENERGOCHŁONNOŚĆ PROCESU URABIANIA

The article presents the outcomes of extensive computer investigations the purpose of which was to identify the impact of cutting heads' rotational speed on the load applied on the cutting heads drive as well as on the efficiency and energy consumption of the cutting process. The investigations were performed based on a simulation of the rock cutting process within a wide range of rocks' compressive strength with a roadheader transverse head equipped with 80 conical picks. Variations were taken into consideration in the rotational speed of the cutting heads and variations in the factors connected with the properties of the drives driving the cutting heads on the load condition of the cutting system and on the energy consumption of the cutting process.

The computer simulations carried out indicate that a reduction is possible in the energy consumption of cutting the rocks with low workability by decreasing the cutting heads' rotational speed thus preventing also the excessive load on the cutting heads drive. Possibilities are presented along with a concept of the heads' automatic speed adjustment according to the power utilised in the cutting process.

Keywords: roadheader, cutting heads, rotational speed adjustment, cutting process, load, energy consumption

W artykule przedstawione zostały wyniki obszernych badań komputerowych, których celem było określenie wpływu prędkości obrotowej głowic urabiających na obciążenie napędu głowic urabiających, wydajność oraz energochłonność procesu urabiania. Badania te przeprowadzone zostały w oparciu o symulację procesu urabiania skał w szerokim zakresie ich wytrzymałości na ściskanie głowicą poprzeczną kombajnu chodnikowego wyposażoną w 80 noży stożkowych. Uwzględniono przy tym wpływ sposobu zmiany prędkości obrotowej głowic urabiających oraz czynników związanych z właściwościami napędów realizujących ruch głowic urabiających na stan obciążenia układu urabiania oraz energochłonność procesu urabiania.

Przeprowadzone symulacje komputerowe wskazują na możliwość redukcji energochłonności urabiania trudnourabialnych skał w wyniku obniżania prędkości obrotowej głowic urabiających, co przeciwdziała

*   INSTITUTE OF MINING MECHANISATION, FACULTY OF MINING AND GEOLOGY, SILESIAN UNIVERSITY OF TECH-NOLOGY, AKADEMICKA 2, 44-100 GLIWICE, POLAND

także nadmiernemu przeciążeniu napędu głowic urabiających. Wskazano możliwości oraz przedstawiono ideę układu automatycznej zmiany prędkości obrotowej głowic w oparciu o moc zużywaną do realizacji procesu urabiania.

Słowa kluczowe: kombajn chodnikowy, głowice urabiające, regulacja prędkości obrotowej, proces urabiania, obciążenie, energochłonność

1. Introduction

Rock cutting with the cutting heads of a boom-type roadheader is performed when picks are moving along a set trajectory. The shape of such trajectory and the movement speed of the picks (cutting speed) are the result of combining the cutting head's rotary motion and its advance motion. The rotary motion of a cutting head is caused by a drive in the cutting system, whereas rotational speed depends on the rotational speed of the driving motor rotor and on the ratio of the toothed gear (reduction gear) intermediating in the transmission of power onto the cutting heads. On the other hand, the advance speed of the cutting heads in advance motion and speed direction results from the type of motion performed (slotting of the heads, a boom deflecting parallel to the floor, a boom deflecting perpendicular to the floor, or, optionally, the combination of such movements). The basic working motion of boom-type roadheaders in the classical technology of cutting the heading face consists of the advancement of the heads in the direction parallel to the floor. The individual layer of the rock are cut during such motion. The field area of the lateral section of such layers depends on the size of the web and on the height of the cutting layer resulting from the advancement of the heads in the direction parallel to the floor. The advancement of the cutting heads in the direction parallel to and perpendicular to the floor is carried out by means of actuator mechanisms. The advancement speed is resulting, therefore, from the kinematic structure of such mechanisms and from the hydraulic drive's characteristic. In case of a roadheader equipped with a transverse head, the peripheral speed vector of boom swinging in the working motion (parallel to the floor) is perpendicular to the pick rotation plane. As a result, the picks are moving along the helixes described at the side surface of the torus. The speed is variable and its value results from:

− a load applied on the boom swinging mechanism generated by rock cutting resistance with specific mechanical properties, which results from the properties of a hydraulic drive,
− a value set by the operator – if proportional control is used in a roadheader.

The nominal rotational speed of cutting heads in the majority of roadheaders produced at present is constant. The speed can be changed in some cases, however. This can be done in two ways – using two-speed electrical motors or two-speed gears (Dolipski & Cheluszka, 2002). As a result – cutting can be done by means of two different rotational speeds of cutting heads – a higher speed when cutting soft rocks and a lower speed when cutting rocks with low workability and strongly abrasive rocks. A reduction in the rotational speed of cutting heads is leading to decreased cutting speed, which is advantageous due to the limited wear of picks. When cutting rocks with low workability with high abrasive properties, a value of 1.5 m/s is given as the maximum cutting speed due to efficiency maximisation and pick wear minimisation (Driesch, 1994; Driesch & Kleinert, 1993). The parameters of the cutting process, including – most of all – cutting speed, should therefore be accommodated to the properties of the cut rocks. The

determination of rocks' workability and abrasivity is hence fundamental for predicting cutting efficiency and the wear of picks (Vasek et al., 2006).

Two-speed motors used in the drives of roadheaders' cutting heads enable to adjust rotational speed on a 1:2 or 1:3 basis. The motors feature (approximately) a constant nominal value of the torque reached with both speeds (the rated capacity of the motor is not the same for both speeds). The situation looks differently if two-speed reduction gears are used. As the gear ratio is changing, so is changing – apart from rotational speed – the torque value transmitted onto the cutting heads (torque for lower speed is higher as adjustment is done at a constant value of rated capacity). Two-speed gears are characterised by their complicated construction as they are usually equipped with the pairs of gears, incorporated manually into a kinematic chain, producing different ratios. Toothed gears are used in some roadheaders in a cutting heads drive where a gear ratio can be changed by replacing the set of gears.

The articles embarks on the concept of accommodating the rotational speed of cutting heads considering the possibility of reducing a load on the cutting unit and of minimising energy consumption in the rock cutting process. Two technical options of adjusting such speed were examined into in the computer investigations based on the simulation of a process of cutting with a roadheader's transverse head: by changing the rotational speed of a motor rotor and by changing the reduction gear ratio. The first method consists in applying a two-speed motor in the driving unit of the heads or a frequency converter in an asynchronous motor supply system. The other method consists in applying a multi-speed gear.

2.   Research methodology

Computer investigations into the impact of a cutting head's rotational speed on its load and on energy consumption of cutting were carried out by simulating the process of cutting the heading face surface with a transverse head equipped with 80 pickboxes (Fig. 1). The head was designed for cutting hard rocks with a roadheader with the nominal power of the cutting system of $N_n = 200$ kW. The head is equipped with 80 conical picks with the pick angle of $\beta = 93°$ and with extension from the pick of $l_n = 64$ mm. There are 56 picks on the main part of the head, and 24 picks at the part of the head from the side of the reduction gear. The main part has the length of $L_Z = 610$ mm, while the part of the head from the reduction gear's side has the length of $L_R = 140$ mm, giving the distance of the picks measured along the axis of rotation of $L = 750$ mm. Diameters: the maximum and minimum diameter of the pick envelope at the main part of the head is, respectively: $d_{max} = 1100$ mm and $d_{min} = 550$ mm. The minimum diameter of the pick envelope from the reduction gear's side is $d_{min R} = 960$ mm.

