

DRY-CUTTING OPTIONS WITH A CHAINSAW AT THE HOTAVLJE I NATURAL-STONE QUARRY

MOŽNOSTI SUHEGA REZANJA Z VERIŽNO ŽAGO V KAMNOLOMU NARAVNEGA KAMNA HOTAVLJE I.

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This paper presents the results of a study on the possibility of replacing cutting inserts and introducing dry-cutting mode (without water rinsing) with a chainsaw machine in the underground structures of the Hotavlje I quarry. In the experiment a column-driven chainsaw machine Fantini G.70 was used with tungsten-carbide-based cutting inserts. The article presents the physico-mechanical properties of the natural stone called the Hotaveljčan limestone and the state of discontinuities, which has a significant impact on the efficiency of stone cutting. In the experiment the cutting characteristics of two types of inserts, type H-13A and type H6T, were compared. The specimens of both types of the used inserts were subjected to a detailed metallographic investigation to evaluate the changes in the surface structure and hardness, the results of which are presented in detail.

Keywords: tungsten-carbide inserts, chainsaw machine, dimensional stone

V članku so podani rezultati raziskave možnosti zamenjave rezalnih ploščic in vpeljave suhega načina rezanja (brez izpiranja z vodo) naravnega kamna z verižno žago v podzemnih prostorih kamnoloma Hotavlje I. V poskusu je bila uporabljena verižna žaga Fantini G.70 na hidravličnih stojkah. V članku so predstavljene tudi fizikalno-mehanske lastnosti naravnega kamna, t. i. pisanega apnenca "Hotaveljčana", in stanje diskontinuitet, kar pomembno vpliva na učinkovitost rezanja naravnega kamna. Pri poskusu so bile primerjane rezalne karakteristike dveh vrst rezalnih ploščic tipa H-13A in H6T. Materiala obeh tipov rezalnih ploščic sta bila po poskusu detajlno metalurško preiskana glede spremembe trdote površine, rezultati pa so tudi podrobneje prikazani.

Ključne besede: rezalne ploščice, verižni zasekavalni stroj, okrasni kamen

1 INTRODUCTION

The efforts to study and understand the cutting mechanisms applied to hard limestone using chainsaw machines are not new in Slovenia. The first chainsaw machines were introduced in Slovenian natural-stone quarries in the late nineties; they were originally equipped with carbide cutting tools and later progressively replaced with the new generation of tools. The new generation of tools for metal machining included inserts of tungsten carbide coated with a thin film of a hard material that was chemically deposited on the substrate and welded to the metal shank.

Until now, no research project aiming at a better understanding of the stone-cutting mechanisms using a chainsaw has been initiated in Slovenian natural-stone quarries. For example, in Belgium the first results obtained with this technique were widely published in specialized literature¹⁻⁹; Mingels (1971)¹⁰ and Focant (1977)¹¹ described sawing applications in Belgian red marble; Boxho (1971)¹², Brych (1975)¹³ and Neerdael (1975)¹⁴ worked with Belgian blue stone. Later, very few scientific publications were dedicated to the chainsaw-cutting problems.

Research objectives were at first aimed at decreasing the exploitation costs of the chainsaw machines and then

at optimizing the technological parameters in order to correctly set up the cutting machines. The very first studies tried to investigate the machine's performance with respect to the intrinsic properties of the stone being cut, comparing it with the results of the cutting tests performed in a laboratory. These studies highlighted the considerable losses of the machines due to the friction generated at the contact between the chain and the arm of the machine, and also the losses in the hydraulic system driving the machine.

Although the sawing techniques have been particularly improved in the last 20 years, they are still problematic when hard and/or abrasive stones are cut. The main problems encountered with this type of materials are a low productivity, a high consumption of cutting tools and, thus, the related high production costs.

2 EXTRACTION OF NATURAL STONE FROM THE HOTAVLJE I QUARRY

For the hard materials such as Hotavlje calcareous limestone, brittle breakage is typical. This means that this kind of material, when burdened with an additional load, can only sustain a minor degree of plastic strains (approximately 5 %). Thus, it can instantly break in a

plastic zone⁸. Because of these characteristic, the areas with plastic zones are considered unstable and dangerous for the stability of the underground structure.

The occurrence of cracking requires a consideration of the rocks with cracks and their statuses. Thus, an observed rock is called a mound. It is the cracks that cause local differences in the mechanical properties of the rock which differ considerably from those measured in the laboratory. Examinations of mechanical and physical properties of natural stone were carried out in accordance with European Union standards EN 12058:2004 (Natural stone products – Slabs for floors and stairs – Requirements). **Table 1** shows the physico-mechanical properties of three color variations of natural decorative stone called Hotaveljčan.¹⁵

