Monograph

Aspects of fracture and cutting mechanics of materials

Edited by
Józef Jonak

Societas Scientiarum Lublinensis
Lublin 2010

Contents

Józef JONAK[1], Jerzy PODGÓRSKI[2], Jarosław ZUBRZYCKI[3]

3. Problems of rock cutting with disc tools

3.1. Introduction

Rapidly increasing demand for highly effective technologies of tunnelling (underground tunnels, engineering structures) realized often in hardly mineable grounds requires improving machine structures – especially cutting tools. The most common are rotary tangential cutting picks and disc tools. Rotational cutting picks exhibit significantly higher strength comparing to classic wedge tools, thus they are the most popular in equipping heads of shearers. Disc tools, due to different mechanism of rock mining, exhibit higher strength than rotational cutting picks. However, mechanism of chip elements loosening process is relatively insufficiently investigated. The tools are mainly used in TBM machines (full-face tunnelling) but in recent years there were trials of applying them in longwall shearers and roadheaders.

3.2. Rock loosening mechanism – disc tool

As one can assume, currently two technologies of loosening are distinguished in case of disc tools. First, tangential operation of asymmetrical disc on edge (Fig. 1a)[1]. In this case one can observe undercutting similar to classic cutting. This solution has been used in e.g. machines for mining very hard and abrasive formation of grounds (ARM 1100 shearer). Second way includes rotation of symmetrical disks initially pressed to the ground (Fig. 1b) with movement equal to scale value in each run (mounted e.g. on TBM-type shearer head).

In mentioned cases of operation different mechanisms of crushing the rock structure occur. However, nature of these processes is not fully known – that is why a lot of effort has been made to investigate mechanics of them.

[1] professor D. Sc. Eng. Head of Department of Machine Design, j.jonak@pollub.pl, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

[2] Ph. D. Eng. Department of Structural Mechanics, Faculty of Civil Engineering and Architecture, j.podgorski@pollub.pl, Lublin University of Technology

[3] Ph. D. Eng. Professor Assistant, Institute of Technological Information Systems, Department of Mechanics, Lublin University of Technology, j.zubrzycki@pollub.pl, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

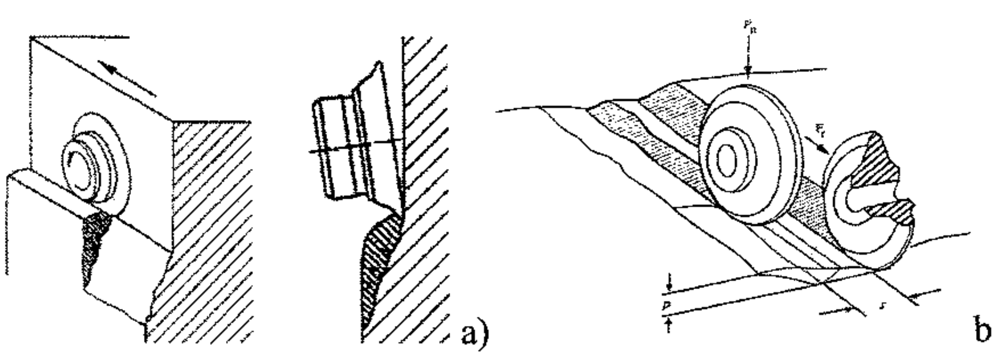


Fig. 1. Disc operation: a) mining tangentially to surface [1], b) perpendicular to surface [7, 13]

In case of symmetrical discs it is assumed that in initial penetration into even surface it is crushed (Fig. 2a) and crushes expand in a radial way. Increasing pressure of crushed ground in so called crushed zone contributes in creation and propagation of tensile stresses in the ground. They cause "tensile" cracks [3,4]. Between mentioned zone and solid ground some scientists assume existence of transition (contact) zone.

In order to achieve energetically optimal solution of the mining process it is necessary to maintain accurate relation between disc penetration depth and distances of successive runs (or spacing of disks operating together). Literature shows that optimal relation scale/penetration depth in case of symmetrical discs lies in relatively wide range (10÷20), depending mainly on the properties of mined ground.

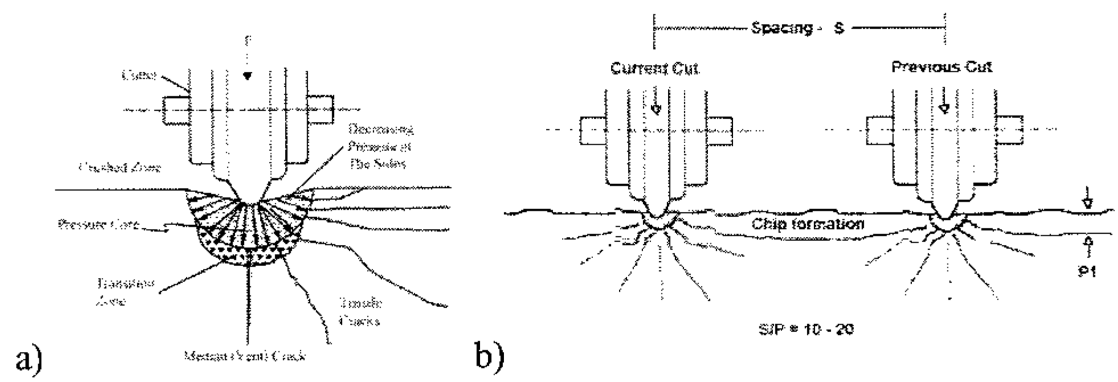


Fig. 2. Operation of symmetrical disc a) and set of discs b)

In case of asymmetrical discs there is a series of interpretations of the rock crushing process. According to one of them (Fig. 3)[8], disc crushes rock with its edge only a little bit, causing generation of cracks by shearing the material at the beginning of destruction process. Further crack development associated to loosening larger chip element results from formation of tearing stresses.

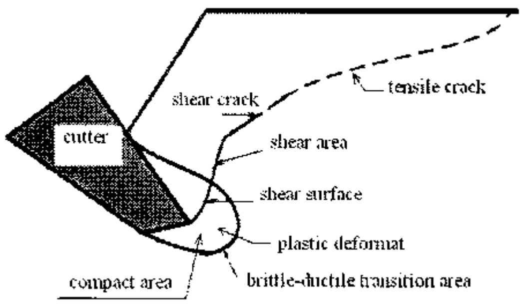


Fig. 3. Operation of asymmetrical disk in case of soft ground [8]

Shearing and tearing process, from energetic point of view, is much more advantageous comparing to the process based more on crushing the material.

3.2.1. Cutting stratified grounds

Paradoxically, despite probably the largest part of mining practice, cutting stratified grounds is relatively weakly known. According to one of the interpretations (Fig. 5), e.g. [6], stratification of rocks significantly changes mechanism of chip elements loosening.