The cutting picks on the main part of the head are highly ordered as they are arranged at four helixes with a large twisting angle and they form at the same time 12 helixes with a small twisting angle (with 4 or 5 picks). The picks at some area of the cutting head from the reduction gear side are arranged along a line being the continuation of helixes from the main part of the head. Owing to the twisting direction opposite to the direction of head revolutions, the first to touch the cut rock in each helix with a small twisting angle is the pick situated closest to the axis of head revolutions.

Investigations into the load applied on cutting heads and into energy consumption were performed in a programme for aiding the design process and for selecting the cutting heads called *Kreon v.1.1*. A computer simulation module allows to produce a number of characteristics of the cutting process forming a basis for assessing the suitability of the investigated cutting head in
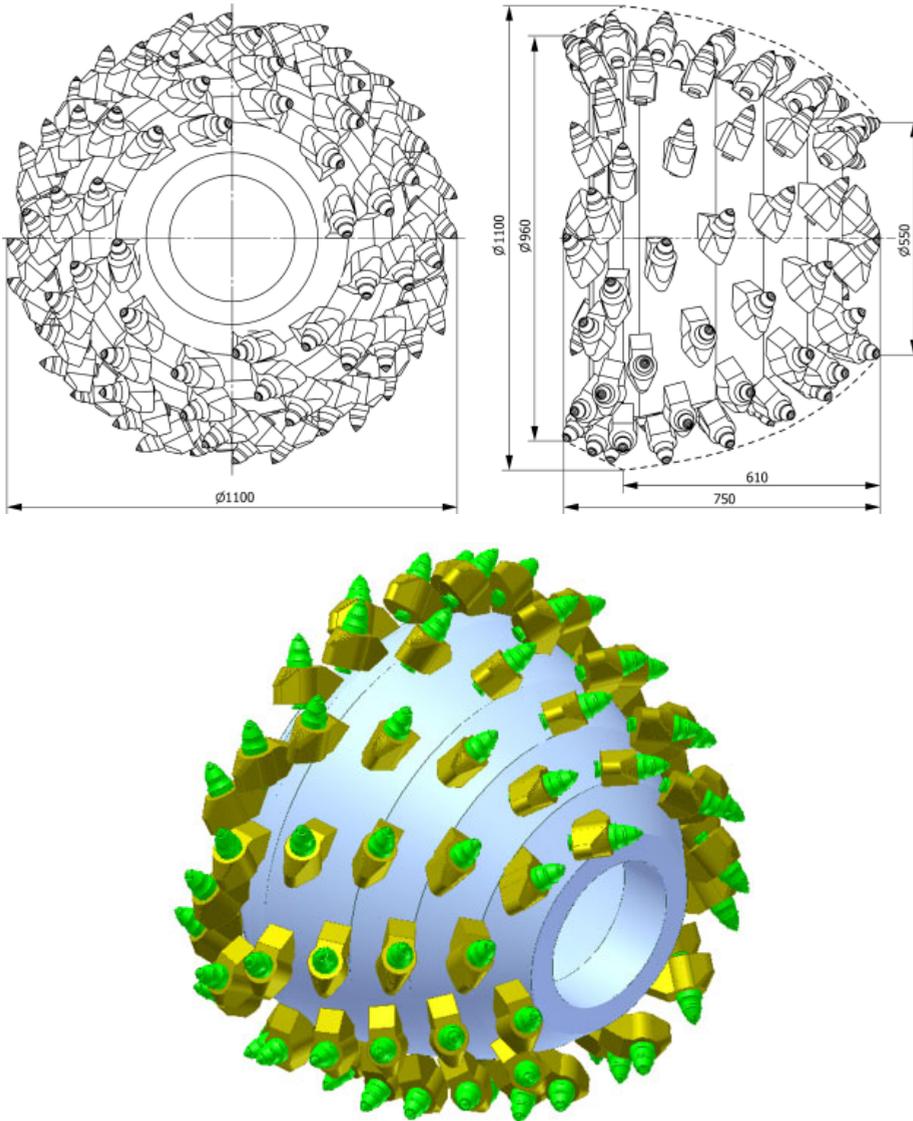
6

Fig. 1. A roadheader transverse head equipped with 80 pickboxes designed for cutting hard rocks

a roadheader's given operating conditions (Dolipski et al., 2006). The mean values of the following parameters characterising the cutting process progress were analysed for the purpose of performing these investigations:

- power at the motor output shaft in the driving unit of the heads N_U,
- energy consumption of the cutting process E_j,
- torque of the boom in a plane parallel to the floor M_{ow},
- efficiency of the cutting process Q.

A starting point for determining the values of the above parameters was to generate the graphics of a breakout in form of a projection of cuts made with particular picks taking part in the cutting process (Fig. 2). The values of parameters of particular cuts (cutting depth, cutting pitch, kinds of cuts) were so determined which formed a basis for determining picks' load and further – a cutting head's load (Dolipski & Cheluszka, 1999) – Fig. 3. At the same time, it was hence possible to determine the volume of cuts and also the cutting process' efficiency on such basis (Fig. 4). The cutting of a layer with the height of $h = 0.85$ m and with the web of $z = 0.2$ m was simulated (the height of the cutting layer is maximum for the assumed size of the web). Rocks with the compressive strength R_c of between 20 and 120 MPa and the breakability number of $\kappa = 15$ were cut in the investigations.
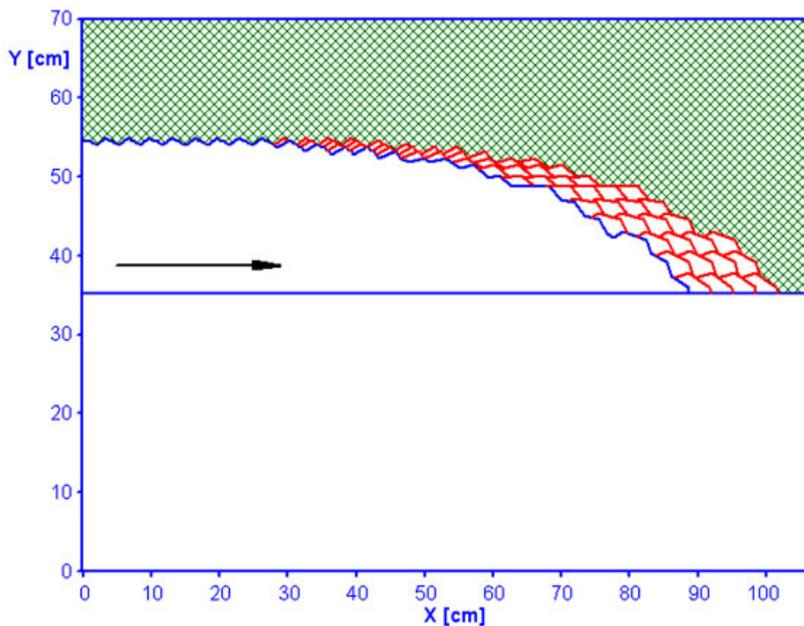

Fig. 2. A projection of cuts made with the examined cutting head for $n = n_n = 40$ RPM and $v_{ow} = 0.087$ m/s