Table 1: Mechanical properties of natural stone called Hotaveljčan¹⁵

Tabela 1: Mehanske lastnosti naravnega kamna, imenovanega "Hotaveljčan"¹⁵

Type of investigation	Unit	Hotavlje red	Hotavlje gray	Hotavlje gray-pink
Density without pores and cavities	t m ⁻³	2.90	2.74	2.73
Density	t m ⁻³	2.74	2.71	2.71
Coefficient of density		0.94	0.99	0.99
Porosity	%	0.06	0.01	0.70
Water absorption	%	0.36	0.23	0.25
Grinding wear	cm ³ 50 cm ⁻²	29.5	27.1	
Modulus of elasticity	GPa	25.0	25.0	25.0
Angle of internal friction	°	22–35	–	–
Bending tensile strength	MPa	–	14.7	
Bending tensile strength after 48 freeze/thaw cycles	MPa	–	13.6	
Average compressive strength:			90.2	
– dry	MPa	137.8	114.0	–
– wet	MPa	150.8	156.0	–
– after 25 freeze/thaw cycles	MPa	187.8	118.0	–

Since the knowledge on rock-mass fracturing is very important in our case in order to determine the geomechanical properties of a rock mass, it has to be described by means of a statistical examination of the dispersion of the measured cracks in the quarry and wells, and a description of its occurrence. The main statistical characteristic of a particular occurrence of a large statistical dispersion indicates that random cracks and crevices thicken considerably with a mild dip to the northeast.

There are two quarries of colored calcareous stone in the Hotavlje deposit. The Hotavlje I quarry, also called the lower quarry, is the older and larger quarry, operating in the northern part of the deposit, 435 m to 450 m above sea level. In the central part of the deposit a new and smaller quarry is in its opening phase. The Hotavlje II



Figure 1: Column-driven chainsaw machine Fantini G.70 on the location in the Hotavlje I quarry

Slika 1: Verižna žaga Fantini G.70 na hidravličnih/vpenjalnih stebrih na lokaciji poskusa v kamnolomu Hotavlje I.

quarry, also called the upper quarry, lies between 478 m and 488 m above sea level. Both quarries are situated on the steep eastern side of the Srednje Brdo Mountain¹⁶.

In 1993, in the colored-calcareous-stone Hotavlje I quarry, a new method of natural-stone-block production was introduced, called the underground stopping, which, until then, had not been used in the Republic of Slovenia. This method was proposed because of the geological structure and the state of the quarry, and also due to an increasing demand for this particular stone. Extraction in the gallery is done with a diamond-wire saw and chain-saw combined. This method proved to be the most efficient one (**Figure 1**).

For the extraction of natural stone from the Hotavlje I underground quarry a chain machine with hydraulic/clamping columns is used (**Figure 2**). Hydraulic pillars allow the machine blade with the cutting chain to move in both horizontal and vertical directions. The cutting chain machine is placed directly in front of the stoppage and is rigidly attached. Horizontal cuts are first made at the bottom and top and finally on the sides. Process water is used for cooling the saw chain and washing the stone slurry out of the cut.

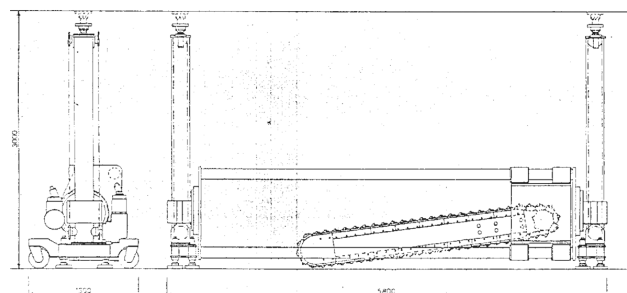


Figure 2: Column-driven chainsaw machine Fantini G.70⁹

Slika 2: Verižna žaga Fantini G.70 na hidravličnih/vpenjalnih stebrih⁹

Table 2 shows technical details/characteristics of the column-driven chainsaw machine Fantini G.70 used in underground quarries.

Table 2: Technical properties of column-driven chainsaw machine Fantini G.70⁹

Tabela 2: Tehnični podatki verižne žage Fantini G.70 s hidravličnimi/vpenjalnimi stebri⁹

Weight of the chainsaw/Weight of the hydraulic unit	6000 kg/2000 kg
Total installed power	52.2 kW (70 HP)
Chain rotation speed	0–0.71 m s ⁻¹
Arm/blade cutting-speed rate	0–0.07 m ² min ⁻¹
Cutting width	38 mm
Arm/blade length	2900 mm
Water consumption	20 L min ⁻¹
Cutting speed	2–4 m ² h ⁻¹

As presented in **Table 2** the cutting speed is between 2 m² h⁻¹ and 4 m² h⁻¹, the cut width is 38 mm and the cut depth is 2.40 m or more. The speed of the blade movement is up to 0.07 m min⁻¹ and the chain speed is up to 0.7 m s⁻¹. The minimum stope-face width is 5.80 m. The cutting method is based on cutting the rock using widia or diamond plates that are mounted on the cutting chain machine’s blade. The cutting machine’s blade moves along the cogged rail and guiding rails. Process water is used for cooling the saw chain and washing the stone slurry out of the cut.