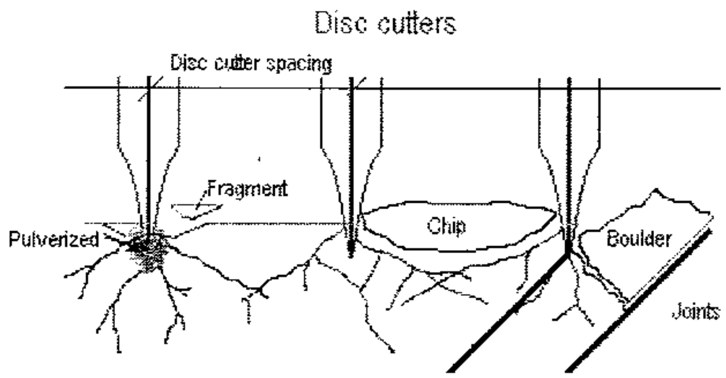


Fig. 4. Forming chip elements with symmetrical disc in a stratified ground – [6]

Depending on the stratification direction, combination of strength parameters of the particular rock layers, binder between them and possible cracks different course of rock loosening is obtained. It also affects energy consumption in case of given process and other technological parameters. Influence of the foliation on chip creation with disc tools is additionally illustrated in Fig. 5.

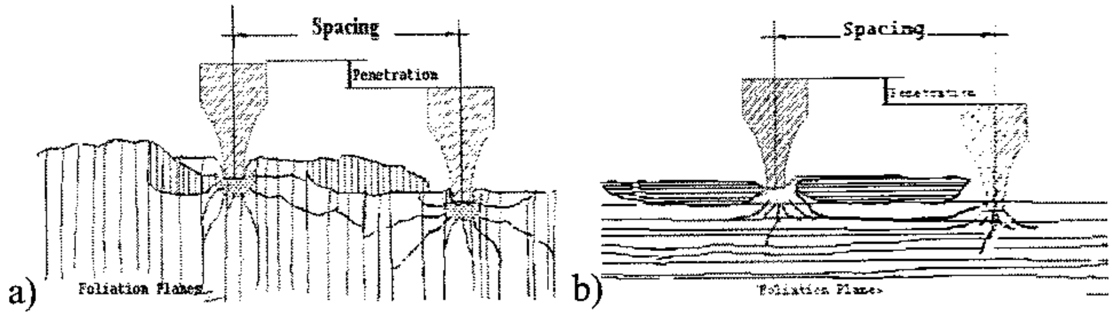


Fig. 5. Influence of the rock mass stratification on formation of chip elements during mining with discs [11]

As it is shown in the Figure above, operation of disc in case of mass stratified perpendicularly to the mined surface causes limited loosening and many cracks, but gaps rarely reach level of accessible surface. It results in disadvantageous energy consumption. Cutting ground stratified parallel to the mined surface increases horizontal range of the cracks (between discs) leading to increase amount of loosened element what improves energy efficiency.

However, the problem is more complicated in case of milling heads or heads of TBMs since cutting or boring direction of rock mass is varying (Fig. 6).

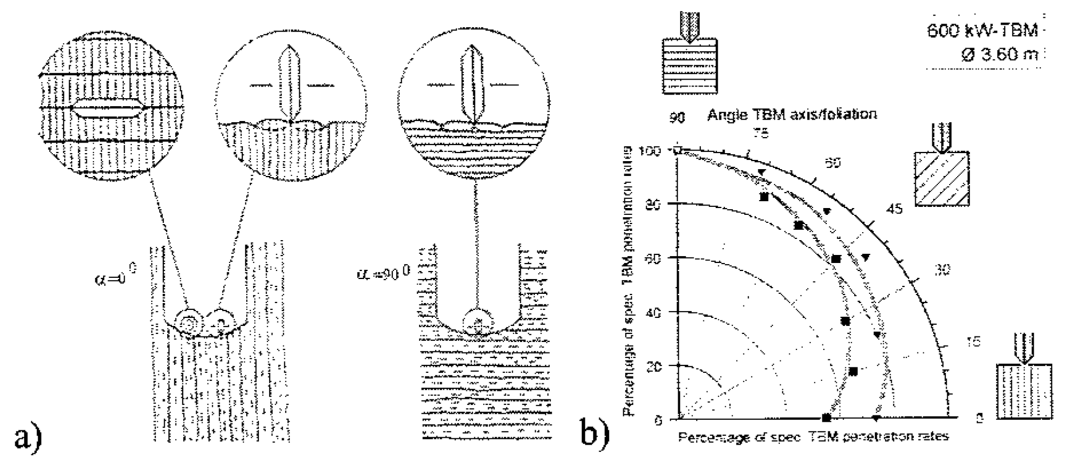


Fig. 6. Possible cases of operation in stratified rock mass a) (according to Gehring) and influence of stratification direction on shaping relative efficiency of miming (TBM) b)[2]

Fig. 6b shows that mining with TBM shearers stratified grounds strongly depends on direction of stratification with respect to the axis of full-face shearer. If efficiency of mining pseudo isotropic dusty rocks as a reference, one can observe that mining rocks stratified in parallel way to the cut surface exhibit similar efficiency (relative efficiency coefficient – 100%). Mining rocks stratified perpendicularly to cut surface results in the lowest value of the coefficient i.e. 45÷55%.

Numerical simulations performed using Disctinct Element Method increases state of knowledge about mechanism of cracks penetration in stratified materials (Fig. 7). Results of investigation are very similar to the ones obtained using numerical simulations performed for rocks (e.g. [10]), since similar mechanisms of structure destruction were observed. As indicated in Fig. 7, direction of stratification significantly affects penetration indicators before tool edge.

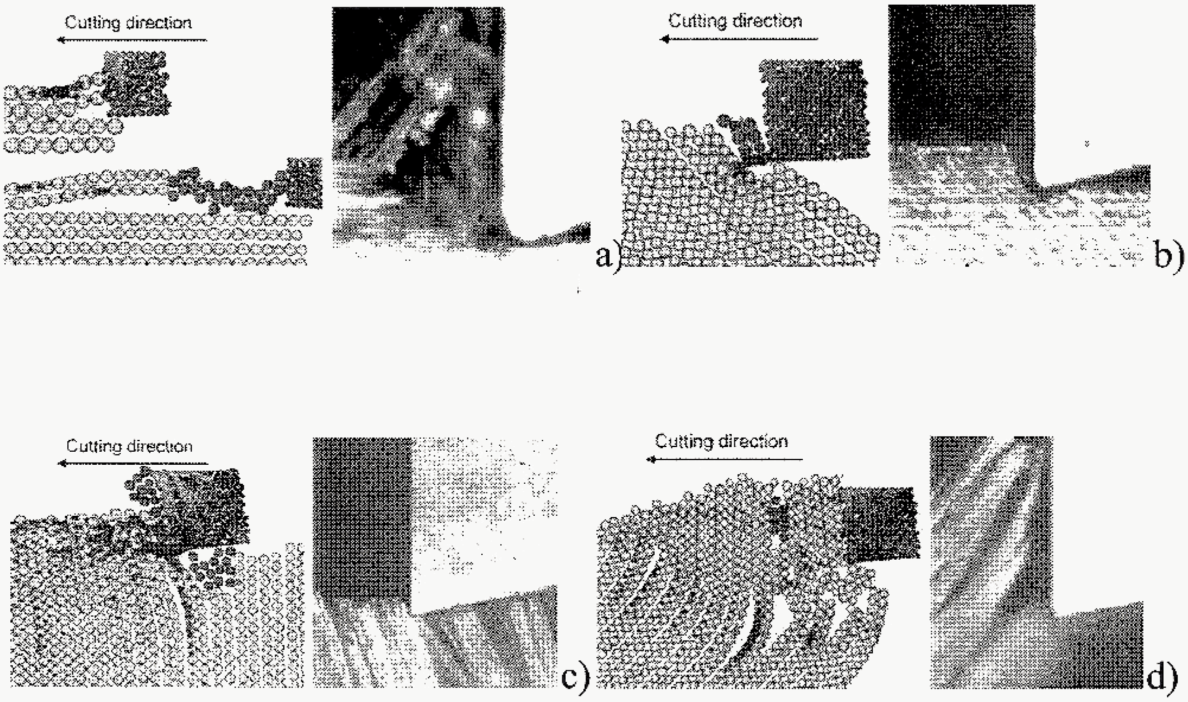


Fig.7. Influence of stratification direction on cracking the material attacked with a tool [14]