An analysis of values of the parameters characterising the progress of the cutting process included two cases. It was assumed in the first case that cutting is carried out at the movement speed of the cutting heads v_{ow} corresponding to the permitted load of the boom swinging mechanism (the assumed maximum value of the boom torque of $M_{ow}^{max} = 285$ kNm). It is, therefore, the highest movement speed of cutting heads achievable in the given conditions. The progress of the cutting process was simulated in the other case by assuming that the load of the boom swinging mechanism is not a factor limiting the movement speed of cutting heads. It is thus assumed that the maximum boom swinging moment is sufficient for performing the cutting process, whereas a limiting factor is the power in the drive of the cutting heads.
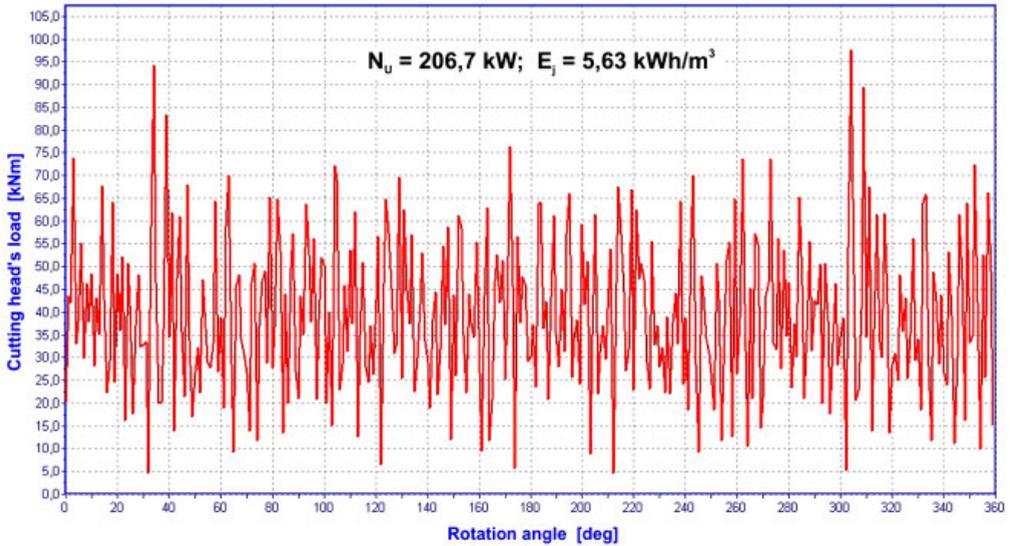
8

Fig. 3. The curve of the moment of load forces on the cutting head shaft while cutting the rock with the compressive strength of $R_c = 80$ MPa
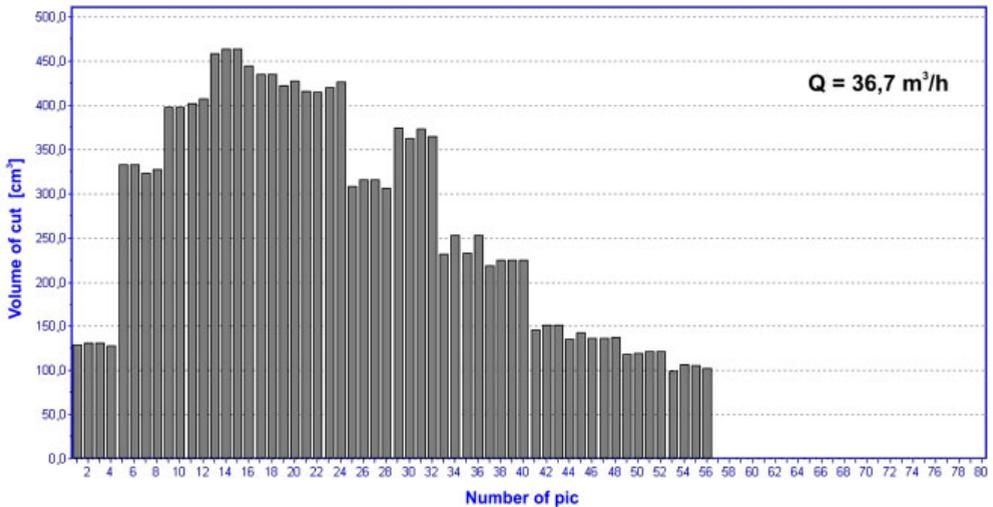

Fig. 4. The volume of cuts made with a cutting head's picks during one of its revolutions

The rotational speed of the cuttings heads n was changed in the investigations within the range of 10 to 60 RPM. The nominal rotational speed of a cutting system of the investigated roadheader was $n_n = 40$ RPM. A load on the cutting system and the energy consumption of cutting was therefore analysed both, for the rotational speed of cuttings heads smaller and higher in relation to the nominal value.

3. Analysis of computer simulations′ results

Fig. 5 shows a group of characteristics representing a relationship between the unit energy of cutting and efficiency for six different rotational speeds of cutting heads n and a maximum movement speed of the cutting heads v_{ow} according to a load on the boom swinging mechanism. The relationships are of a hyperbolic character, and the higher is the rotational speed of the heads, the closer are such characteristics to higher cutting efficiencies. For example, for $n = 10$ RPM (blue line), the forecast efficiency of the cutting process Q is between 7 m^3/h to 26 m^3/h which corresponds to the cutting of rocks with the compressive strength R_c of 20 to 120 MPa. The maximum efficiency resulting from the power parameters of the boom swinging mechanism (the maximum level was reached for the average boom torque M_{ow}) was obtained for $R_c = 20$ MPa. While efficiency is growing, the energy consumption of cutting E_j is lowering within 8.3 to 1.3 kWh/m^3. A nearly 4-fold increase in efficiency is hence accompanied by a 6-fold reduction in the energy consumption of cutting.
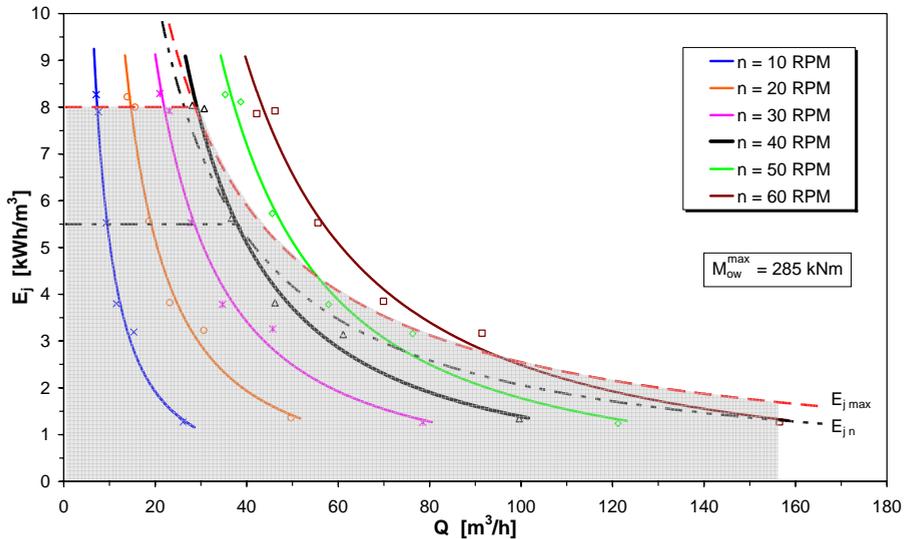

Fig. 5. The energy characteristics of the cutting process for various rotational speeds of cutting heads

Substantial growth in cutting efficiency was caused by increasing the rotational speed of the cutting heads to 60 RPM (brown line). The cutting efficiency of rocks with compressive strength from within the investigated range is, in such case, within 42 to even 156 m^3/h. Higher cutting efficiency is, therefore, proportional to the higher rotational speed of cutting heads. The energy consumption of the process for the mentioned range of efficiency assumes values from the range of 1.3 to 7.9 kWh/m^3. This range approximates the variability range of cutting efficiency corresponding to the lowest of the investigated rotational speed of cutting heads. High speeds allow, therefore, to achieve higher cutting efficiencies with the same energy consumption of the

process. By increasing the rotational speed of cutting heads, cutting can be done for higher boom swinging speeds with their maximum value depending on the hydraulic system's performance.