3 THEORY OF NATURAL-STONE CUTTING

An improvement of the sawing techniques in the Hotavlje I quarry initially requires an understanding of the cutting responses of the tools currently available on the market. This implies a development of the working methodology, making it possible to correctly characterize the performances of cutting configurations independently of the machines, the operators and any other parameters that can influence the operations of the machines. The field experimental approach was selected because it makes it possible to very quickly estimate the performances of various types of cutting tools used in a quarry.

Rake angle α : Cutting and normal forces decrease monotonically with the increasing rake angle as seen in **Figure 3**. Most of the benefit to the insert forces is achieved at a rake angle of 20°, beyond which a further marginal improvement weakens the cutting insert’s strength and its potential to survive. The rake angle can be either positive or negative. The rake angles between +20° and +30° can be chosen for cutting weak rocks and coal. High rake angles may not be beneficial since the inserts with these angles are more susceptible to a gross failure.

Wear angle φ : The wear flat is almost parallel to the cutting direction; however, it generally tends to incline in the opposite direction forming a wear angle. This angle

is only a few degrees and it becomes smaller for the hardest and strongest materials. The occurrence of the wear flat changes the tool-tip geometry and, consequently, results in the generation of higher tool forces. The normal force is the component most affected by the wear, e.g., a wear flat of around 1.0 mm can drastically increase the F_n/F_t ratio. It is also reported that a large clearance angle relieves the wear effect and provides a better overall efficiency even if, as a consequence, a small or slightly negative rake angle is introduced.

Clearance angle β : The clearance angle, which is between the lower surface of the insert and the plane parallel to the cutting direction, also has pronounced effects on the cutting insert’s forces. The investigations showed that the tool forces drop sharply after a value of around 5° and stay sensibly constant. To meet the kinematic needs, the clearance angle is generally designed to be around 10°.

When cutting stone with a chainsaw two forces are acting on the cutting inserts (**Figure 3**):

- Axial (thrust) force of the chainsaw arm/blade F_n , which allows the cutting inserts to progress from the surface of the stone into the depth d ,
- Force of the chain rotation F_t , which allows the cutting and progression of the chainsaw arm/blade to the depth d of the cutting grooves.

The cutting depth of individual cuts depends on the axial force F_n which is proportional to and decreases with the increasing cutting surface and the cutting resistance of the rock (strength, toughness and hardness of the rock). Rock cutting begins when the critical pressure is reached, which must be greater than the strength of the rock.

A chip formation can be described as a destruction of the stone consistency using a tool. In the literature, the models based on simple geometries of the cutting edges divide the process of forming a cut into two mechanisms^{1,2}. The cutting mechanism of marble is explained as a plastic deformation (a crushed zone) and a brittle

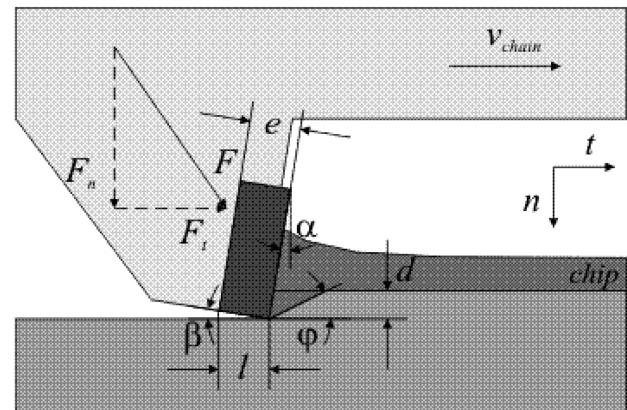


Figure 3: Forces active during the chainsaw cutting of natural stone (α – rake angle, φ – wear angle, β – clearance angle)

Slika 3: Delovanje sil pri žaganju naravnega kamna z verižno žago (α – kot strganja, φ – strižni kot, β – kot praznjenja rezi)

fracture of stone^{2,17}. The plastic deformation and the brittle fracture are influenced by the cutting conditions such as the depth of cut, the tip shape of the cutting tool, and the properties of the stone. When cutting stone with diamond tools, the mechanical interaction of the tool and the workpiece results in the process forces, mainly caused by the following factors:

- elastic and plastic workpiece deformation by the cutting edges;
- friction between the stone and the matrix;
- friction between the swarf and the matrix.

In front of the grains engaged in the process, stresses are caused by tangential forces. In this zone, the insert is forced out through the grooves in front of and beside the grains. While the rock shows elastic characteristics up to its ultimate stresses, it is necessary for the cutting to reach a certain minimum grinding thickness. The material to be cut is deformed by the compressive stress conducted below the diamond. When the load is removed, an elastic reversion leads to critical tensile stresses, which cause a brittle fracture. This mechanism affected by tensile stresses is termed the secondary chip formation. The general insert is carried away by the coolant. The following factors influencing this process are directly or indirectly contained in the model:

- physical material properties of the stone;
- forces between the diamonds and the materials;
- stress distribution in the rock;
- temperatures at the tool/workpiece interface.

