COMBINED THEORETICAL AND EXPERIMENTAL ANALYSIS OF MECHANICAL ROCK SALT CUTTING AND CUTTING TOOL CHARACTERISTICS

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Abstract: This paper investigates the mechanical cutting of rock salt with the aim of determining the cutting characteristics relevant to the optimization of cutting machine performance. Experimental studies were conducted under laboratory and in situ conditions to evaluate specific cutting resistance, cutting forces, chip detachment angles, and specific energy consumption, as functions of cutting depth and tool geometry. Tests were performed on rock salt samples from Romanian deposits using instrumented cutting tools and a Ural-33 cutting machine. The results highlight distinct cutting behavior of rock salt compared to other sedimentary rocks, particularly coal, and demonstrate that appropriate optimization of cutting tool layout significantly improves cutting efficiency. The proposed methodology provides a reliable basis for reducing energy consumption and increasing productivity in mechanized rock salt mining.

Keywords: Rock salt cutting; Mechanical excavation; Cutting forces; Specific energy consumption; Cutting tool layout

1. INTRODUCTION

Mechanized mining of rock salt involves material disintegration through mechanical cutting, typically performed using cutting machines. Cutting represents the primary operation in the mining process and is characterized by relatively high energy consumption. Consequently, this operation must be optimized to ensure high efficiency. For a given installed power of the cutting machine, a reduction in the specific cutting energy results in an increase in cutting productivity.

The selection and design of cutting machines suitable for specific operating conditions depend largely on the cutting characteristics of rock salt. Determining these

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characteristics requires comprehensive theoretical and experimental investigations conducted under laboratory and/or in situ conditions.

2. THEORETICAL AND EXPERIMENTAL ASPECTS

This study presents experimental results concerning the specific cutting resistance, the forces acting on the cutting tool, the chip detachment angle, and the specific energy consumption during cutting, as well as their dependence on the geometric characteristics of the cutting tools and the properties of the generated chips. Experimental investigations were carried out at the University of Petroşani mining machines lab, using a test stand equipped with a strain-gauge dynamometer connected to data acquisition and recording equipment interfaced with a personal computer.

The experimental setup allowed for the measurement of the components of the resultant force acting on the cutting tool during the cutting process, namely: the cutting force F_x, the penetration force F_y, and the lateral force F_z.

Standard cutting tools with predefined conventional geometries, including both parallelepiped and conical types, were employed in the experiments. Tests were performed on 25 rock salt samples collected from the Romanian salt mines (Ocnele Mari and Dej. The specimens were cubic, with dimensions of 400 × 400 × 400 mm. A total of 156 cutting tests were conducted at cutting depths h_0 of 0.5, 1, 1.5, and 2 cm.

Following mathematical processing of the experimentally obtained force–displacement diagrams, the average values of the specific cutting resistance A_m were determined using the following relationship:

$$A_m = F_{xm} \cdot h_0 \text{, [N/cm]} \tag{1}$$

where F_m represents the actual average value of the cutting force [N].

In addition to the cutting forces, several other parameters were determined simultaneously during the experiments, including the volume of material removed per cut V and the cutting length l. Based on these measurements, the cross-sectional area of the cut S, the chip detachment angle ψ , and the specific energy consumption E_s were calculated using the following formula:

$$S = \frac{V}{l} \text{, [cm}^2\text{]} \tag{2}$$

$$\psi = \text{arctg}\left(\frac{S}{h_0^{\,2}} - \frac{b}{h_0}\right) \text{, [°]} \tag{3}$$

$$E_s = \frac{F_{xm}}{360 \cdot S} \text{, [kWh/m}^3\text{]} \tag{4}$$

$$E_s = \frac{F_{xm}}{100 \cdot S}, \text{ [J/cm}^3\text{]} \tag{5}$$

Figure 1 illustrates the variation of the specific cutting resistance A_m as a function of cutting depth, while Fig. 2 presents its variation with respect to the rake angle α of the cutting tool. For rock salt, it can be observed that the specific cutting resistance varies linearly with cutting depth and nonlinearly with the rake angle of the tool.