If an increase in the movement speed of cutting heads is proportional to the growth of their rotational speed (v_{ow}/n ratio is constant), then the average load of cutting heads when cutting rocks with the same compressive strength does not change. As cutting power is directly proportional to the rotational speed of cutting heads and cutting efficiency is directly proportional to their movement speed, thus a unit cutting energy does not change. Assuming, therefore, that boom swinging speed is set at a level corresponding to the maximum load value of the boom swinging mechanism, a change in the rotational speed of cutting heads does not influence the energy consumption of cutting, and the process efficiency only.

A factor limiting the speed of cutting heads' advancement is usually the maximum load of the drive unit of cutting heads, characterised by the amount of power consumed for implementing the cutting process. This limitation results from the permitted overload of the driving motor. It is assumed that the maximum overload of the drive of cutting heads during continuous work should not exceed $1.2 \cdot N_n$. This is a value commonly assumed in the settings of controllers of cutting machines' working parameters, for example the haulage speed of longwall shearers (Jaszczuk, 1999). Due to the dynamic character of the cutting process, the maximum load of the cutting heads drive mentioned above refers to the mean value of the power consumed in cutting N_U, in the time corresponding to the subsequent revolutions of cutting heads. A limiting curve (red dotted line) corresponds to the assumed, permitted overload of cutting heads drive ($N_U = N_{max} = 1.2 \cdot N_n$). Double-point line reflects the energy consumption of cutting for a nominal load of the heads drive ($N_U = N_n$).

The grey field outlines the area of the roadheader's effective work. The shape of this image is substantially influenced by the method of changing the rotational speed of cutting heads. If adjustment is done by repositioning the reduction gear (adjustment at constant power), a limiting curve is hyperbolic within the entire variability range of cutting heads' rotational speed. On the other hand, if speed is changed by changing the rotational speed of the motor rotor, for example as a result of applying a frequency converter, then – for the rotational speeds of cutting heads lower than nominal speed (here: $n < 40$ RPM), the maximum energy consumption of cutting corresponding to the assumed drive overload is constant (dotted line parallel to the axis of abscissa). This is the torque reached by a drive motor in this range is constant, and the power of the motor is proportional to the rotational speed of its rotor (adjustment at constant torque).

Fig. 6 illustrates the impact of the method of changing the rotational speed of cutting heads on the load applied on their drive. A dependency of the power consumed in the cutting process in the function of circumferential speed of boom swinging is decreasing. The lower is the rotational speed of cutting heads the smaller is the power consumed in the cutting process. At the same time the variability range of the cutting heads' advance speed v_{ow} is increasing narrower. As the rotational speed of cutting heads is dropping, their advance speed is nearing the smaller values. The permitted variability ranges are marked in the figure next to the nominal value of drive power corresponding to the individual rotational speeds of cutting heads (black double-point lines). It was assumed that the average power consumed in the cutting process should be within the range of $N_{min} = 0.8 \cdot N_n$ (green dotted line) to $N_{max} = 1.2 \cdot N_n$ (red dotted line). This interval reflects the optimum use of power of cutting heads drive. If the upper limit of this range is exceeded, this means that the drive is overloaded, whereas loading smaller than the lower limiting value signifies that the power installed in the cutting system is underutilised.
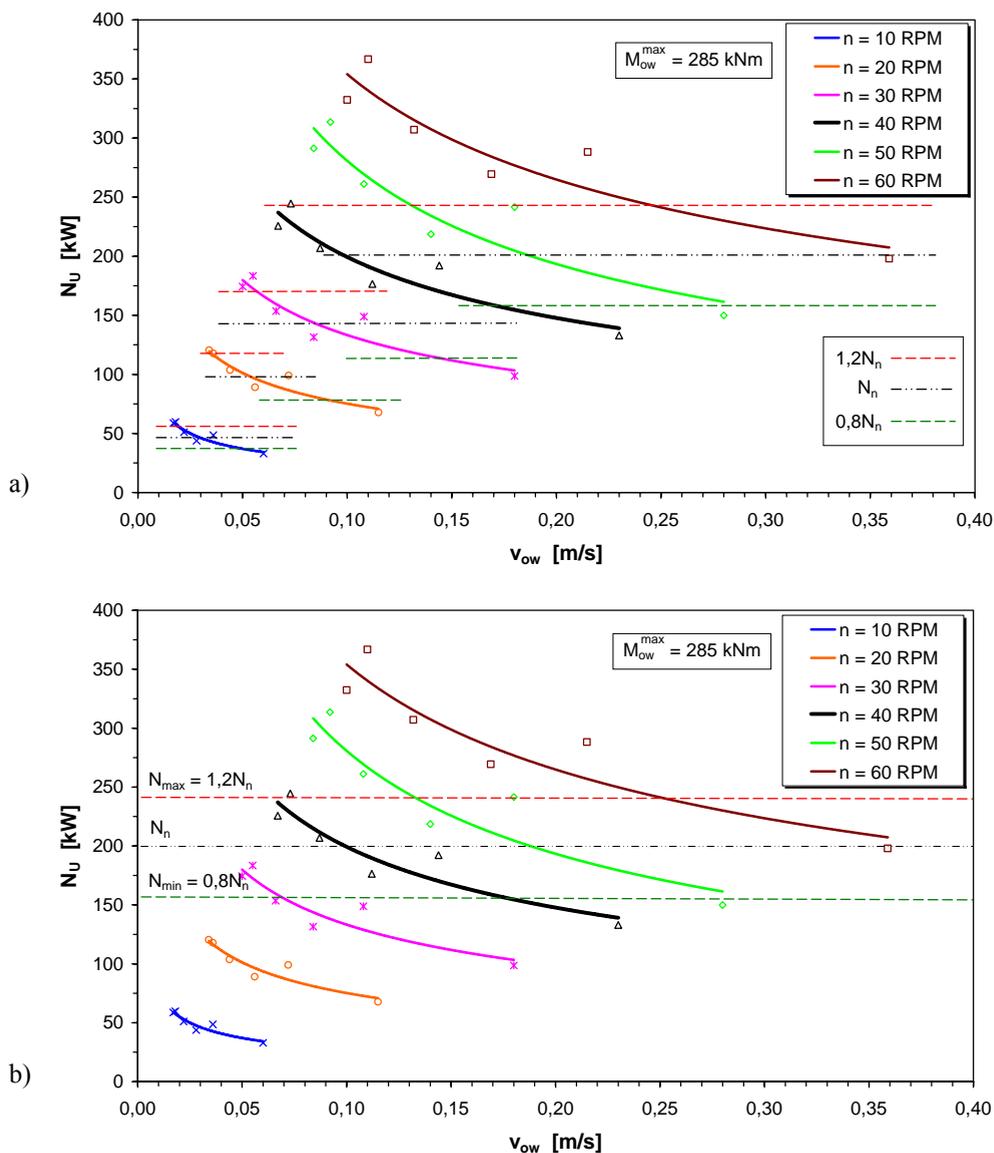
Fig. 6. A relationship between the power consumed by the cutting heads drive according to boom swinging speed in a plane parallel to the floor for various rotational speeds of cutting heads: a) change of the rotational speed of the drive motor rotor, b) change of a reduction gear ratio in the cutting system

When adjusting the rotational speed of a motor by changing power frequency, it was assumed within the range of speeds smaller than nominal that nominal power corresponds to the nominal value of torque. Nominal power for speeds higher than nominal speed is constant. The torque value reached by a drive motor changes, however.