The cutting force and energy play important roles in all the stone-machining processes. They are functions of the maximum chip thickness and the geometry of the idealized sawing chip.

The axial (thrust) force of the chainsaw arm/blade, F_n , was calculated by Purtić¹⁸:

$$F_n = \frac{\sigma_u \cdot l \cdot d \cdot \sin(\alpha + 2\varphi)}{\cos \alpha \cdot \cos^2 \varphi} = k \cdot \sigma_u \cdot l \cdot d \quad (1)$$

where

σ_u (MPa) – compressive strength of the rock
 l (m) – length (thickness) of the cutting inserts
 d (m) – depth of the insert penetration into the rock
 k (m) – coefficient of friction.

Coefficient of friction:

$$k = \frac{\cos \alpha \cdot \cos^2 \varphi}{\sin(\alpha + 2\varphi)} \quad (2)$$

The value of coefficient of friction k is dependent on the angle of the rock internal friction φ and the rake angle α :

Coefficient of friction k	0.27	0.30	0.36	0.44
Angle of rock internal friction $\varphi/^\circ$	15	17	20	22

The cutting speed v_{cut} is usually obtained with the following equation:

$$v_{cut} = d \cdot m \cdot v_{chain} \quad (\text{m}^2 \text{ s}^{-1}) \quad (3)$$

where

d (mm) – depth of cutting

m (–) – number of cutting inserts

v_{chain} (m s⁻¹) – speed of the chain with cutting inserts.

The depth of cutting is strongly dependent on the compressive strength of the rock and the force of the chainsaw arm or blade (Figure 4). Specific energy is also a very important factor in determining the efficiency of cutting systems and it is defined as the work required to excavate a unit volume of a rock. Hughes¹⁹ and Mellor²⁰ demonstrated that specific energy can be formulated in the following way:

$$S_E = \frac{\sigma_u^2}{2E} \quad (4)$$

where

S_E – specific energy

σ_u – compressive strength of the rock

E – elasticity modulus.

The work done with the cutting force F_n is the work needed to excavate a unit volume of yield. Dependent on rock strength and toughness, degree of fracturing, machine type and method of operation, cutting insert type and condition, available tool forces (machine size and power) and penetration depth, the specific energy amounts to:

$$S_E = \frac{\sigma_u^2}{2E} = \frac{90.2^2 \text{ MPa}}{2 \cdot 25.000 \text{ MPa}} = 162.7 \text{ kPa}$$

Stone cutting is the result of the interference between the insert grits and hard stone at the stone-tool interface. The traditional tool is constituted of diamond grits that are joined to the metal shank with the metal matrix. The new-generation tools in metal machining are constituted of inserts of tungsten carbide, coated with a thin film of diamond that was chemically deposited on the substrate

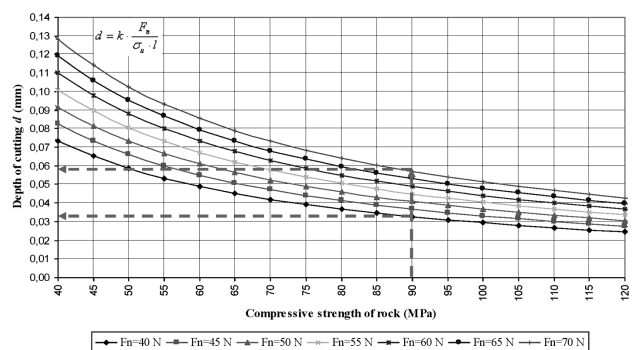


Figure 4: Graph of the expected depth d of the insert penetration at different compressive strengths of natural stone and the axial (thrust) force of the chainsaw arm/blade F_n

Slika 4: Graf pričakovanih globlin d penetracije rezalnih ploščic v naravnih kamnih različnih tlačnih trdnosti in različnih v naravnega kamna ter z različnimi osnimi (potisnimi) silami meča verižne žage F_n

(chemical-vapor-deposition (CVD) diamond inserts) and welded to the metal shank²⁻⁴.

4 EXPERIMENTAL WORK: IN-SITU ATTEMPTS TO USE DIFFERENT INSERTS

The presented research undertaken at the Faculty of Natural Sciences and Engineering, the University of Ljubljana, in 2009/2012 in collaboration with the Marmor Hotavlje company was conducted to understand the main problems encountered while cutting hard limestones such as Hotaveljčan and to propose technical solutions for increasing the competitiveness of the column-driven chainsaw machine Fantini G.70 in the Hotavlje I quarry (Figure 1).

The main objectives of the research were as follows:

- Increasing the machine's performance so that it reaches a higher productivity when cutting the hard Hotaveljčan limestone. The operators usually empirically determined the operating parameters of the machines on the basis of their personal experiences. Consequently, the performance was strongly influenced. The determination of the optimum parameters that should increase the performance required a fundamental scientific study.
- Identifying the potential implementation of dry cutting without the use of process water for rinsing the stone debris from the cut and cooling the inserts.