3.3. Numerical investigation of disc cutting process

Numerical investigation of the cutting process (mining) are performed mainly to achieve optimal spacing between disks and select the best disc geometry (maximum output, the smallest energy consumption) according to the local conditions of operation. Rapid development of computation methods (FEM, DEM) facilitate the analysis but they do not allow more exhaustive description of damaging the rock structure during operation of tools. Using Voronoi diagram, Coulomb – Mohr's model for the elements and elastic-perfectly plastic Coulomb's condition in the elements contact zone allow analyzing influence of tools spacing on the course of damaging the material by the disc for different movements of successive runs (Fig. 8). Damaging of the following sandstone structure was analyzed: cohesion 36MPa, R_c=50MPa, R_t=3.75MPa, E=20GPa, friction angle 23°. Disc angle 90°. Material of the elements (grains): E=18GPa, cohesion 49MPa, friction angle 23°, ν=0,33, R_t=14.6MPa. Parameters of binder: friction angle after damaging 19°, R_t=7.3MPa, cohesion 24.5MPa, normal stiffness 195GPa, tangent 97GPa.

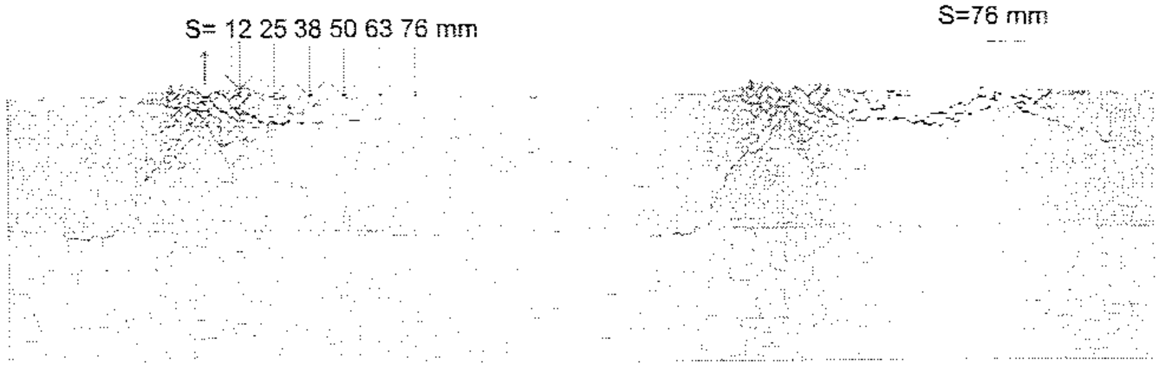


Fig. 8. Simulation of disc operation in successive runs [15]

The simulations show propagation of radial cracks and expansion and connecting of cracks leading to larger loosening between discs what is good representation of practical situations.

3D simulations performed by Jung-Woo Cho (et al. [9]), allow spatial analysis of the results (distribution of stresses, deformations) as illustrated in Fig. 9.

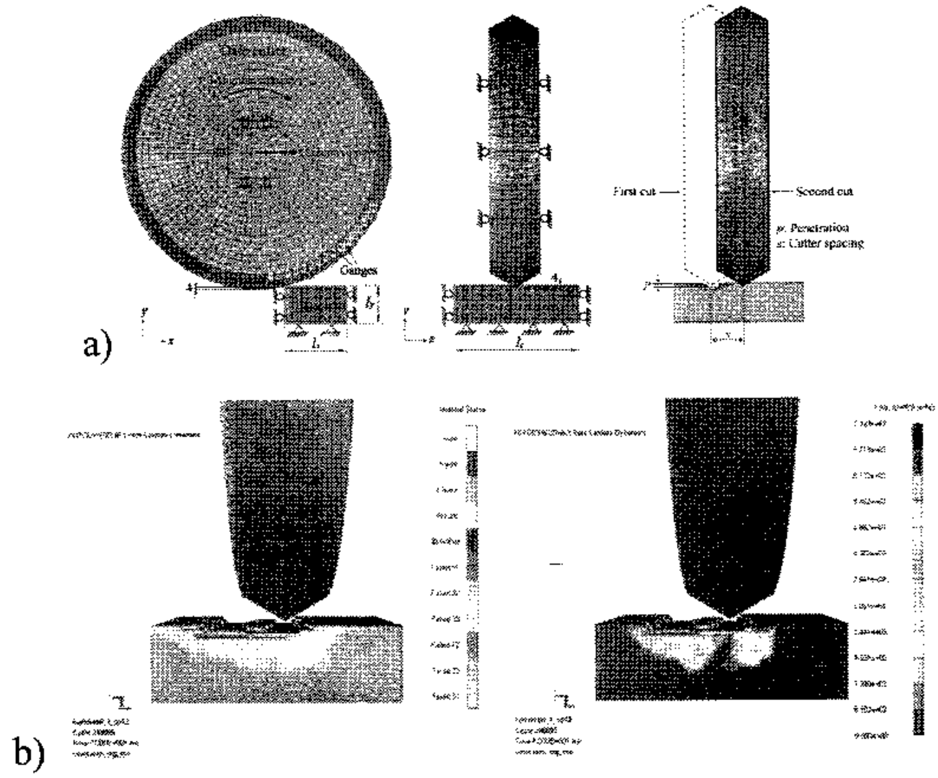


Fig. 9. Cutting model and obtained distribution of material plastification and tensile stresses [9]

Performed numerical research using FEM [11] for asymmetrical disc showed that in case of single runs optimal s/d ratio should be equal to 6. Taking into account parallel operation of the second disc, located symmetrically with respect to normal to the surface in a point where crack reaches the mined surface, one can approximately assume that optimal relation of discs penetration depths to their spacing (s/d) is close to 12 what is very close to the results obtained in practice and to the simulation results [9].