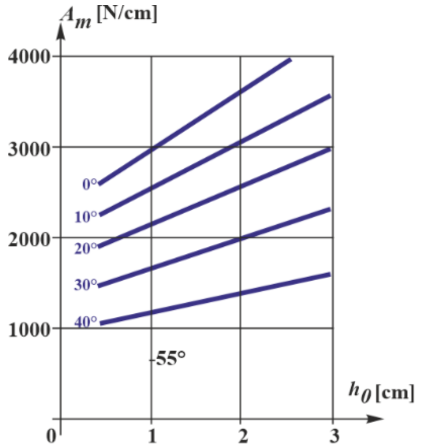

Fig. 1. Specific cutting resistance as a function of the cutting depth.

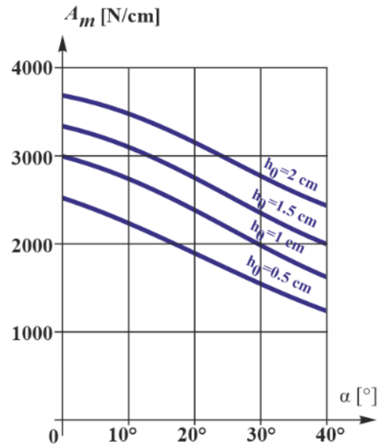

Fig. 2. Specific cutting resistance as a function of the tool rake angle.

According to Eq. (1), in the case of rock salt, the cutting force F_{xm} increases in a parabolic manner, in contrast to the behavior reported in the specialized literature for coal. This trend is evidenced by the family of curves shown in Fig. 3.

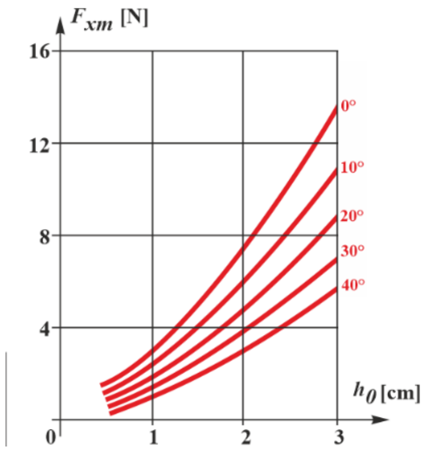

Fig. 3. Cutting force as a function of the cutting depth.

The chip detachment angle ψ exhibits an increasing trend with increasing cutting depth h_0, as shown by the families of curves in Figs. 4 and 5, with values ranging between 20° and 50°.

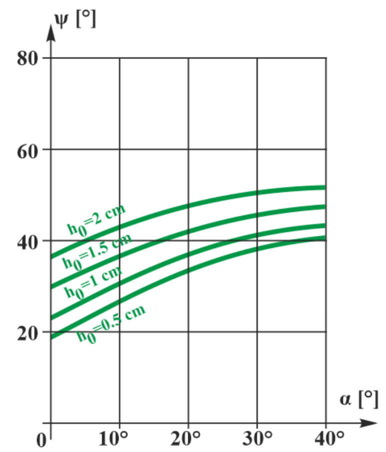

Fig. 4. Chip detachment angle as a function of the tool rake angle.

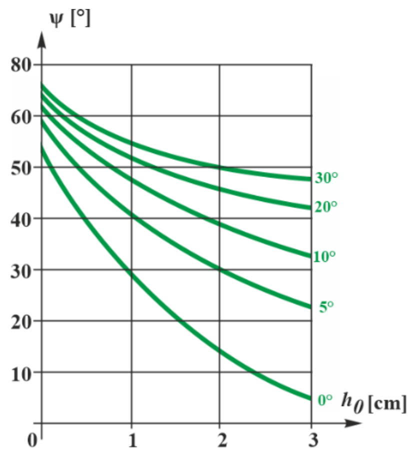

Fig. 5. Chip detachment angle as a function of cutting depth.