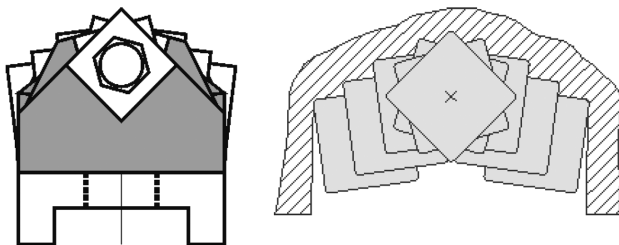


Figure 5: Cutting configuration with 13 mm wide square cutters/inserts (a system of 7 holders (n0-n6))

Slika 5: Postavitev rezanja 13 mm kvadratnih rezalnih ploščic (sistem s 7 nosilci (n0-n6))

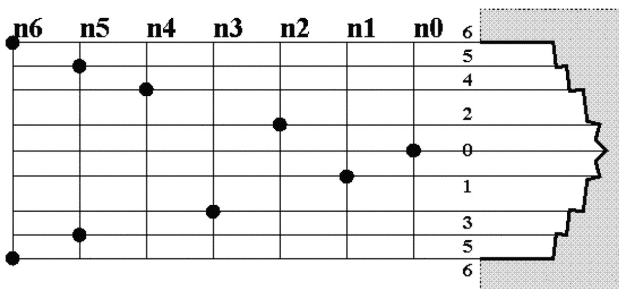


Figure 6: Schematic view of the cutting system with 7 cutting insert holders and their positions on the chainsaw chain (on the right, a schematic view of the cutting grooves)

Slika 6: Shematski prikaz sistema razporeda 7 nosilcev in lege nosilcev rezalnih ploščic na verigi verižne žage (na desni shematski prikaz rezalne brazde)



Figure 7: Detail of the chain and arm/blade of the chainsaw machine
Slika 7: Detajl verige in zobnika roke/meča verižne žage

- Increasing the lifespan of the cutting tools and reducing the maintenance costs of the chain-saw machines.

Two different values of the side rake angle, at the insert/tool holders from n1-n6, angle -6° and at the insert/tool holder n0, angle -25° , were adopted. These were used to simulate the actual engagement between the insert and stone during sawing and, therefore, the cracking phenomena between the insert and stone during sawing. A scheme of the tool engaged in stone cutting is shown in Figures 5 and 6, while Figure 7 depicts a detail of the actual set up of the cutting machine. The cutting force along the cutting direction F_n and the cutting force F_t perpendicular to the cutting direction were evaluated from Figure 3.

In the experiment, two types of inserts were used, namely:

- Fantini Sandvik H6T CT30 insert grade (a hardness of 1753 HV) and
- Fantini Segatrice H-13A insert grade (a hardness of 1310 HV).

The cutting force along the cutting direction F_n and the cutting force F_t perpendicular to the cutting direction were calculated using the data from Table 3.

Table 3: Data on the cutting parameters used for the calculations

Tabela 3: Podatki o parametrih rezanja, uporabljenih za izračune

v_{chain}	Rotation speed of the chain with tungsten-carbide inserts Hitrost verige z rezilnimi ploščicami	0-6.000 cm min ⁻¹
	Arm/blade cutting speed rate Hitrost pomika meča pri žaganju	0-10 cm min ⁻¹
v_{cut}	Average chain cutting speed Povprečna hitrost rezanja verižne žage	0-8 m ² h ⁻¹
	Width of the cut Širina reza	38-42 mm

In addition to the data from Table 3, the values of the cutting speed (0-60 m min⁻¹ (the average of 55 m min⁻¹))

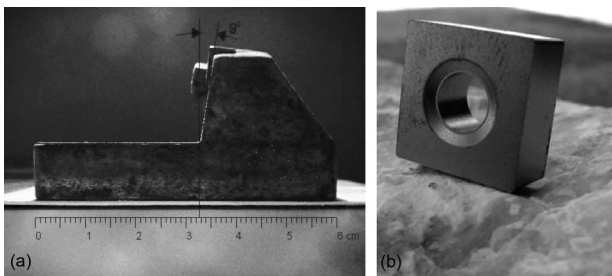


Figure 8: a) Insert holder n5 with a rake angle $\alpha = 9^\circ$ and b) a tungsten-carbide insert

Slika 8: a) Nosilec rezalne ploščice n5 s kotom strganja $\alpha = 9^\circ$ in b) volfram-karbidna rezalna ploščica

and many different values of the depth of cut (between 0.03 mm and 0.06 mm) were also used.

The forces exerted on the cutting inserts, as presented in **Figure 8**, led to the wear of these inserts during the cutting operation, presented in **Figure 9**.