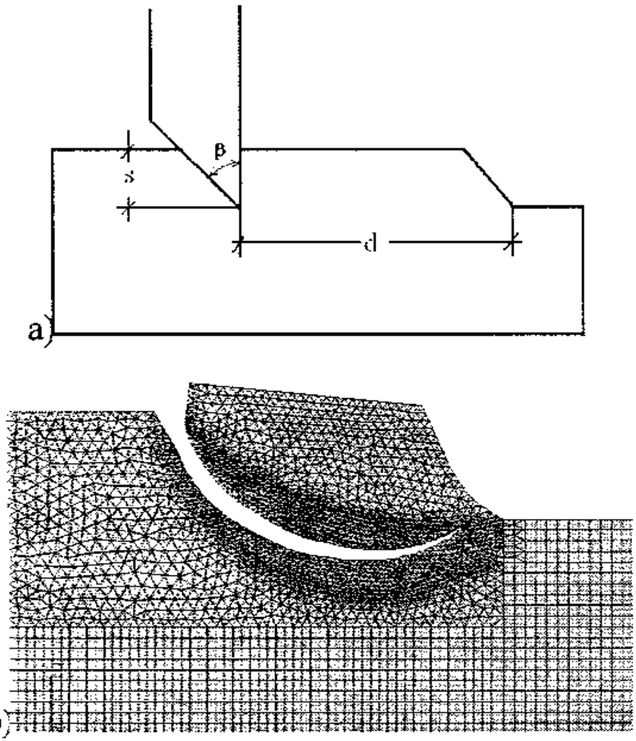


Fig.10. Course of chip loosening, asymmetrical disc, s/d=6, isotropic material [11]

Results of the numerical and empirical research presented above do not include research over cutting stratified ground. Authors of this paper perform numerical research – results are presented in separate paper [16].

Acknowledgements
The work has been supported by Polish Ministry of Science and Higher Education (MNiSzW) grant N N524 368337

Bibliography

[1]. Pickering R.G.B., Ebner B.: Hard rock cutting and the development of a continuous mining machine for narrow platinum reefs. The Journal of the South African Institute of Mining and Metallurgy, January/February 2002.

[2]. Thuro K., Plinninger R.J.: Hard rock tunnel boring, cutting, drilling and blasting: rock parameters for excavatability. ISRM 2003- Technology roadmap for rock mechanics, The South African Institute of Mining and Metallurgy, 2003.

[3]. Lindqvist, P.E., and Ranman, K.E., 1980, "Mechanical Rock Fragmentation Chipping Under a Disc Cutter," University of Lulea, Lulea, Sweden, Technical Report 59T.

[4]. Fenn, O., 1985, "The Use of Water Jets to Enhance the Performance of Free Rolling Cutters in Hard Rock," DEng thesis, Rand Afrikaans University, Johannesburg, Republic of South Africa.

[5]. Schubert: Rock Excavation by Drill & Blast. Institute für Rock Mechanics and Tunneling. TU Graz. http://tunnel.tugraz.at/fileadmin/tunnel/files/fmt/FMT_2007_L07.pdf.

[6]. Nyqvist L.: Tunnelling options in long driver. Metodval vid langa tunnlar. Master's Thesis. Lulea University of Technology. 2005.

[7]. Bilgin N., Copur H., Balci C., Tumac D., Akgul M., Yuksel A.: The selection of a TBM using full scale laboratory tests and comparison of measured and predicted performance values in Istanbul Kozyatagi-Kadikoy metro tunnels. World Tunnel Congress 2008 - Underground Facilities for Better Environment and Safety – India.

[8]. Jing Xue, Yimin Xia, Zhiyong Ji, Xiwen Zhou: Soft rock cutting mechanics model of TBM cutter and experimental research. Second International Conference ICIRA 2009, Singapore, December 2009, Proceedings.

[9]. Jung-Woo Cho, Seokwon Jeon, Sang-Hwa Yu, Soo-Ho Chang: Optimum spacing of TBM disc cutters: A numerical simulation using the three-dimensional dynamic fracturing method. Tunneling and Underground Space Technology 25 (2010) 230–244.

[10]. Podgórski J., Jonak J.: Numeryczne badania procesu skrawania skał anizotropowych. LTN, Lublin, 2006r.

[11]. Jonak J. (red.): Zagadnienia mechaniki pękania i skrawania materiałów kruchych. LTN, Lublin 2008r.

[12]. Cigla M., Yagiz S. and Ozdemir L.,: "Application of Tunnel Boring Machines in Underground Mine Development", International Mining Congress, 2001, Ankara, Turkey.

[13]. Nelson, P.P., 1993 "TBM performance analysis with reference to rock properties", Chapter 10, Comprehensive Rock Engineering, Vol.4, Excavation, Support and Monitoring (J. A. Hudson, ed.),261- 291, Oxford, Pergamon Press.

[14]. Iliescu D., Gehin D., Iordanoff I., Girot F., Gutiérrez M.E.: A discrete element method for the simulation of CFRP cutting. Composites Science and Technology 70 (2010) 73–80.
[15]. Christian Lunow, Heinz Konietzky: Two dimensional simulation of the pressing and the cutting rock destruction. EURO: TUN 2009 2nd International Conference on Computational Methods in Tunneling Ruhr University Bochum, 9-11 September 2009 Aedificatio Publishers, 1-4.
[16]. Podgórski J., Jonak J. :Symulacje oddziaływania dyskowego narzędzia urabiającego na skały uwarstwione. Konf. N.T.: Zagadnienia mechaniki pękania i skrawania materiałów. Kazimierz Dolny n. Wisłą, 21-23.10.2010.

Jerzy PODGÓRSKI[1], Józef JONAK[2]

4. Simulation of operation of disc cutting tool on stratified rocks

4.1. Introduction

Disc tools are one of the most popular mining tools that ensure achieving high efficiency, particularly in case of highly abrasive rocks exhibiting large compression strength (Fig. 1). They have been researched for years [2][3], both in Poland and abroad – mainly in case of so called symmetrical disks used in full-face shearers (TBM) used in tunnelling.

Data available in the literature shows that significant factors of rock mining with disc tools are:

- Properties of the rock (e.g. compression strength, tensile strength),
- Disc geometry (disc angle, nose radius),
- Technological parameters of cutting process (cutting depth, i.e. depth of disc penetration into the ground, distance from previous disc run called cutting scale).

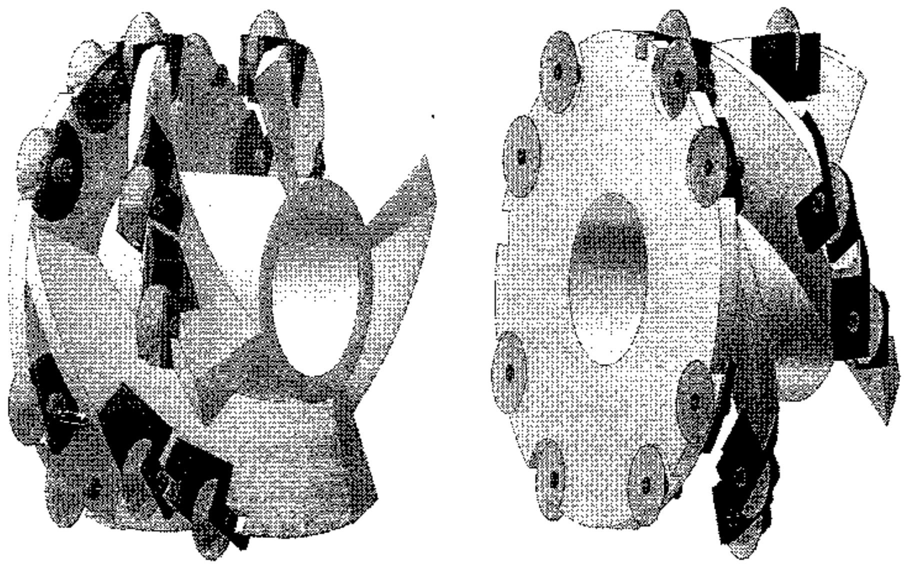


Fig. 1. Cutting head with mounted asymmetrical discs [1]

