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THERMAL DEGRADATION OF CEMENTED-CARBIDE CUTTING INSERTS AND INFLUENCE OF DRY CUTTING ON REPEN LIMESTONE

TERMIČNA DEGRADACIJA REZALNEGA ORODJA IZ KARBIDNE TRDINE IN VPLIV METODE SUHEGA ŽAGANJA REPENSKEGA APNENCA

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This paper presents the results of a thermographic analysis of Fantini Sandvik H6T cutting inserts during the dry cutting of dimension stone – Repen limestone – using a Fantini 70-RA-BU bank chainsaw machine in the underground rooms of the Debela Griža quarry, Slovenia. It is known from literature that the temperature reached at the contact between a cutting insert and stone is also an important factor affecting the service life and cutting performance when cutting dimension stone. Furthermore, the critical temperature for thermal damage during granite cutting was identified as 100–200 °C, while for cutting sandstone or limestone, it was 100 °C. Specimens of the used H6T cutting inserts were subjected to a detailed metallographic investigation to evaluate the changes in the surface structure and hardness. Additionally, possible reasons for the wear of cutting inserts due to the contact temperature and surface tension were discussed.

Keywords: chainsaw machine, dimension stone, thermographic analysis, cutting inserts

V članku avtorji predstavljajo rezultate termografske analize (TGA) rezalnih ploščic Fantini Sandvik H6T pri suhem (nemazanem) načina rezanja naravnega kamna – Repenskega apnenca s tirno verižno žago Fantini 70-RA-BU v podzemnih prostorih kamnoloma Debela Griža na Krasu. Iz literaturnih virov je znano, da je dosežena temperatura na kontaktu med rezalno ploščico in obdelovancem pomemben dejavnik, ki zelo vpliva na življenjsko dobo rezalne ploščice in zmogljivost rezanja kamna nasploh. Raziskana in potrjena je bila možnost začetka toplotne degradacije pri rezanju blokov naravnega kamna, ki se glede na literaturne vire v primeru magmatskih kamnin (granita) prične pri temperaturah okoli 200 °C in v primeru sedimentnih kamnin (peščenjak/apnenec) okoli 100 °C. Vzorci uporabljenih rezalnih ploščic H6T so bili podvrženi podrobni metalografski preiskavi za oceno sprememb površinske strukture in trdote. Poleg tega so bili obravnavani možni vzroki za obrabo rezalnih ploščic zaradi kontaktne temperature in površinske napetosti.

Ključne besede: naravni kamen, termografska analiza, verižna žaga, rezilne ploščice

1 INTRODUCTION

The problems of the currently used technologies for mechanical extraction of high-strength or abrasive natural stone are mainly related to the low productivity of extracting stone blocks, high consumption of cutting tools and consequently high production costs. In practice, two technologies for cutting natural stone predominate: cutting with a wire saw or cutting with a chainsaw. The latter method reduces production and time losses, directly producing blocks for sale and generating less waste material in comparison to cutting with a diamond wire saw. The cutting capacity of a chain saw depends on the geological and geotechnical conditions of natural stone in the deposit, the mechanical parameters of the chainsaw, the operating parameters in the quarry, etc. In practice, a chainsaw is almost never used for cutting very hard and heavily fractured stone.

The cutting technology using chainsaw machines is not new in Slovenia. The first chainsaw machines for cutting limestone were introduced in the Hotavlje quarry in 1996 and in the Debela Griža quarry in 2014.[1] Despite their common use, very few research investigations on rock-cutting mechanisms in chainsaw cutting have been conducted, with notable exceptions being Refs.[1,2] However, the first results of this technique obtained in Belgium were widely published in specialized literature.[3–16] Lately, few scientific publications have been dedicated to chainsaw-cutting problems, with some exceptions being Refs.[17,18]

For optimal stone cutting both cutting forces and temperature must be controlled. For example, in Ref.[19], investigating drilling in stone, it was determined that the formation temperature and heat generation play important roles in rock crushing. The effects of cutting conditions (dry/wet) on the temperatures of cutting inserts and the cutting temperature influence on the rock debris size

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have so far been analysed only rarely; however, this is exactly the focus of the present article. Both heat generation and influence of temperature on rock debris and cemented carbide cutting inserts are analysed.

The main goal of the investigation was to provide a plan for optimising dimension stone extraction in the Debela Griža quarry. On the one hand, this was achieved by measuring surface temperatures of cutting inserts on the chainsaw, both during dry and wet cutting of Repen limestone. On the other hand, the inserts were metallographically examined to demonstrate the influence of their microstructure on the insert properties and to elucidate typical reasons for their fracture.