The chainsaw cutting machine (Fantini G-70) operates using the following stepwise procedure to cut natural stone: It starts in Position 0 (**Figure 9**) where the initial cut using only the tip of the cutting blade is made and it is then forced into Position 1 (a blade angle of 10° to 72°). Then the blade is repositioned into Position 2 where it starts to move towards Position 3 (a blade angle of 72° to 81°). In this arrangement the chain with the cutting inserts is cutting the stone piece along the whole of the width, i.e., from 0–250, generating the highest forces exerted on the blade and on the cutting chain. When Position 3 is finally reached, the blade starts to rotate slightly so as to move into Position 4 (a blade angle of 81° to 107°). Finally, it moves into Position 5 (a blade angle of 107° to 166°). This is done in a manner very similar to the one at the beginning of the cutting process. The extent of horizontal cuts is limited to a depth of 2.50 m and the minimum length of 5.75 m. Vertical cuts are limited to a depth of 2.5 m and a height of 4.6 m. The construction of the cutting machine also

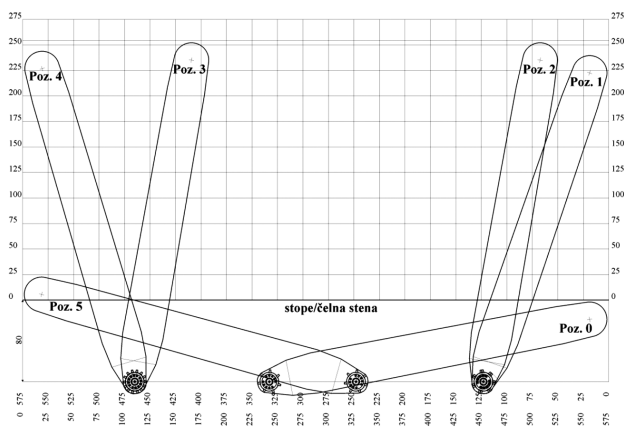


Figure 9: Stages (Pos. 0 to Pos. 5) of making a horizontal cut with two types of cutting inserts

Slika 9: Faze (Poz. 0 do Poz. 5) rezanja horizontalnega reza z različnimi tipoma rezalnih ploščic

enables the cuts to be made under different angles, exerting additional forces on the blade and the chain, thus leading to premature wear of the cutting inserts.

5 RESULTS AND DISCUSSION

The results of the cutting process described in the section about the experimental work associated with **Figure 9** are depicted in **Figures 10** and **11**. Two different cutting inserts were employed for the cutting purposes. Both cutting inserts were mounted on the same chain of the Fantini G-70 cutting machine so as to make the comparison of the cutting inserts as reliable as possible. **Figure 10** shows the behavior of the H6T C30 Fantini Sandvik cutting inserts mounted on the cutting chain cutting the natural stone from the Hotavlje quarry in the horizontal manner. For this purpose the following process parameters were used: the chain speed varied from 53.0 m min^{-1} to 55.3 m min^{-1} and the average cutting speed increased from $3.5 \text{ m}^2 \text{ h}^{-1}$ to $5.5 \text{ m}^2 \text{ h}^{-1}$. The entire duration of the pure horizontal cut with the chainsaw took 186 minutes. Throughout the cutting process, the consumption of time was also recorded. In the case of the cutting inserts H-13A Fantini Segatrice (**Figure 11**) the horizontal cutting manner was also applied and the chain speed varied from 51.5 m min^{-1} to 55.6 m min^{-1} , while the average cutting speed varied from $6.3 \text{ m}^2 \text{ h}^{-1}$ to $7.9 \text{ m}^2 \text{ h}^{-1}$. The entire duration of the pure horizontal cut with the chainsaw took 169 min. A comparison of the results from **Figures 10** and **11** indicated that the yield in the case of the H-13A cutting inserts was higher in relation to the average cutting speeds, whilst the time consumption was pretty much the same. However, the variation in the chain speed was smaller in the case of the H6T cutting inserts which applies to the average cutting speeds as well. In the case of H6T, these showed less dissipation or variation in all the positions or incisions (Pos. 0 to Pos. 5) which inevitably led to less pronounced wear of the cutting inserts due to fragmentation than in the case of the H-13A cutting inserts. When the H-13A cutting inserts were used, the variations in the chain speeds were much more obvious as the

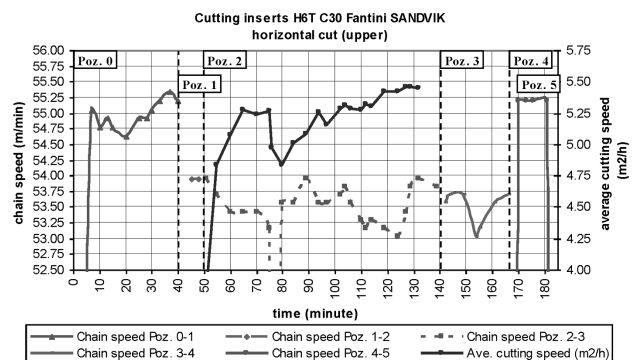


Figure 10: Results of a horizontal cut with the H6T cutting inserts
Slika 10: Rezultati rezanja horizontalnega reza z rezalnimi ploščicami H6T