If the rotational speed of cutting heads is adjusted and the rotational speed of the motor rotor is changed, for example by means of a frequency converter (Fig. 6a), the power consumed for the rotational speed of the cutting heads $n \leq n_n$ in the cutting process is, basically, within the range of 0.8 to 1.2 of nominal power. In case of the nominal speed of heads ($n = 40$ RPM), when cutting rocks with high workability, even at high advance speeds of the heads, the cutting system may underloaded ($N_u < 0.8 \cdot N_n$). This stems from the fact that the loading of the boom swinging mechanism is so small that the cutting heads are advanced with a maximum speed resulting from pump capacity in a roadheader's hydraulic system.

A drive load for the rotational speeds of cutting heads larger than the nominal value is different. In such case, the power available for performing the cutting process is equivalent to the nominal power of the drive motor. When cutting rocks with small workability (within the lower range of speed v_{ow}), although the mechanical load of boom swinging mechanism does not exceed the permitted value, the drive of cutting heads is considerably overloaded. As a result, energy characteristics for the rotational speeds of cutting heads higher than nominal speed are partially running over the limit curve marked in Fig. 5 (the working point is lying outside the area of a roadheader's effective work).

If the rotational speed of cutting heads is changed as a result of changing the gear ratio in the drive, then the degree of installed power utilisation changes within a broad range and greatly depends on the rotational speed of cutting heads (Fig. 6b). Only for $n = n_n = 40$ RPM, the power consumed in the cutting process is within the range of $(0.8 \div 1.2) \cdot N_n$ for almost the entire variability range of cutting heads' advance speed. It is important that the maximum cutting power basically does not exceed the permitted overload of cutting heads drive. This signifies that the picks system of the investigated cutting head has been selected correctly for the roadheader's designed capacity.

The drive, however, is overloaded for cutting heads' rotational speed values larger than nominal. This effect is analogous as in the case of adjusting the rotational speed of heads by changing the rotational speed of the drive motor rotor. On the other hand, when the rotational speed of cutting heads is smaller than nominal speed, then the drive is underloaded. This effect is amplified, in particular, for the smallest investigated values of this speed. This results from the fact that at low rotational speeds of heads, the torque developed by a drive is even 6 times higher than this required.

Fig. 7 shows the influence of mechanical properties of the cut rocks on the load of the cutting heads drive. If the rotational speed of cutting heads is changing as a result of the changing rotational speed of a motor rotor (Fig. 7a), the analysed characteristics coincide within the range of the heads' rotational speed values $n < n_n$. The higher is the compressive strength of the cut rock, the higher is the load on the drive. The load is basically within the assumed interval of power variability to cutting: $(1 \pm 0.2)N_n$. This signifies that the value of the torque developed by a motor is well accommodated to the predicted load generated in the rock cutting process (average values of the moment of load forces on the cutting heads shaft represent the level of the nominal torque – reduced to the cuttings heads shaft – developed by a drive motor, corresponding to the given rotational speed).

In case of the rotational speed of cutting heads with the value higher than nominal ($n > n_n$), the average load on the drive may reach even the value of up to 1.8 of the nominal value. A possibility of cutting rocks with poor workability is thus largely limited here. The average power reaches the assumed permitted level of drive overload when cutting rocks with the compressive strength of: ~60 MPa – for $n = 50$ RPM and ~30 MPa – for $n = 60$ RPM. The analogous effect exists when the rotational speed of cutting heads is changed by changing the reduction gear ratio
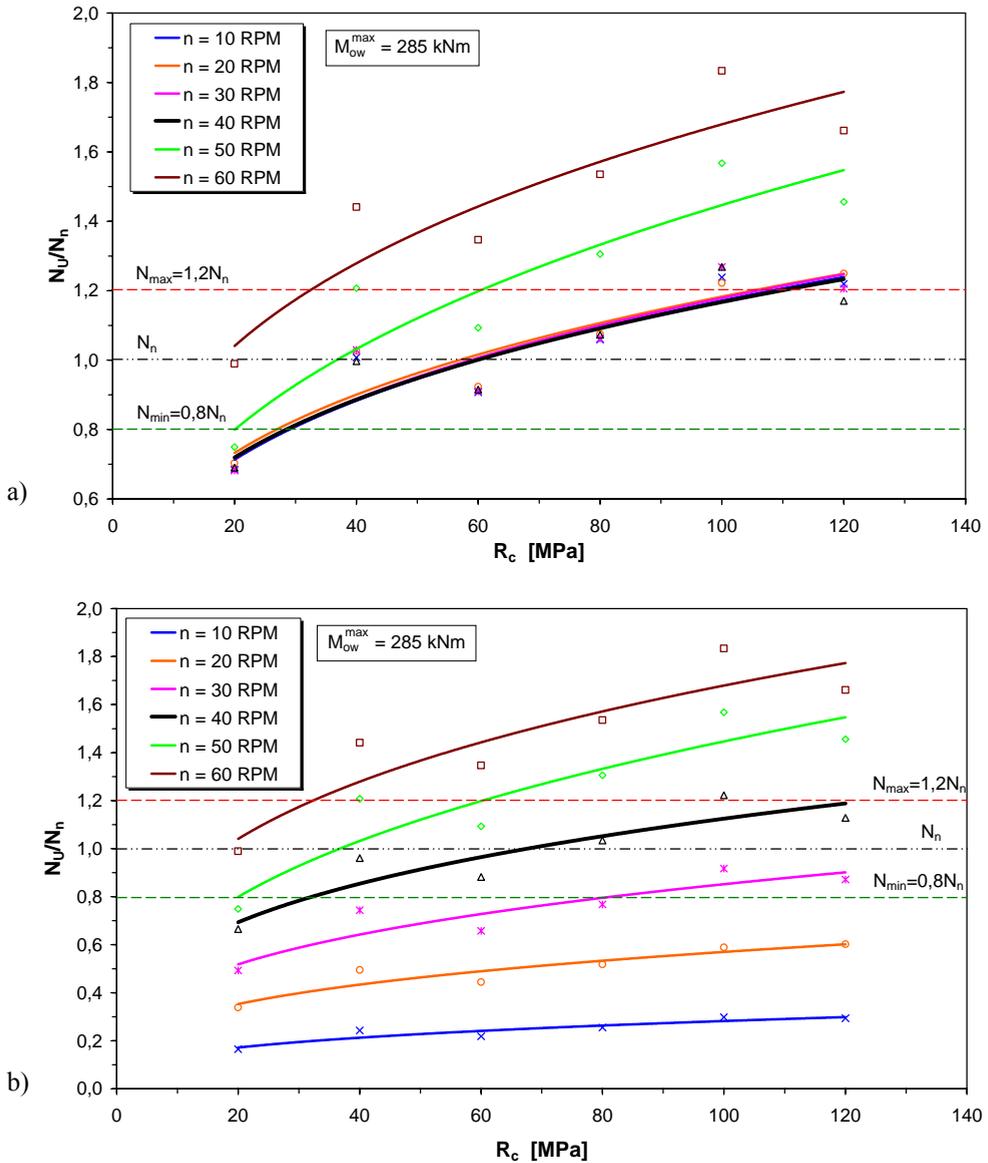
Fig. 7. The utilisation degree of power installed in a drive of cutting heads according to the compressive strength of the cut rock for various rotational speeds of cutting heads: a) change of the rotational speed of the drive motor rotor, b) change of a reduction gear ratio in the cutting system