Regarding the specific energy consumption during rock salt cutting, this parameter decreases with increasing cutting depth h_0 and rake angle α of the cutting tool. The recorded values range between 4 and 16 J/cm³ (equivalent to 1.2–4.5 kWh/m³) for cutting depths h_0 between 0.5 and 3 cm and rake angles α between 0° and 40°, as illustrated in Fig. 6.

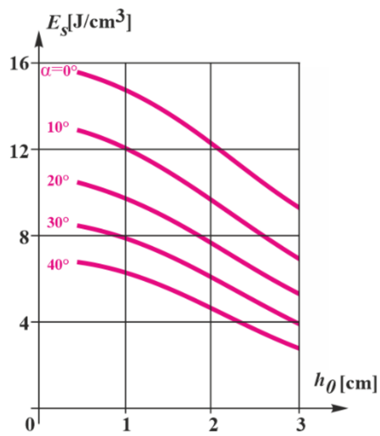

Fig.6. Specific energy consumption as a function of cutting depth.

In order to improve the performance characteristics of cutting tool arrangements mounted on the cutting chain of a cutting machine, with specific energy consumption used as a performance criterion, it is necessary to analyze the mechanism by which salt chips are detached from the rock mass. This analysis can be carried out effectively using the method of cutting evolution diagrams. These diagrams provide a graphical representation of the successive chip detachment process, viewed in a plane parallel to the advance direction of the cutting machine at the face.

The construction of cutting evolution diagrams requires knowledge of the chip detachment angle ψ, the cutting speed v_t, and the advance (haulage) speed v_a of the cutting machine. Based on these parameters, the thickness of the chip removed by each cutting tool can be determined as follows:

$$h = p_c \frac{v_a}{60 \cdot v_t} \cos\delta \text{ , [mm]} \tag{6}$$

where: δ denotes the inclination (dip) angle of the cutting tool relative to the plane intersecting the longitudinal axis of the cutting chain; v_a is the advance (haulage) speed of the cutting machine (m/min); v_t represents the cutting speed; and p_c is the mounting pitch of the cutting tools.

3. EXISTING AND PROPOSED TOOL LAYOUT ANALYSIS

Further investigations were conducted within the Department of Mechanical, Industrial and Transport Engineering at the University of Petroșani, focusing on the mechanical disintegration of rock salt using cutting machines in several Romanian salt deposits. For this purpose, rock salt extracted from Dej deposit was selected. The experimental and analytical studies were performed using a Ural-33 cutting machine (see figure 7) equipped with a cutting chain that allows the implementation of multiple cutting tool layouts without modifying the basic structural configuration, as the tools are mounted in dedicated tool holders. While certain characteristics of the cutting tool arrangement remain constant, others vary depending on the selected layout design.

Fig. 7. Ural 33 cutting machine

The cutting tool layout comprising 54 tools (as provided by the manufacturer) is presented in Fig. 8, and the corresponding cutting evolution diagram for an advance speed of v_a=1.5 m/min is shown in Fig. 9. It can be observed that the chips generated in the central region of the face ($\delta = 0$) are symmetrical, whereas those formed in the lateral regions are asymmetrical. This indicates the occurrence of blocked cutting at the face, associated with the well-known disadvantages of this cutting mode.