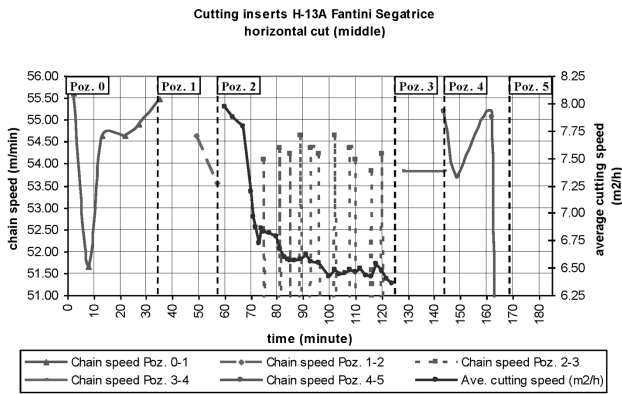


Figure 11: Results of a horizontal cut with the H-13A cutting inserts
Slika 11: Rezultati rezanja horizontalnega reza z rezalnimi ploščicami H-13A

speeds varied, for all the incisions (Pos. 0 to Pos. 5), with sharp peaks and drops.

This led to less uniform wear and a more frequent deformation of the cutting inserts due to fragmentation. The recorded peaks and drops in the chain speeds in the case of H-13A are visible in **Figure 12** showing an array of grooves made in a stepwise manner as the mechanical properties of the natural stone were changing locally, as were the mechanical properties of the cutting inserts.

The measurements of the surface and subsurface microhardness of the cutting inserts showed that the degradation of the surface hardness was severe but it was, in all the cases, limited to an area within a few tenths of a millimeter under the surface (**Table 4**).

A brief metallographic overview of the applied cutting plates provided us with a definite proof of surface and subsurface degradation. This was observed using LM and the microhardness measurements made on the surface and, in a stepwise manner, also under the surface. **Table 4** summarizes the Vickers hardness measurements with the average number of measurements of 5.

Table 4: Microhardness measurements of HV 0.05 for H-13A and H6T CT30 cutting inserts

Tabela 4: Mikrotvrdote HV 0,05 rezalnih ploščic H-13A in H6T CT30

Cutting insert	Average hardness on the surface	Average hardness 0.1 mm under the surface
Grade H-13A	1240.75	1471.40
Grade H6T CT30	1269.00	1614.67

It is clear that in both cases the hardness degrades quite rapidly and dramatically from the surface towards the inner region of a cutting plate, which is a consequence of the thermomechanical load on the surface of the cutting plate. On the micrographs of the H-13A cutting inserts in **Figures 13a** and **13b** severe material wear can be observed on the cutting edges of the cutting inserts due to a complete rounding and cracking of the initially rectangular edges. On the top (**Figure 13b**), the indents of the diamond pyramid can still be seen allow-



Figure 12: Visible grooves or a cut profile made by the cutting inserts
Slika 12: Vidni kanal oziroma profil reza, ki nastaja med rezanjem z rezalnimi ploščicami

ing clear indications of the places where the microhardness HV measurements were made. The protective TiN layer of the surface and the edges of H6T CT30 is still intact, which was also confirmed with the HV measurements showing a higher hardness of the cutting inserts after the operation (**Figure 13c**). It has to be noted here that the H-13A cutting inserts were used for the so-called dry cutting, whereas the H6T CT30 inserts were water cooled. Namely, the H-13A cutting inserts were constructed to be used for dry cutting although we believe that the use of a lubricant or coolant would most likely prolong their service time too.

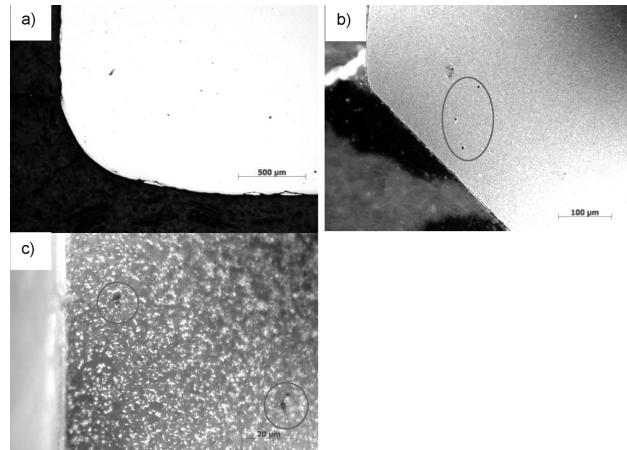


Figure 13: LM micrographs of the cutting inserts after the operation: a) cutting edges of H-13A cutting inserts and b) with clear positions of the indents (circle) of the diamond pyramid used in HV measurements. Uniformity in the grain size of WC can be seen in b). The surface of H6T CT30 exhibits fewer defects and still has the protective layer of TiN. Positions of the indents caused by the diamond pyramid are visible in c).

Slika 13: LM-posnetki uporabljenih rezalnih ploščic: a) rezalni robovi ploščic H-13A in b) z lepo vidnimi vtiski po uporabi diamantne piramide v okviru HV-meritev. Na sliki b) je prikazana enakomerna velikost delcev WC. Površina rezalne ploščice H6T CT30 izkazuje veliko število majhnih poškodb na še vedno prisotni zaščitni plasti iz TiN. Na sliki c) so vidna mesta z diamantno piramido nastalih vtiskov.