2 CUTTING TECHNOLOGY FOR REPEN LIMESTONE

One of the machines for dimension stone extraction in the Debela Griža quarry is a Fantini 70-RA-BU bank chainsaw machine, shown in **Figure 1**. This is a rather common stone cutting machine, frequently used for deepening surface quarry benches or underground galleries.

The main feature of Fantini 70-RA-BU is the single rail, allowing it to be rapidly repositioned longitudinally without the need for lifting equipment; a single operator is hence sufficient to operate the machine. This model can cut up to 5.1 m deep into hard stone, the chainsaw blade allowing vertical and horizontal cuts at the quarry face. During cutting, the machine is placed 0.5 m from the slope face and fixed to the ground, as shown in **Figure 1**. The initial width of the gallery, which is related to the length of the rail of the Fantini 70-RA-BU chainsaw machine, is 5.1 m and the initial height of the gallery is 4.0 m. Cutting stone blocks usually begins with a cut at the bottom of the projected block, then at the top, and lastly on the sides; no water or any other coolant is used during the process, neither for cooling the chainsaw nor for washing stone debris out of the cut. More technical data regarding the machine in question are shown in **Table 1**.

Figure 1: Fantini 70-RA-BU bank chainsaw machine in the Debela Griža quarry, Slovenia. Gallery width of 5.1 m and height of 4.0 m.

Table 1: Technical characteristics of the Fantini 70-RA-BU bank chainsaw machine[19]

Installed power	50 kW (67 HP)
Total weight	6200–6700 kg
Cutting width/Arm rotation	38 mm/360°
Chain rotation speed	0–0.7 m s^{-1}
Arm movement speed	0–13 mm min^{-1}
Effective cutting depth	max. 5.1 m
Stone cutting speed (with a 3.2 m long blade)	0–0.042 m^2 min^{-1}

The stone cutting speed in **Table 1** is equivalent to 2.5 m^2 h^{-1}. Furthermore, the length of the single rail is around 5.80 m.

Fantini 70-RA-BU uses a chisel-type (also called wedge-type) cutting tool system with inserts made from cemented carbide mounted on the cutting chain of the blade in a rectangular prism-like geometry; a schematic view of this method of mounting inserts is shown in **Figure 2**. Eight insert holders, numbered n0 to n6, with an additional n5BIS, are shown. In this cutting system, an insert holder with the manufacturer's mark n5BIS is added between n5 and n6. This insert holder is a slightly improved version of n5, with a more appropriate placement of cutting inserts, allowing for more efficient cutting of natural stone than the cutting system with 7 cutting insert holders[1]. On five holders, only one insert is mounted, while three holders have two of them; the distance between insert holders is around 10 cm. This type of cutting tool system has proved to be currently the most effective in cutting hard stone, such as Repen limestone from the Debela Griža quarry, Slovenia. Some mechanical properties of Repen limestone are: density of 2.680 ± 0.003 t m^{-3}, porosity of 3.85 ± 0.25 %, average uniaxial compressive strength of 213.5 ± 20.5 MPa and modulus of elasticity of 25.0 ± 1.5 GPa[20].

Stone cutting is the result of an interaction between cutting inserts and stone at the stone-tool interface.[2] For successful cutting, the inserts must demonstrate sufficient hardness, which is why cemented carbide inserts are nowadays standard in stone cutting. Recently, how-

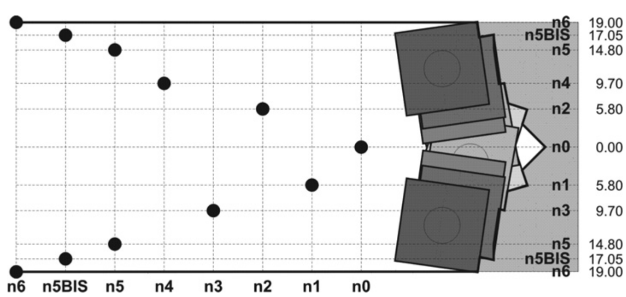

Figure 2: Schematic view of the cutting tool system with 8 insert holders (n0 to n6 with n5BIS) on the chainsaw chain (left) and cutting insert profile with the distances of the cutting grooves from the centre (right)[2]