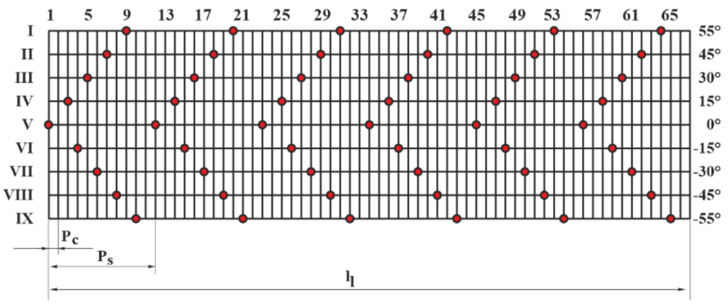

Fig.8. Existing cutting tool layout

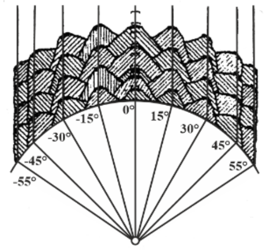

Fig. 9. Existing cutting evolution diagram

To mitigate these drawbacks, a detailed analysis was conducted and a new cutting tool layout was designed, as illustrated in Fig. 10. The cutting evolution diagram corresponding to an advance speed of v_a=1.5 m/min (Fig. 11) highlights the formation of relatively symmetrical, rhomboidal-shaped chips over most of the cutting width. Only in the lateral zones does a semi-blocked cutting regime occur, a phenomenon that is largely unavoidable under practical operating conditions.

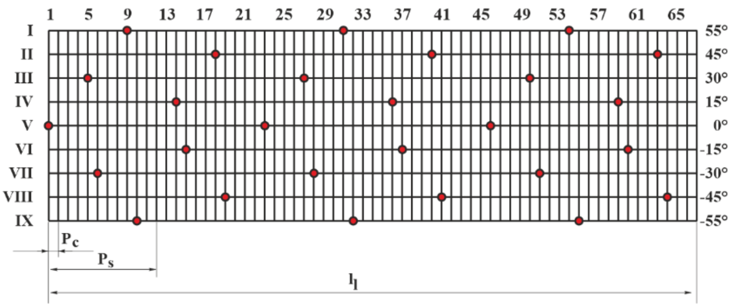

Fig.10. Proposed cutting tool layout

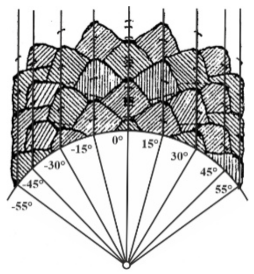

Fig. 11. Proposed cutting evolution diagram

Experimental tests and measurements performed under actual operating conditions confirmed the results obtained from the theoretical analysis and laboratory investigations, thereby validating the methodology used to determine the characteristics of the cutting tool layout and, implicitly, the performance of the cutting unit of the cutting machine.

Measurements conducted under identical operating conditions highlighted several significant improvements, including a reduction in specific energy consumption by approximately 25–35%, an increase in cutting productivity of about 40–50%, a decrease in airborne dust concentration at the workplace, and a reduction in cutting tool consumption.

4. CONCLUSIONS

The experimental investigations demonstrated that the cutting behavior of rock salt is strongly influenced by cutting depth and tool geometry. The specific cutting resistance increases linearly with cutting depth and exhibits a nonlinear dependence on the rake angle of the cutting tool, while the cutting force shows a parabolic increase with cutting depth. These trends highlight important differences between rock salt and other materials commonly addressed in the literature, such as coal, and emphasize the need for material-specific cutting models.

The chip detachment angle was found to increase with cutting depth, generally falling within the range of 20° to 50°. This parameter significantly affects chip formation and cutting efficiency and must be considered in the design and arrangement of cutting tools. At the same time, the specific energy consumption decreases as both cutting depth and rake angle increase, reaching values between 4 and 16 J/cm³, which indicates that higher cutting depths are energetically advantageous for rock salt excavation.

The use of cutting evolution diagrams proved to be an effective analytical tool for understanding the chip formation mechanism and for evaluating the interaction between successive cutting tools on the cutting chain. Based on this analysis, an improved cutting tool layout was developed for the Ural-33 cutting machine, leading to a more uniform chip geometry and a reduction in blocked cutting at the face.

Field tests conducted under real operating conditions confirmed the validity of the laboratory and theoretical results. The optimized cutting tool layout resulted in a substantial reduction in specific energy consumption, a significant increase in cutting productivity, lower dust concentrations in the working environment, and reduced cutting tool wear. These outcomes confirm that the proposed experimental–analytical approach is suitable for optimizing cutting machine performance in mechanized rock salt mining.