in their head (Fig. 7b – green and brown lines). In the case of rotational speeds of heads smaller than nominal speed within the entire studied range of variability of compressive strength of the worked rocks, the cutting system is underloaded. The average cutting power for very low rotational speeds (n = 10 RPM) represents the one–fourth of the nominal power.

14

Computer investigations into the cutting process were carried out in the further part for the scenario where a boom swinging mechanism is not a factor limiting the advance speed of cutting heads (the maximum torque value of the boom swinging is so high that it is able to balance the reaction of rock caused by a cutting process within the entire investigated range of boom swinging rotation speed). Demand for power needed for the cutting process changes according to the advance speed of cutting heads in a complicated manner (Sobota, 2009). Several local extremes are seen in the curve of the function $N_U = f(v_{ow})$ (Fig. 8). In the lower range of boom swinging speed, the load of the cutting system is growing as the speed is rising. After reaching a local maximum, the power consumed in the cutting process is initially decreasing, and then rising again reaching the next maximum. The load of the cutting system is falling as the advance speed of cutting heads is further increased. For small rotational speeds of cutting heads, however, the strong growth of the power consumed in the cutting process is seen again once the minimum is reached. This is caused by the significant growth of picks' load due to the unfavourable consequence of cuts (picks are making recessed cuts mainly).
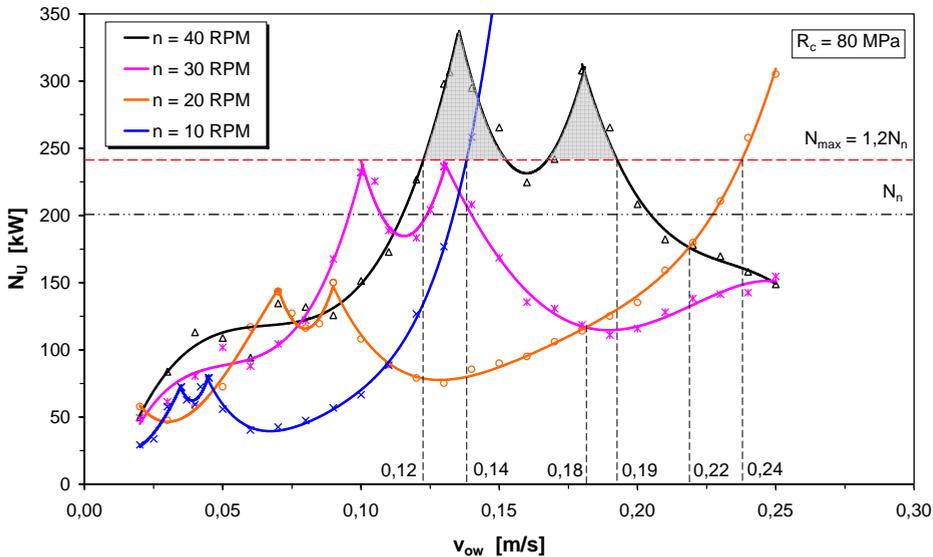

Fig. 8. A relationship between power consumed in the cutting process according to boom swinging speed for various rotational speeds of cutting heads

The boom swinging speeds equivalent to local load maximums clearly depend on the rotational speed of cutting heads. For example, for the nominal rotational speed of heads ($n = 40$ RPM), they occur at the constant speed of boom swinging v_{ow} of: ~0.13 and 0.18 m/s (black line). The power necessary for carrying out the rock cutting process with the compressive strength of 80 MPa exceeds then 300 kW. It is thus 50% higher than the nominal power of the motor in the cutting system. The cutting heads drive is, for this reason, substantially overloaded. Changes in power within the range of the displacement speed of cutting heads of 0.13 to 0.18 m/s are caused

by a changed arrangement of the cuts made by picks, which not only influences their depth but also their type (opening cuts, semi-open cuts, etc.). The type of cuts with specific depth made in rock with specific properties is substantially influencing the picks' load value, and, therefore, the load of the cutting heads drive.

For the nominal rotational speed of cutting heads, within the range of their displacement speed of 0.115 to 0.205 m/s, the load of the cutting system generated by the cutting process of rock with the compressive strength of $R_c = 80$ MPa is higher than a nominal value. When the speed v_{ow} is within the range of 0.12 to 0.15 m/s and of 0.17 to 0.19 m/s, the power used in the cutting process is higher than the adopted permitted load ($1.2 \cdot N_n$). This means that high cutting efficiencies cannot be obtained despite the fact that in case of high speeds of boom swinging, the load on the heads' drive is much smaller than permitted. As boom swinging speed increases, a load on the drive of cutting heads reaches a level that may cause this speed to be limited by a protection system (for example by reducing a stream of fluid supplied to hydraulic actuators of the boom swinging mechanism).

If the rotational speed of cutting heads is reduced by 25% ($n = 30$ RMP), this has positive influence on the load condition of the cutting heads drive (Fig. 8 – violet line). Average power used in the cutting process within the whole examined range of boom swinging speed, i.e. between 0.02 and 0.25 m/s, is smaller than the assumed permitted level of drive overload. At the same time, the local maximums of power of about 235 kW correspond to the peripheral speed of boom swinging of $v_{ow} = 0.1$ m/s and 0.13 m/s. For the range of speeds higher than the latter of the mentioned values, the function: $N_U = f(v_{ow}, n)$ reaches the minimum – for $v_{ow} = {\sim}0.19$ m/s. This is equivalent to the minimum energy consumption of cutting for this peripheral speed ($E_j = 1.35$ kWh/m^3).

As the rotational speed of cutting heads is dropping, the local maximums of power are approaching even smaller speeds. For example, for $n = 20$ RMP, they correspond to the boom swinging speed of 0.07 and 0.09 m/s (orange line), and for $n = 10$ RPM – the speeds account for: 0.035 and 0.045 m/s (blue line). For these rotational speeds of heads, however, very intensive growth in the load of the cutting heads drive is seen as their displacement speed increases from the value at which it reaches the minimum ($v_{ow} = 0.13$ m/s – for $n = 20$ RPM and $v_{ow} = 0,06$ m/s – for $n = 10$ RPM). Cutting power reaches the maximum permitted drive overload for the boom swinging speed of, accordingly: 0.24 m/s – for $n = 20$ RPM and 0.14 m/s – for $n = 10$ RPM. When $v_{ow} = 0.18$ m/s, the analysed characteristics for the rotational speed of cutting heads of 20 and 30 RMP intersect. This means that for this advance speed of cutting heads, for both rotational speeds, the load generated with the cutting process reaches a similar level. The energy consumption of cutting is then the same and is 1.5 kWh/m^3. Although the mentioned working point can be achieved for both rotational speeds of cutting heads, the load of the cutting system for boom swinging speeds higher than 0.18 m/s is, however, definitely smaller, when $n = 30$ RPM. Cutting power and energy consumption of this process are not even two times smaller in this case as compared to the values of such parameters corresponding to the rotational speed of cutting heads of 20 RPM.