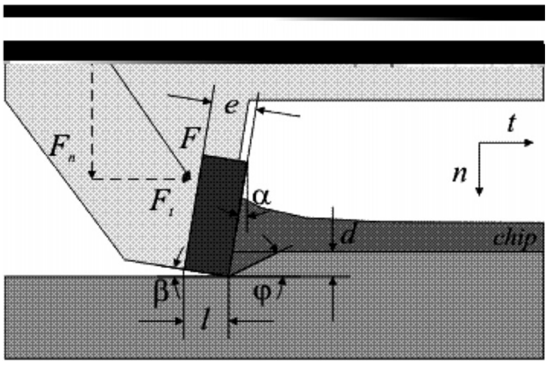

Figure 3: Forces active during the cutting of dimension stone with a chainsaw (α – rake angle, φ – wear angle, β – clearance angle)[2]

ever, there has been a steady increase in the use of newer-generation inserts made from tungsten carbide, yet coated with diamond using chemical vapour deposition (CVD).[3–5]

The cutting depth is strongly dependent on the compressive strength of the rock, σ_u and the axial force of the chainsaw blade, F_n, as shown in **Figure 3**. F_n can be calculated using Purtić's equation from Ref.[21]; in the case of cutting Repen limestone with a chainsaw, its values are between 45 N and 70 N.[2] This means that the depth of cutting is between 0.03 mm and 0.05 mm per cutting insert per cut;[2] if the area of the stone-tool interface is estimated as 1 mm^2, a stress of 45–70 MPa is expected to be achieved on the surface of the stone.

For optimal cutting, the rake angle α, shown in **Figure 3**, is usually around 5° in the analysed cutting tool system with 8 insert holders. The rake angle can be adjusted, allowing slightly worn inserts to cut with a sharp edge again. In general, insert wear depends on the type of cutting profile, microstructure of the inserts and hardness of the stone; these determine the type, shape and amount of wear. Additional factors influencing wear include cuts made at different angles and additional forces exerted on the blade, leading to premature wear of the cutting inserts.

3 TEMPERATURE INFLUENCE ON CUTTING TOOLS

It is well-known that during stone cutting with cemented carbide tools several wear mechanisms such as abrasion, adhesion, oxidation, diffusion, etc., take place simultaneously; consequently, determining the dominant wear mechanism is often difficult.[22] At low speeds (under 1 m s^{-1}), abrasion is usually the most important mechanism, followed by adhesion at moderate speeds (between 1–10 m s^{-1}) and diffusion at high speeds (over 10 m s^{-1}). Besides cutting speed, important factors influencing the dominant wear mechanism are also insert materials and stone characteristics.

In the case of Fantini 70-RA-BU, the cutting speed is 0–0.7 m s^{-1} (see **Table 1**), which falls in the category of low speeds. Another important influence on the tool wear rate and tool life is the temperature, influenced by the cutting speed.[22] Takeyama and Murata proposed equation (1), which combines the expected tool life, t (i.e., average time before fracture) with the highest temperature during wear, T, while a and b are empirical constants.[23] The equation describes wear the best when a single wear mechanism is considerably more prominent than the others.[23]

$$t = a \cdot T^b \tag{1}$$

When cutting stone with cemented carbide inserts, studies have shown that at practical cutting speeds – when no built-up edge is observed – the dominant wear mechanism is diffusion, as the insert temperature can exceed 800 °C.[22] When investigating the wear of cutting tools, Takeyama and Murata[23] argued that the most common mechanisms of tool flank wear are abrasion and diffusion, proposing that wear is the sum of abrasion and diffusion wear. The former is proportional to the cutting distance and independent of the cutting tool temperature, while the latter is temperature sensitive[23].

In the present investigation, Fantini Sandvik H6T cutting inserts with an average hardness of 1753 HV were used.[2] Cutting-tool-surface temperature measurements were carried out using a VOLTCRAFT WBP-110 25 Hz thermal imaging camera with a temperature measurement range of –20–550 °C and thermal sensitivity of 50 mK (see **Figure 4a**). The cutting-tool surface temperature was measured during dry (**Figure 4b**) and wet cutting (**Figure 4c**). In these figures, S represents the temperature measured in the image centre and H represents the maximum measured temperature in the image.

The results of the cutting tool temperatures are shown in **Figure 5**. The average tool temperature during dry cutting was 124.3 ± 41.9 °C, while during wet cutting with running water at 8.7 °C, it was 59.7 ± 20.7 °C. The measured temperatures were all under 200 °C, which, according to Ref.[23], means that the dominant wear mechanisms were abrasion and adhesion.