In case of so called asymmetrical discs, main factor that significantly affects mining process and that is relatively weakly known is disc orientation i.e. its setting regarding previous breakout made by a previous disc (located on the

[1] Ph. D. Eng. Department of Structural Mechanics, Faculty of Civil Engineering and Architecture, j.podgorski@pollub.pl, Lublin University of Technology

[2] professor D. Sc. Eng. Head of Department of Machine Design, j.jonak@pollub.pl, ul. Nadbystrzycka 36, 20-618 Lublin, Poland

mining head spiral). This problem have been researched earlier by the authors [3] and some aspects of orientation of asymmetrical discs orientation have been developed.

4.2. Influence of direction of ground stratification

Series of investigations [4, 5, 6, 7, 8] show that rocks cutting process highly depends on their stratification. Dependence includes values of loosening forces, shape of propagating trajectory and chip range.

In case of simple crushing of rock samples the analyses performed by Pietruszczak et al. [5] shows that strength of stratified material depends on direction of foliation regarding applied load and reaches maximum value for approx. 45° angle as shown in fig. 2. In case of more complex rock cutting issues analyzed in the work [7], shape of mentioned dependency is slightly different (Fig. 3), since asymmetry caused by cutting direction can be easily observed – cutting direction was parallel to the layers inclined by β=0°.

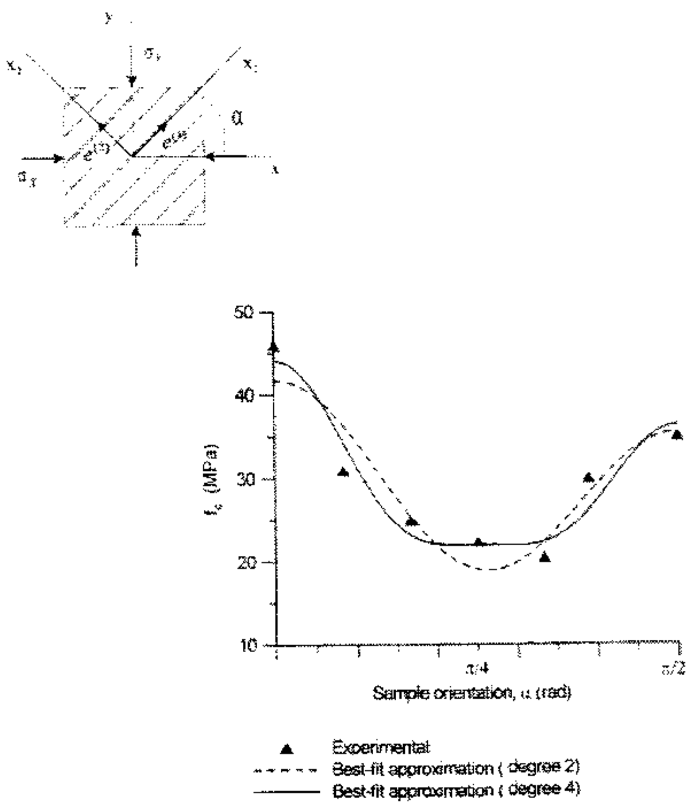


Fig. 2. Influence of foliation angle on the value of compressive strength [5]

Influence of ground stratification on parameters of disc cutting tool is still not deeply investigated and is intensively researched both empirically and using analytical and numerical methods [9].

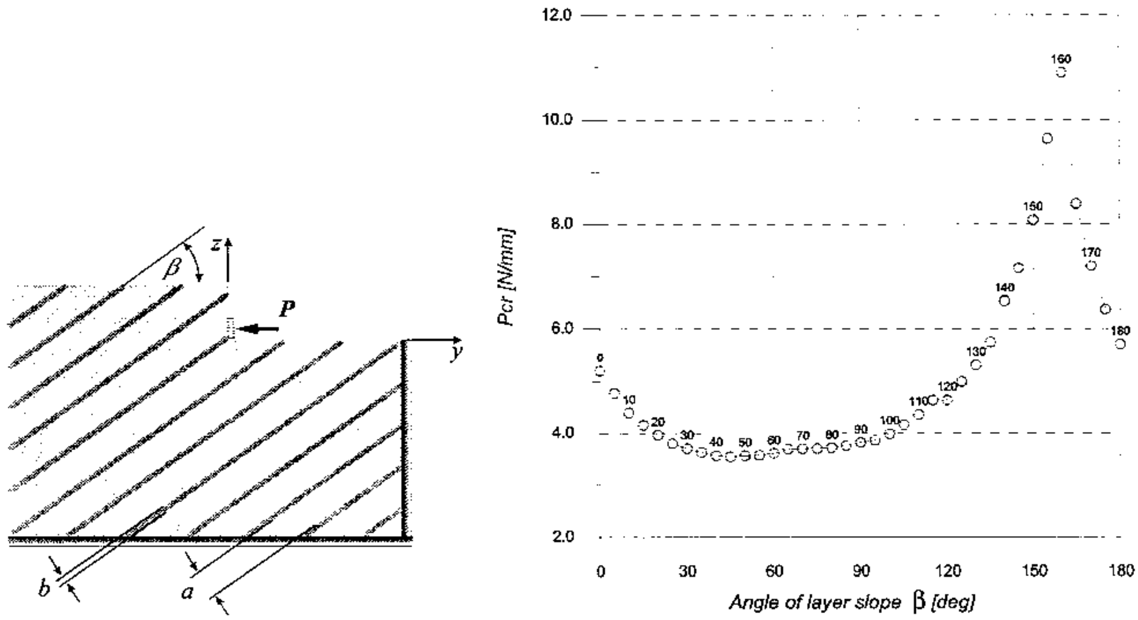


Fig. 3. Maximum value of critical force depending on change of foliation angle [7]

The authors also work on this subject using numerical methods and tools tested earlier in matters connected with cutting of rock materials [3,6,7,10,11]. Numerical simulations using finite element method (FEM) were performed to answer the question regarding influence of the stratification inclination (foliation) on the loosening trajectory and forces necessary to obtain critical point.

4.3. Numerical simulations

The analysis takes into account operation of an asymmetrical disk with draft angle 30°, directed with base into earlier runs (mined surface) as it is shown in Fig. 4. The issue has been analyzed as two-dimensional state of strain in the plane of disc axial section, perpendicular to the direction of its reeling and both perpendicular to the bottom of the cut mined by the disc. Shape of the analyzed model corresponds to the one of cases of cutting homogenous ground described in previous work of the authors [3].