The characteristics shown in figure 8 indicate it is possible to reduce the load of cutting heads and energy consumption of cutting by reducing the rotational speed of cutting heads, for example by changing the reduction gear ratio in their head. By assuming that a two–speed gear with the output shaft rotation speed ratio of 1:2 is used in a roadheader's cutting system and that the rotational speeds of cutting heads represent: for high gear – $n_I = n_n = 40$ RPM, and for

low gear – $n_{II} = 0.5 \cdot n_n = 20$ RPM, the idea of adjustment of rotational speed of cutting heads (change of gears) is as follows. Cutting is basically carried out for the nominal rotational speed of a cutting head ($n = n_I$). The working point is, therefore, situated on the characteristic corresponding to the rotational speed of $n = 40$ RPM (black line). As the advance speed of cutting heads increases, the drive load (power) increases and reaches the maximum permitted load (the speed in the considered case is $v_{ow} = 0.12$ m/s). If the load of the cutting system reaches a permitted value, this indicates that the drive is switched to a low gear. The drive's working point is hence transiting to a characteristic corresponding to rotational speed n_{II} (Fig. 8 – orange line). As a result, a load on the drive of cutting heads decreases, thus it is possible to further increase boom swinging speed. Cutting efficiency grows while energy consumption of the process decreases. The value of the power consumed in the cutting process for both gears would equalise at the speed of $v_{ow} = 0.22$ m/s. This speed during cutting with a high gear cannot be reached as this would mean large overload for the drive of cuttings heads.

As the power consumed in the cutting process represents a control signal in a unit adjusting the rotational speed of cutting heads, it can be determined according to the intensity of current drawn from the network by a motor in the cutting heads drive. It is a parameter commonly measured and used in a roadheader's overload protection systems.

The minimisation of energy consumption of cutting by reducing the rotational speed of cutting heads is justified when cutting hard rocks with their compressive strength in excess of 60 MPa (Fig. 9). A load on the cutting heads drive during cutting in such conditions is so high that average power will exceed the assumed permitted overload level. This is a condition for changing a gear ratio (switching to a low gear). When cutting rocks with high and medium workability ($R_c \leq 60$ MPa), at the nominal rotational speed of cutting heads, a load on the cutting
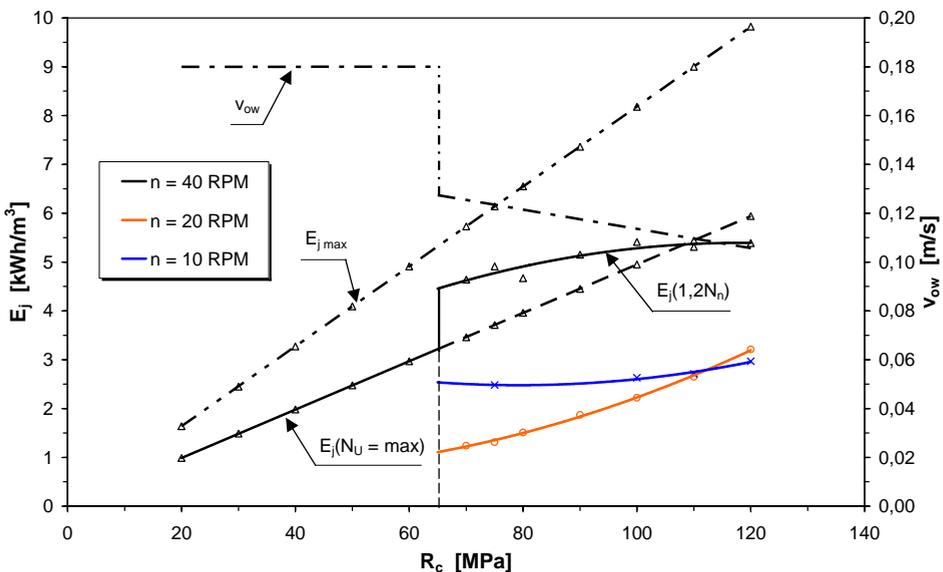

Fig. 9. The effect of reduction of rotational speed of cutting heads on the energy consumption of rock cutting for rocks with different compressive strength

heads drive is definitely smaller and does not exceed the permitted level. Two intervals can be differentiated for the curve of relationship between the unit energy of cutting and the compressive strength of the cut rock for the nominal rotational speed of cutting heads (continuous black line). This is a linear growing function in the first case – for $R_c \leq 60$ MPa. The function represents the energy consumption of cutting corresponding to the maximum power consumed for performing the process ($N_U = $ max) corresponding to the rotational speed of boom swinging $v_{ow} = 0.18$ m/s (spotted line). As the compressive strength of the cut rock increases, the energy consumption of cutting grows within the limits of ~2 kWh/m^3 – for $R_c = 20$ MPa to nearly 3 kWh/m^3 – for $R_c = 60$ MPa.

When cutting rocks with their compressive strength higher than 60 MPa, the energy consumption of cutting corresponding to maximum power would continue to grow in a linear way (dotted line). Considering, however, that cutting power is limited to $1.2 \cdot N_n$, the function $E_j = f(R_c)$ changes its character. It appears that for $N_U = 1.2 \cdot N_n$, the energy consumption of cutting is higher than the value corresponding to the maximum power and changes in a non-linear in the function R_c. The boom swinging speed at which power consumed in the cutting process reaches the assumed level of drive overload, is provided in a relatively small range of 0.105 m/s – for $R_c = 120$ MPa to 0.125 m/s – for $R_c = 70$ MPa (spotted line).

When analysing the influence of rotational speed of cutting heads on the energy consumption of cutting the rocks with the compressive strength of over 60 MPa, clear benefits are obvious for reducing such consumption. When the rotational speed of cutting heads is reduced two times, this leads to a reduction in energy consumption of cutting within the limits of 40 to nearly 75% (orange line). As the compressive strength of the cut rock increases, energy consumption is such case changes between 1.24 kWh/m^3 – for $R_c = 70$ MPa to 3.21 kWh/m^3 – for $R_c = 120$ MPa. The highest reduction in the energy consumption of cutting is achieved when cutting rocks with the compressive strength of 70 – 80 MPa.

When the rotational speed of cutting heads is reduced to 10 RPM, this also leads to a clear reduction in the energy consumption of cutting (blue line). Such reduction is smaller, however, as compared to this obtained for $n = 20$ RPM, especially for rocks with the compressive strength of 70 to 90 MPa. The impact of the strength of the cut rock on energy consumption is small for this rotational speed of cutting heads. Within the range of R_c 70 to 120 MPa, the energy consumption of cutting changes from 2.48 to 2.97 kWh/m^3. A reduction in the rotational speed of cutting heads from 40 to 10 RPM is thus leading to a reduction in the energy consumption of cutting by approx. 50%. For such low rotational speed of heads, the advance speed range of such heads is very narrowed, however (see Fig. 8). For this reason, high cutting efficiencies cannot be achieved.