Acknowledgements

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REFERENCES

[1]. Kovacs, I., Ilias, N., Nan, M.S. *Regimul de lucru al combinelor miniere,* Editura Universitas, Petrosani, 2000.

[2]. Tomuş, O. B., Andraş, A., Jula, D., Dinescu, S. *Aspects relating to the reliability calculation of the cutting-teeth mounted on the bucket wheel excavators used in lignite mining*, In MATEC Web of Conferences (Vol. 290, p. 01020). EDP Sciences, 2019.

[3]. Păsculescu, D., Romanescu, A., Păsculescu, V., Tătar, A., Fotău, I., Vajai, G. *Presentation and simulation of a modern distance protection from the national energy system*, In 2011 10th International Conference on Environment and Electrical Engineering, pp. 1-4. IEEE, 2011.

[4]. Fîță, N. D., Lazăr, T., Popescu, F. G., Pasculescu, D., Pupăză, C., Grigorie, E. *400 kV power substation fire and explosion hazard assessment to prevent a power black-out*, In International Conference on Electrical, Computer Communications and Mecatronics Engineering-ICECCME (pp. 16-18), 2022.

[5]. Cozma, B.Z., Urdea, G.B. *The study of the detachable bits for rotating drillings.* Mining Revue/Revista Minelor, 15(7), 2009.

[6]. Dumitrescu, I., Cozma B.Z., Itu R.B. *Safety mechanisms for mining extraction vessels,* 16th International Multidisciplinary Scientific GeoConference: SGEM, pages: 759-766, Sofia, 2016.

[7]. Tomus, O.B., Andraş, A., Andraş, I. *Study of the dependence between the cutting direction relative to stratification and the digging characteristics of lignite in Oltenia coal basin (Romania),* 17th International Multidisciplinary Scientific GeoConference. ISSN 1314-2704, 17(13), 825-830, (2017). DOI: 10.5593/sgem2017/13/S03.104.

[8]. Andraş, A., Brînaş, I., Radu, S.M., Popescu, F.D., Popescu, V., Budilică, D.I. *Investigation of the Thermal Behaviour for the Disc-Pad Assembly of a Mine Hoist Brake Using COMSOL Multiphysics*. Acta Tech. Napoc.-Ser. Appl. Math. Mech. Eng. 64, 227234, 2021.

[9]. Popescu, F.D.; Radu, S.M.; Andras, A.; Brinas, I.; Marita, M.-O.; Radu, M.A.; Brinas, C.L. *Stability Assessment of the Dam of a Tailings Pond Using Computer Modeling—Case Study: Coroiești, Romania.* Applied Sciences 2024, 14: 268.

[10]. Radu S.M, Chmielarz W., Andras A. *Mining Technological System's Performance Analysis,* Annals of the University of Craiova for Journalism, Communication and Management 2016, 2(1), 56–64

[11]. Ladányi, G., Sümegi, I., Virág, Z. Laboratory rock cutting tests on rock samples from Visonta South Mine. Annals of the University of Petroşani, Mechanical Engineering. 2007, 9, 209–218.

[12]. Szirbik, S., Virág, Z. Finite Element Analysis of an Optimized Hybrid Stiffened Plate. *MATEC Web Conf.* **2021**, *342*, 06003.

[13]. Ladanyi, G., Virag, Z. Examining the bucket wheel excavator's bucket after renewal, Annals of the University of Petrosani, Mechanical Engineering. 2016, 18, 93-98.

[14]. Fita, N. D., Obretenova, M. I., Pasculescu, D., Tatar, A., Popescu, F. G., & Lazar, T., „STRUCTURE AND ANALYSIS OF THE POWER SUBSECTOR WITHIN THE NATIONAL ENERGY SECTOR ON ENSURING AND STABILITY OF ENERGY SECURITY", Annals of' Constantin Brancusi, University of Targu-Jiu, Engineering Series/Analele Universităţii Constantin Brâncuşi din Târgu-Jiu, Seria Inginerie, (2), 2022.