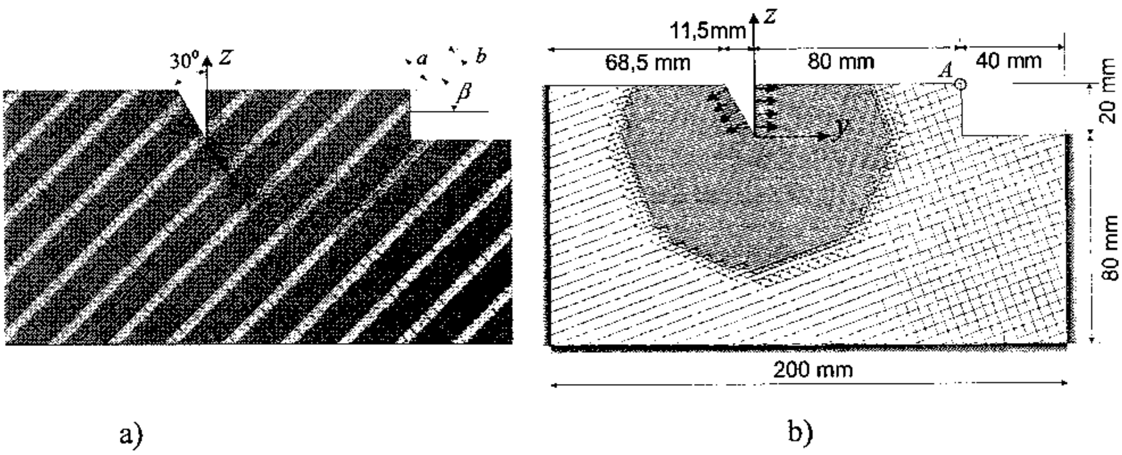
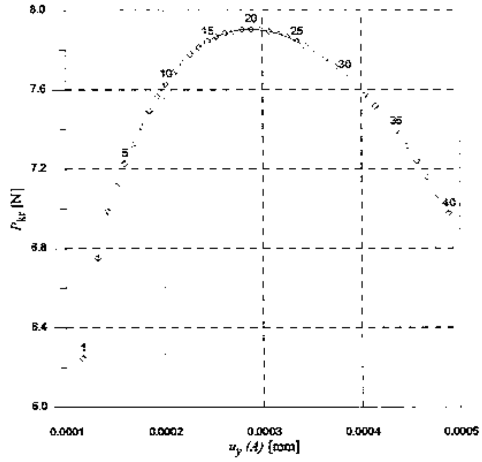


Fig. 4. FEM model for the rock affected by an asymmetrical disk, a) stratification parameters, b) dimensions and boundary conditions of FEM model

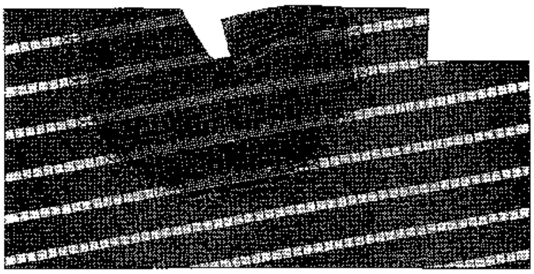
Rock strength parameters:
1. Stronger layer with thickness a=12mm
- Young's modulus E=2,0×10^4MPa,
- Poisson ratio ν=0,2,
- Compression strength R_c=20MPa,
- Tensile strength R_t= 2,0MPa.
2. Weaker layer with thickness b=4mm:
- Young's modulus E=1,0×10^4MPa,
- Poisson ratio ν=0,22,
- Compression strength R_c=5,0MPa,
- Tensile strength R_t= 0,5MPa.

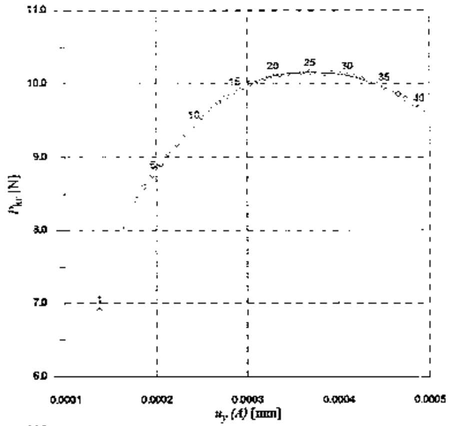
Boundary conditions assumed in FEM model (Fig. 4b) include full fixing (u_y=0, u_z=0) at bottom edge of the model and blocking horizontal displacements (u_y=0) at both vertical edges. Disc reaction on the rock is represented by constant pressure applied to the cut edges. Analyzed models included layers inclinations: β= 0°, 10°, 20°, 30°, 45°, 90°, 135°, 140°, 150°, 160°, 170°, 180°.

Numerical analysis was performed applying finite element method using own software *CrackPath3*[6,7,10] and selected modules of ALGOR package. Gap initiation criterion was assumed as *PJ* criterion, proposed by J. Podgórski [12]. Computed results were visualised by ALGOR *Sview* module and shown in Fig. 5(a÷f). The figures show shapes of loosenings and dependencies between P_{kr} – force necessary to propagate the gap and $u_z(A)$ – horizontal displacement of *A* point, marked in 4b with blue circle.