As mentioned at the beginning, the cutting of rocks with small workability at low rotational speeds of cutting heads is advantageous considering the wear intensity of picks. For the examined cutting head, the maximum value of cutting speed given in the literature for such type of rocks of 1.5 m/s will not be exceeded when the rotational speed of cutting heads is smaller than 25 RPM. This condition is met if a two-speed gear with the rotational speed of 40 and 20 RPM is used in the drive of the considered cutting heads. The maximum cutting speed in such case will be: 2.3 m/s – for high gear and 1.15 m/s – for low gear.

The double–point line in Fig. 9 sketches the maximum energy consumption of cutting of rocks with the compressive strength of 20 to 120 MPa recorded within the whole examined variability range of the peripheral speed of boom swinging (from 0.02 to 0.25 m/s). The values are higher than a value determined for maximum power and the permitted level of overload of the

cutting heads drive. Energy consumption is higher with regard to maximum power by approx. 65%. The maximum values of the energy consumption of cutting correspond to the low speeds of boom swinging ($v_{ow} < 0.05$ m/s). This is because a cutting process is characterised by high energy consumption for small cutting efficiencies.

4. Summary

The outcomes of the extensive computer investigations presented in the article allowed to identify the impact of cutting heads' rotational speed on the load applied on the cutting heads drive as well as on the efficiency and the energy consumption of the cutting process. Such an analysis was carried out in connection with the technically feasible methods of rotational speed adjustment, in consideration of the factors having impact on the load condition of the cutting system and on the energy consumption of the cutting process and connected with the properties of the drives actuating the movement of cutting heads (rotational and advance movement). Considering the relations between the strength parameters of a roadheader (the ratio of power in the cutting heads drive to the maximum force developed by a boom swinging mechanism), the energy consumption of rock cutting was investigated within a wide range for rocks with high compressive strength in consistency with the conditions of works performed in coal mining in Poland.

The investigations conducted have shown that a method of changing the rotational speed of cutting heads is important considering the load condition of their drive (including degree of installed power utilisation) as well as the energy consumption of cutting. When adjusting the rotational speed of cutting heads as a result of changing the rotational speed of a motor rotor (for example with a frequency converter) or as a result of applying a two-speed motor, a reduction in the rotational speed of cutting heads means that the power developed by a drive motor is reduced. As a result, the power of the drive may be fully practically utilised within the whole range of advance speed of cutting heads, corresponding to a given rotational speed of heads. Low power is required for cutting at smaller rotational speed of heads, if a sufficient torque is available. If a multi-speed gear is used, this in turn leads to a change in torque on the shaft of cutting heads. When rock is cut at a low rotational speed of the heads, the torque in this case may substantially exceed the value required for performing such a process. As a result, the utilisation degree of power installed in a drive of cutting heads will be low.

By assuming that a factor limiting a maximum peripheral speed of boom swinging is a load on its swinging mechanism, the energy consumption of cutting the rocks for specific compressive strength will be constant for any rotational speed of cutting heads. A condition for that, however, is a constant value of a ratio of cutting heads' advance speed to their rotational speed, which takes place when a boom swinging mechanism is loaded with a maximum, attainable force. A change of the rotational speed of cutting heads does not impact in such case the energy consumption of cutting and only the efficiency of the process. The higher the rotational speed of heads, the higher cutting efficiencies can be obtained.

If we assume that a force is developed by a boom swinging mechanism, this does not limit the advance speed of the heads (it is so high that the movement of heads with a maximum speed resulting from a hydraulic pump's efficiency is possible), this speed will be limited by a motor load in the drive of cutting heads. This concerns most of all the cutting of rocks with low work-ability with the compressive strength exceeding 60 MPa. This happens because in such conditions, at certain speeds of boom swinging, a cutting system may be strongly overloaded. According to

the mechanical performance of asynchronous motors used for driving the cutting heads of road-headers, the maximum load is limited by critical moment. This moment is usually equivalent to a value exceeding 2 times the nominal torque. In order to ensure a cutting system's failure-free operation, the permitted load (understood as a value averaged within a specific time interval) should, however, be smaller. For this reason it has been assumed in this paper that the maximum cutting power should not exceed a value corresponding to 120% of the motor's nominal torque. This value will be limiting the advance speed of cutting heads.

The computer simulations performed reveal, in the curve of power consumed for performing the cutting process in the function of peripheral speed of boom swinging, that there are values of such speed at which a load on the cutting heads drive exceeds the assumed level of the permitted overload ($N_U > 1.2 \cdot N_n$). If the rotational speed of cutting heads is reduced, the power consumed in the cutting process decreases, and the occurring local extremes approach the smaller advance speeds of cutting heads.

A reduction in the rotational speed of cutting heads may lead to a substantial reduction in the energy consumption of cutting. In case of cutting the rocks with low workability, a reduction in the rotational speed of cutting heads by a half enables to reduce the energy consumption of cutting by two-third, ensuring at the same time a possibility of achieving high advance speeds of cutting heads. Reduction in the rotational speed of cutting heads should be accomplished here once reaching the assumed permitted level of drive overload in the cutting system.

The extensive computer investigations carried out may constitute a starting point for developing a system of automatic adjustment of rotational speeds of cutting heads to reduce the energy consumption of cutting. The power used in cutting may be used as a control signal for this purpose.

References

Dolipski M., Cheluszka P., 1999. *Dynamic model of a roadheader's cutting system which incorporates transverse cutter heads.* Archives of Mining Science, Vol. 44, No. 1, p. 113-146.

Dolipski M., Cheluszka P., 2002. *Dynamika układu urabiania kombajnu chodnikowego.* Wydawnictwo Politechniki Śląskiej, Gliwice.

Dolipski M., Cheluszka P., Sobota P., 2006. *Komputerowe wspomaganie doboru głowic urabiających kombajnu chodnikowego dla określonych warunków górniczo-geologicznych.* 3. Szkoła Mechanizacji i Automatyzacji Górnictwa, p. 13-25.

Driesch S., 1994. *Schneidtechnische und verfahrenstechnische Weiterentwicklungen für den maschinellen Vortrieb.* Glückauf-Forschungshefte, 55, Nr. 6, p. 156-160.

Driesch S., Kleinert H.-W., 1993. *Maßnahmen zur Verbesserung der Wirtschaftlichkeit im maschinellen Vortrieb.* Glückauf, 129, Nr. 7, p. 519-523.

Jaszczuk M., 1999. *Wpływ stanu obciążenia kombajnu ścianowego dużej mocy na możliwość uzyskania wysokiej koncentracji wydobycia.* Zeszyty Naukowe Politechniki Śląskiej, s. Górnictwo, z. 240, Gliwice.

Sobota P., 2009. *Komputerowe badania wpływu prędkości wychylania wysięgnika na energochłonność urabiania kombajnem chodnikowym.* Konferencja „Górnictwo zrównoważonego rozwoju 2009", p. 10 (CD-ROM).

Vasek J., Martinec P., Pinka J., 2006. *Laboratory cuttability and abrasiveness tests for prediction of worcable rocks in tunnel and mining praxis.* Archives of Mining Science, Vol. 51, No. 3, p. 355-369.