6 CONCLUSIONS

The present work shows that tungsten-carbide H-13A inserts allow an increase in the cutting efficiency by more than 66 % and, therefore, a decrease in the amounts of force and energy involved in stone sawing. This means that the tool is exposed to the stresses lower than those affecting a tungsten-carbide insert probably causing a reduction of tool wear. Moreover, the cutting power of the tungsten carbide H-13A inserts is lower than that of the tungsten-carbide H6T CT30 inserts.

A single model describes well the actual cutting force caused by the interaction between a tungsten-carbide insert and stone. This means that a unique simple equation can represent the relationship between the cutting force and the chip-cutting area.

An analysis of the tungsten-carbide insert wear over time and of the relationship between the tungsten-carbide wear and the cutting-force value compared to the behavior of the chemical-vapor-deposition (CVD) diamond inserts is currently the topic of further studies in order to verify that this type of tool is suitable for sawing the Hotaveljčan limestone.

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7 REFERENCES

- ¹ F. I. Dagrain, Understanding stone cutting mechanisms for the design of new cutting tools sequences and the cutting optimization of chain saw machines in Belgian blue stone quarries, *Diamante, Applicazioni & Tecnologia*, 17 (2011) 66, 55–67
- ² S. Turchetta, L. Carrino, W. Polini, CVD diamond insert in stone cutting, *Diamond and Related Materials*, 14 (2005) 3–7, 641–645
- ³ H. K. Tönshoff, H. Hillmann-Apman, J. Asce, Diamond tools in stone and civil engineering industry: cutting principles, wear and application, *Diamond and Related Materials*, 11 (2002) 3–6, 736–741
- ⁴ Y. Li, H. Huang, J. Y. Shen, X. P. Xu, Y. S. Gao, Cost-effective machining of granite by reducing tribological interactions, *Journal of Materials Processing Technology*, 129 (2002) 1–3, 389–394
- ⁵ H. D. Jerro, S. S. Pang, C. Yang, R. A. Mirshams, Kinematics analysis of the chipping process using the circular diamond saw blade, *Journal of Manufacturing Science and Engineering*, 121 (1999) 2, 257–264
- ⁶ K. Brach, D. M. Pai, E. Ratterman, M. C. Shaw, Grinding forces and energy, *Journal of Manufacturing Science and Engineering*, 110 (1988) 1, 25–31
- ⁷ H. K. Tönshoff, J. Peters, I. Inasaki, T. Paul, Modelling and simulation of grinding processes, *Annals of the CIRP*, 41 (1992) 2, 677–688
- ⁸ T. W. Hwang, S. Malkin, Grinding mechanisms and energy balance for ceramics, *Journal of Manufacturing Science and Engineering*, 121 (1999) 4, 623–631
- ⁹ Fantini Technical Paper, 2002, 4
- ¹⁰ C. Mingels, Utilisation d'une haveuse Perrier dans une carrière de marbre, *Annales des Mines de Belgique*, 2 (1971) 1, 121–130
- ¹¹ J. Focant, Utilisation des haveuses Perrier dans l'exploitation des carrières de Marbres Rouge, *Annales des Mines de Belgique*, 9 (1977) 2, 819–823
- ¹² J. Boxho, Essai d'une haveuse Perrier dans le Petit Granit, *Annales des Mines de Belgique*, 2 (1971) 3, 131–142
- ¹³ J. Brych, Les outils autoaffutants au service du havage des roches dures, *Annales des Mines de Belgique*, 2 (1975) 1, 165–180
- ¹⁴ B. Neerdael, Contribution à l'étude de la destructibilité des roches dures telles que les calcaires crinoïdiques de Soignies, *Faculté Polytechnique de Mons, Travail de fin d'études*, 1975, 5–18
- ¹⁵ K. Fifer, Natural stone "Hotavlje" geotechnical report / Poročilo o preiskavi naravnega kamna "Hotavlje", ZAG, Department of materials, Ljubljana 2005, 35
- ¹⁶ U. Bajželj, J. Kortnik, B. Petkovšek, K. Fifer, Environment friendly underground excavation of dimension stone, 27th International Symposium on Computer Applications in the Mineral Industries, London, 1998, 11–22
- ¹⁷ J. Kortnik, U. Bajželj, Underground mining of natural stone in Slovenia, 20th World Mining Congress, Tehran, 2005, 277–286
- ¹⁸ N. Purčić, Drilling and Blasting/Bušenje i miniranje, Rudarsko-geološki fakultet, Beograd 1991, 20–22
- ¹⁹ H. Hughes, Some aspects of rock machining, *Int. J. Rock Mech. Min. Sci.*, 9 (1972) 2, 205–211
- ²⁰ M. Mellor, Normalization of specific energy values, *Int. J. Rock Mech. Min. Sci.*, 9 (1972) 5, 661–663