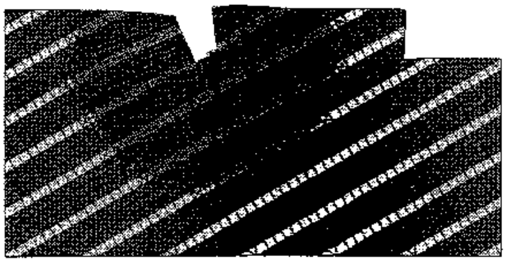


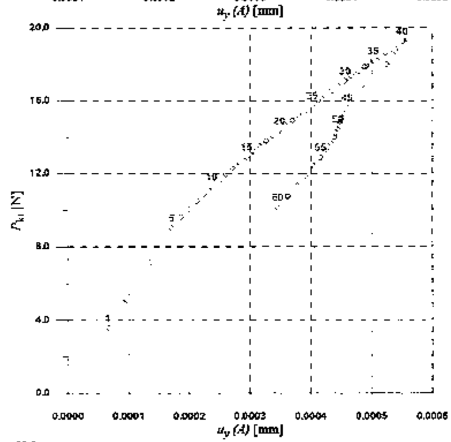
a) $\beta = 0°$



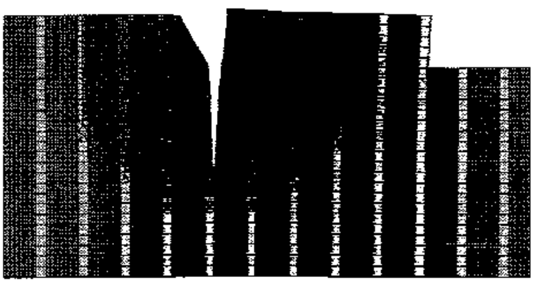


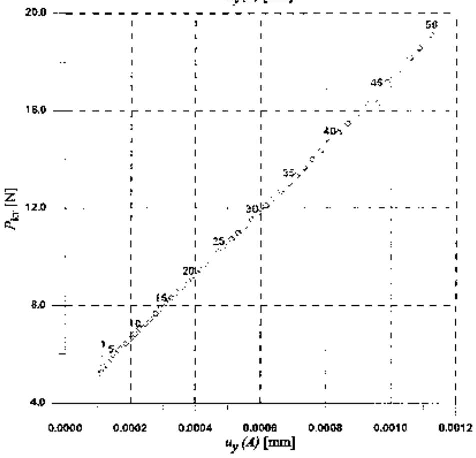
b) $\beta = 10°$



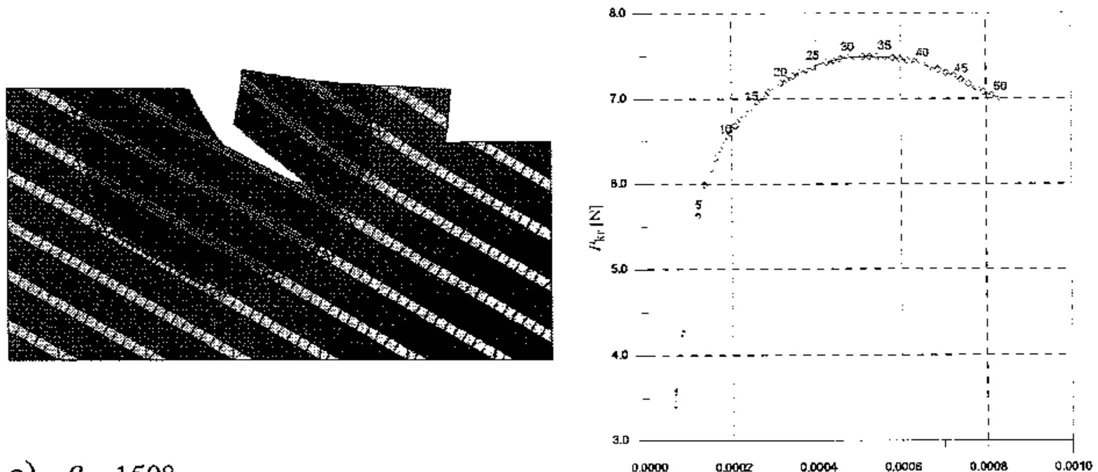


c) $\beta = 30°$

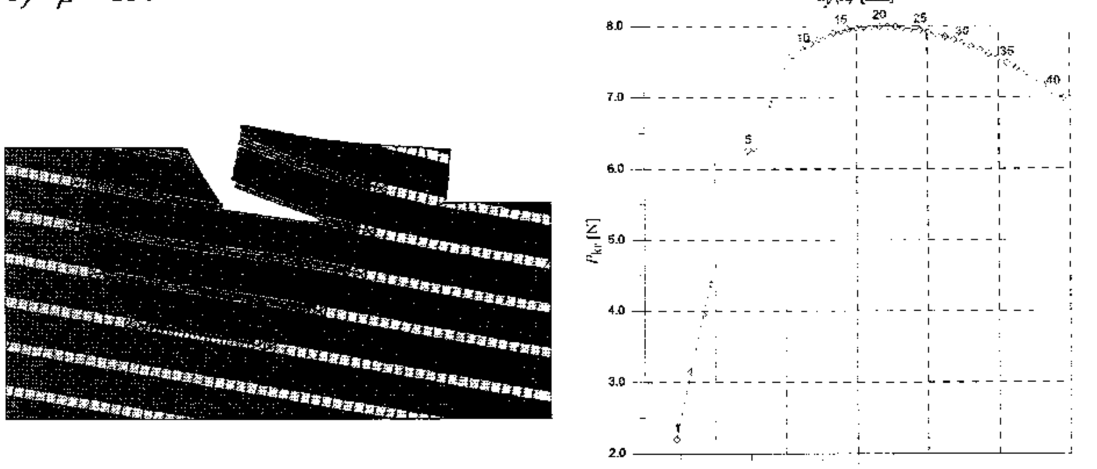




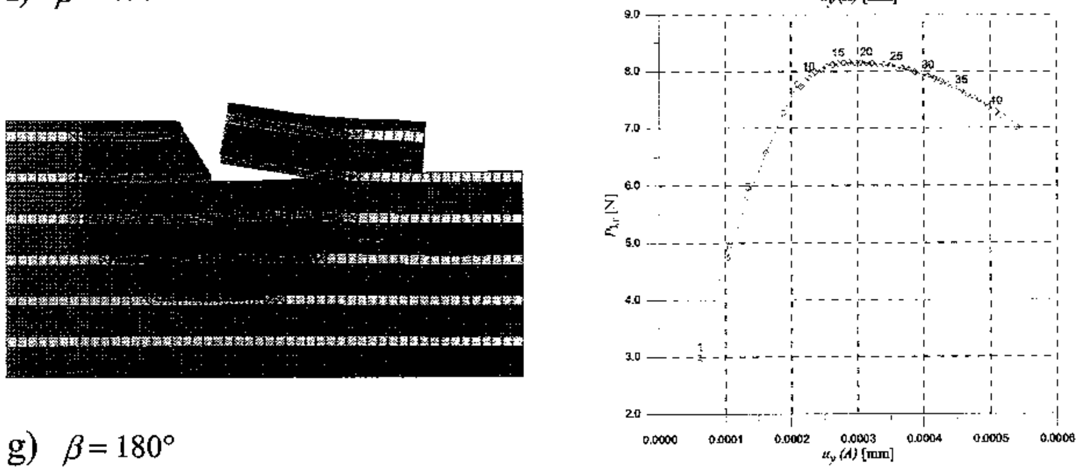
d) $\beta = 90°$



e) $\beta = 150°$



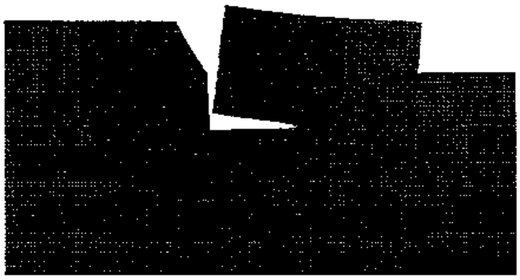
f) $\beta = 170°$



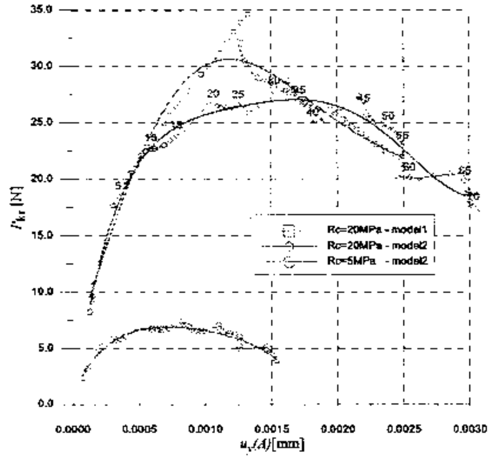
g) $\beta = 180°$

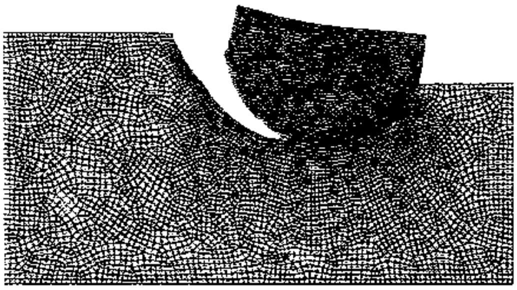
Fig. 5. Chip shapes and force-displacement dependency for different inclinations of stratification