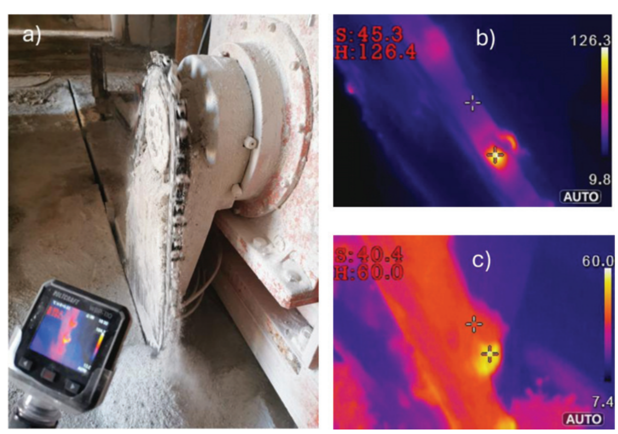

Figure 4: a) Temperature measurement with a Voltcraft WBP-110 thermal camera on the cutting tool surface; b, c) thermographic images captured during b) dry and c) wet cutting

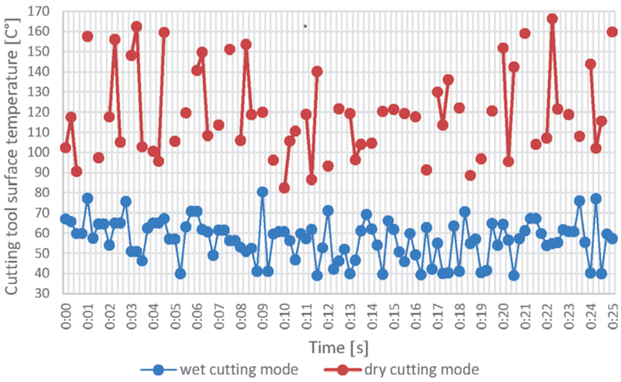

Figure 5: Graph of measured cutting-tool temperatures during cutting

Even though wet cutting caused lower tool temperatures, which would decrease the wear and increase the lifetime of the tool, a major problem was mud, created by stone dust and debris, which stuck to the cutting tool, thereby decreasing its productivity. Another problem with wet cutting was the additional cost of water, which is why dry cutting is a better option for Repen limestone.

4 EXPERIMENTAL WORK

For the purpose of evaluating the influence of cutting parameters on the wear of Fantini Sandvik H6T cutting inserts, some heavily worn inserts were examined using SEM with EDS and XRD measurements. It was established that in some cases worn inserts had small particles attached to their surface, as shown in **Figure 6**. These particles originated from the surface of cut limestone.

Another clear observation from these SEM images is that the adhered particles have gone through a change in their state of matter. Particles have been heavily deformed and are stuck to the surface of the cutting insert due to strong adhesion bonds. For the purpose of the SEM and EDS examination of samples, a Thermo Fisher Quanta 650 scanning electron microscope (SEM) equipped with an Oxford Live EDS Ultim max 40 mm^2 SDD was used, operating at 20 kV for the EDS analyses. For the XRD examination, an Empyrean Multi-Purpose X-ray Diffractometer produced by Malvern Panalytical and equipped with a 1Der detector using $Cu_{K\alpha}$ was employed.

5 RESULTS AND DISCUSSION

The XRD analyses clearly showed that the dominant constituent of Repen dimension stone was calcite – see **Figure 7**.

We examined the remains of the cut dimension stone and made a comparison which showed that in all cases