As a reference, examples of rocks with homogenous strengths equal to R_c=20MPa and R_c=5MPa (equal to strengths of both layers shown in Fig. 4a) were analyzed as well. Results are presented in Fig. 6.



model 1





model 2

Fig. 6. Force-displacement dependency for different materials of FEM model

4.4. Influence of foliation angle on the loosening force

Analysis of the simulation results (Fig. 5,6) allows forming the following conclusion: shape of loosened chip strongly depends on the foliation direction. In the assume algorithm of crack simulation (called also "lost elements" method) trajectory of gap propagation depends on the geometry of FEM mesh. Values of the loosening forces depends also on mesh quality, particularly on the size of finite elements since the "lost elements" method averages value of material effort inside the element, thus increasing size of the elements decreases average values of stresses and material efforts.

Collecting maximum values of the loosening forces according to different foliation angles we can obtain dependency $P_{kr} - \beta$, which is shown in Fig 7. Maximum values of the forces were limited by 25N that can be concluded using graphs obtained for the reference models (Fig. 6).

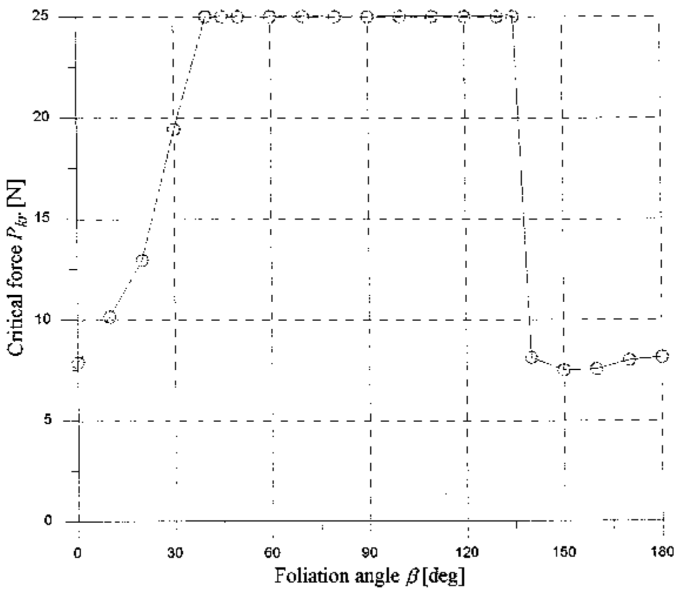


Fig. 7. Critical force – foliation angle dependence

The graph (Fig. 7) shows important conclusion – there is a small range of foliation angles ($\beta = 0° \div 40°$ and $\beta = 140° \div 180°$) at which loosening force is small, comparable to the forces loosening homogenous material of the weaker layer, other angles of foliation can be characterized by large loosening forces comparable to the forces loosening homogenous material of the stronger layer. Transition between both areas of forces is rapid and occurs within the range $\pm(40° \div 45°)$.

Summary

Assumed way of simulating operation of asymmetrical disc is significant simplification of real process that is three-dimensional, thus distribution of stresses is in many areas different than analyzed in the present 2D analysis. Dependency of the FEM analysis results on the quality and geometry of grid causes that values of the loosening forces should be considered as preliminarily estimated. However, quality dependence between forces and changes of the foliation angle remain valid even in case of these estimations.

One of the more interesting observations visible after analyzing computational results is occurrence of two areas with clearly different values of loosening forces. Boundaries between those areas can be characterized with rapid change of value that is different comparing to observation of force changes in the issues of cutting stratified grounds (Fig. 3). Min. values of the loosening forces were observed at approx. 150° foliation angle, max. values at angles larger than 45° what is in accordance with observed maximum cutting force (Fig. 3) with different directions of cutting and loosening with disc taken into account (thus, different signs of foliation angles in both simulations).

Precise 3D simulations, taking into account fine remeshing (changes of the FE mesh) near crack tip and using data obtained from measurement of real cutting process in natural scale, should facilitate verification of observed values of forces and characteristics of the dependence $P_{kr}-\beta$.

Acknowledgements
The work has been supported by Polish Ministry of Science and Higher Education (MNiSzW) grant N N524 368337.

Bibliography

[1] Krauze K.: Organy z narzędziami dyskowymi dla kombajnów ścianowych. Mat. II Międzynarodowe Sympozjum „Nowe rozwiązania w budowie i bezpiecznej eksploatacji polskich wysokowydajnych kombajnów ścianowych", Wisła 7-8 października 2004r, s. 31-39.
[2] Snowdon RA, Ryley MD, Temporal J.: A study of disc cutting in selected British rocks. Int J Rock Mech Min Sci Geomech Abstr 1982;19:107–21.
[3] Podgórski J., Jonak J.: Badania numeryczne oddziaływania dyskowego narzędzia urabiającego na skałę, LTN, Lublin 2008r.
[4] Cigla M., Yagiz S. and Ozdemir L.,: "Application of Tunnel Boring Machines in Underground Mine Development", International Mining Congress, 2001, Ankara, Turkey.
[5] Pietruszczak S., Łydzba D., Shao J.F.: Modeling of inherent anisotropy in sedimentary rocks. International Journal of Solids and Structures 39 (2002) pp. 637-648.
[6] Podgórski J., Jonak J. : Influence of strength heterogeneity factor o crack shape in laminar rock- like materials. Symposium on : Multiscale modeling of damage and fracture processes in composite materials-Book of abstracts. IUTAM – International Union of Theoretical and Applied Mechanics. Kazimierz Dolny, Poland, 23-27 May, 2005.
[7] Podgórski J.: The influence of the layer direction in elastic- brittle material on the progress of crack propagation. Minetech, March- April 2005, Volume 26, No 2, pp. 50-54.
[8] Thuro K., Saun G.: Drillability in hard rock drill and blast tunneling. Felsbau 14 (1996) Nr. 2.
[9] Jonak J., Podgórski J., Zubrzycki J.: Problemy skrawania skał narzędziami dyskowymi, Konf. N.T.: Zagadnienia mechaniki pękania i skrawania materiałów. Kazimierz Dolny, 21-23 Października 2010.
[10] Podgórski J., Nowicki T., Jonak J.: Fracture analysis of the composites with random structure, IWCMM 16, Sep 25-25,2006, Lublin, Poland

[11] Podgórski J.: Influence Exerted by Strength Criterion on Direction of Crack Propagation in the Elastic- Brittle Material. Journal of Mining Science 38 (4); 2002, pp. 374-380, July- August, Kluwer Academic/Plenum Publishers.
[12] Podgórski J.: General Failure Criterion for Isotropic Media. Journal of Engineering Mechanics ASCE, 111 2, 1985, pp.188-201.