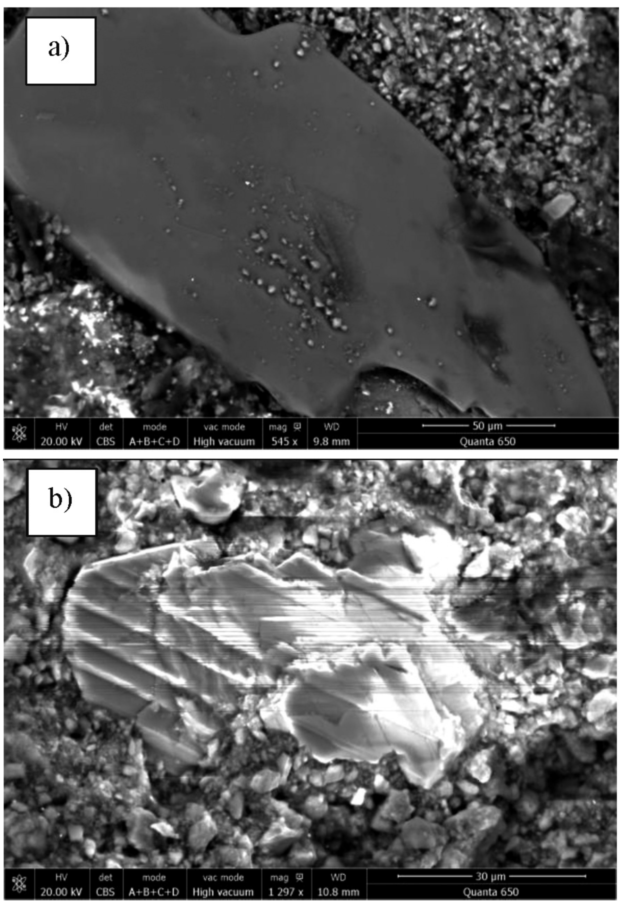

Figure 6: SEM-BSE images of the particles, attached to the surface of the cutting inserts: a) a deformed particle on the surface – its chemical

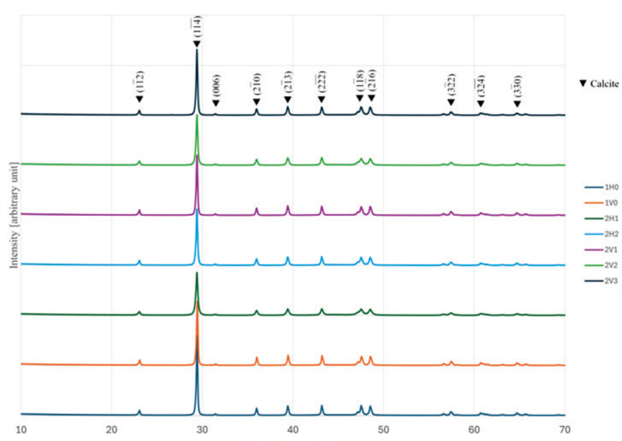

Figure 7: XRD results of seven different samples of cutting remains of Repen limestone

Table 2: Chemical compositions of the particles from **Figure 6**

label	Na	Mg	Al	Si	S	K	Ca	Ti	Fe	W	Total
a)	0.96	0.67	28.35	39.44	–	12.38	10.71	0.64	2.63	4.23	100.0
b)	1.25	0.63	30.73	44.00	0.68	13.22	6.81	–	2.67	–	100.0

calcite was the dominant constituent. Due to previous studies, we are aware of the presence of thin inclusions in dimension stone, which are reddish and visually resemble the structure of veins in living organisms; these inclusions obviously have a different composition than the dominant calcite. This was confirmed by the EDS analysis of the particles shown in **Figure 6** and listed in **Table 2**, presenting their chemical composition in mass% including all constituting elements that are, in our opinion, related to the reddish inclusions in the analysed stone.

From the EDS analyses in **Table 2**, it is apparent that the chemical composition of the particles is complex and contains from 8 to 10 different elements. Furthermore, oxygen and carbon concentrations were omitted as their detection with EDS detectors is very unreliable. Nevertheless, considering the colour of inclusions and knowing the composition of the dimension stone in question, it is plausible to conclude that the particles include a mixture of different oxides and other compounds. Based on the amounts of Fe, K, Ca, Na, Mg, Al and Si, it is likely that these adhered particles contain mixtures of complex multicomponent compounds that could be attributed to clay minerals. Even more striking is the fact that these particles have obviously undergone changes in their state of matter, as they appear smeared across the surface of cutting inserts. This indicates that the combination of contact temperature and pressure exerted by the chainsaw machine on the cutting inserts likely caused these particles to briefly reach temperatures close to their melting point. This led to partial softening of these particles and facilitated their adhering to the surface of cutting inserts, thereby reducing their cutting ability and accelerating their wear.

6 CONCLUSIONS

The presented research was conducted to understand the thermal effects of cutting Repen limestone and to optimise its extraction in the Debela Griža quarry. Using a variety of investigative techniques, it was determined that:

- The average tool temperature during dry cutting was 124.3 ± 41.9 °C, and during wet cutting, it was 59.7 ± 20.7 °C. Dry cutting was proven to be advantageous when extracting Repen limestone due to lower water costs and higher productivity as mud did not stick to the cutting tools.
- Heavily worn cemented carbide cutting inserts exhibited adhered phases originating from the stone. Their composition was very complex; they were likely mixtures of several multicomponent compounds.
- Some of these phases appeared smeared, suggesting that they may have briefly been melted during cutting.
- Using XRD, it was determined that Repen limestone consists mainly of calcite.

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