



# The mechanics of sawing granite with diamond wire

Janusz Stefan Konstany<sup>1</sup>

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## Abstract

Today, wire sawing of natural stone is undergoing widespread commercialization. In addition to rock extraction and processing with single wires, composed of a multitude of diamond-impregnated beads mounted onto a steel rope, this technology is increasingly used for slabbing of granite blocks on multi-wire machines. Evolving sophistication of stone sawing equipment dictates novel tool designs and formulations. For technologists specifying bead compositions, it is a common habit to instinctively follow the circular saw segment design guidelines. A poor tool performance is often an undesirable consequence of such an approach. To meet that challenge, theoretical models of sawing granite by means of a diamond wire saw and a diamond circular saw have been presented and contrasted with respect to diamond loading conditions. The analytical treatments are supported by scarcely available industrial quantitative assessments and qualitative observations. The evaluation of cutting forces and the identification of system characteristics affecting wire vibration and wire rotation are instrumental in both machine design and tool formulation. For practitioners working with granite, the provided knowledge is also essential to diagnose and prevent problems inherent in wire sawing, such as the high incidence of wire breakage, unsatisfactory tool life and cutting capability and eccentric bead wear.

**Keywords** Diamond · Wire saw · Diamond bead · Sawing granite

## 1 Introduction

The first diamond wires were invented in England in the 1950s. Initially, they consisted of electroplated diamond beads threaded onto a multi-strand steel rope. Later, the electroplated beads were complemented with sintered beads, but both types of diamond wire were almost exclusively used to extract blocks in marble and limestone quarries. Further machine and wire developments were needed for igneous rock sawing, and it was not until the past 30 years or so that diamond wire was commonly accepted for squaring granite blocks on stationary single-wire machines. Multi-diamond wire (MDW) machines are the newest type of equipment which is increasingly used for slabbing granite blocks, replacing the traditional steel shot frame saws. Although the first prototypes were

tested in the mid-1990s, MDW sawing of granite is still being developed and has yet to reach its full potential.

For most applications, the wire saw contains 7.3–11-mm diameter diamond-impregnated beads mounted on a galvanised steel rope. The vast majority of MDW machines use 6.3–8.3-mm beads although wires 4.3 mm in diameter have recently been targeted to minimise kerf widths and consequently to maximise the yield of slabs per block [1].

The cutting action of a diamond wire consists in pulling a properly pre-tensioned wire saw across the stone block at a linear speed of between 24 and 30 m/s, and simultaneously lowering it at a down-feed rate tailored to meet the optimum combination of productivity and wire life. As a general rule, the more difficult the stone to cut, the lower the down-feed rate. Cutting rates between 1 and 3 m<sup>2</sup>/h were earlier recommended for both single and multi-wire stationary machines [2]. The recent trend has been, however, toward lower cutting rates of between 0.9 and 1.5 m<sup>2</sup>/h on single-wire machines [3] and 0.6 and 1 m<sup>2</sup>/h on MDW machines [4]. The obvious advantage of slower down-feed rates is enhanced wire rotation [5], whereas smaller bead diameter allows reduced stress on the steel rope thus prolonging its fatigue life. An obvious consequence of using beads 7.3 mm in diameter, or smaller, is restricted thickness of the diamond-impregnated layer,

✉ Janusz Stefan Konstany  
konstant@agh.edu.pl

<sup>1</sup> Department of Physical Metallurgy and Powder Metallurgy, Faculty of Metals Engineering and Industrial Computer Science, AGH – University of Science and Technology, Mickiewicz Avenue 30 30-059, Krakow, Poland

which adversely affects the wire life. This trend is more pronounced as the rock becomes more difficult to cut [2].

A schematic diagram of cutting a block of stone is presented in Fig. 1.

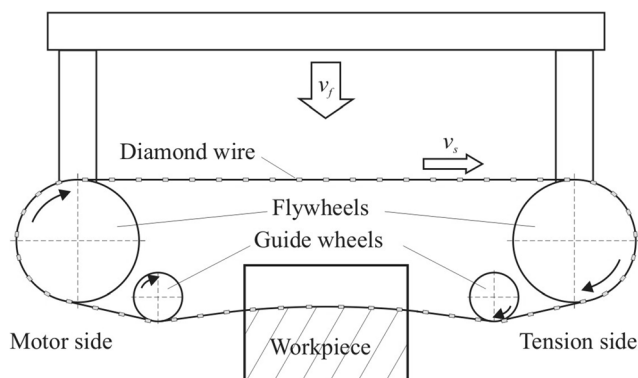
It is essential for the tool performance that the diamond beads are firmly fixed in place on the rope and wear in a uniform manner over the whole working surface. Therefore, the wire saw should continuously rotate but the beads must not rotate around the steel rope holder. In industrial practice, a correct offset and angled pulley arrangements in the machine usually yield satisfactory results, but multiple pre-twisting of the wire before a continuous loop is assembled may aid in preventing eccentric wear of beads along the length of the wire [5]. It has also been found that too high cutting forces resulting from the increasing down-feed rate may eventually overcome the torsional force induced by the machine pulley offset leading to eccentric wear (ovalisation) of beads [5].

While sawing relatively long blocks at low cutting rates, the forces/pressures acting on diamond beads are much lower compared to circular sawing of granite. This fact is usually neglected, and circular saw segment formulations, discussed in detail in Ref. [6], are uncritically adapted to the production of wire saw beads, resulting in poor tool performance. Therefore, the main objective of the present study is to provide a more fundamental understanding of the mechanics of sawing hard rock with a diamond wire in order to make and use the tooling correct, thus avoiding high cost of trial-and-error-based experiments.

## 2 Numerical modelling of sawing stone

In this study, a mechanistic approach is used. A mathematical model of sawing stone blocks with a diamond wire has been proposed and compared with a corresponding model for circular sawing, previously presented in Ref. [7].

The application environment of diamond wires is very complex and poorly controlled. Real-time quantitative data collection systems to date have not been fitted to production



**Fig. 1** Schematic representation of block cutting with a diamond wire saw

equipment. Therefore, the theoretical considerations have been supported by scanty literature reports and limited experimental data acquired by the author.

### 2.1 Force analysis in wire sawing

The diamond-impregnated beads are subjected to various forces resulting from the cutting action, wire tension and weight, and arched shape of cut travelled by the diamond wire with a high linear speed. The dynamics of block cutting by diamond wire saw can be well-explained by the simplistic model shown in Fig. 2.

As the wire exit angle  $\beta$  can be directly measured on the sawing machine, it becomes possible to estimate the radius of curvature  $R$  and  $\alpha$  from equations

$$\frac{L_{bl}}{2R} = \sin \beta \quad \text{and} \quad \frac{L_k}{2R} = \frac{1}{2Rn_L} = \sin \alpha$$

where  $L_{bl}$  is the length of block and  $n_L$  is the number of beads per unit length of diamond wire saw. For small angles

$$\sin \alpha \cong \alpha \quad \text{and} \quad \sin \beta \cong \beta$$

Hence, the above equations can be written as

$$\frac{L_{bl}}{2R} \cong \beta \quad (1)$$

$$\frac{1}{2Rn_L} \cong \alpha \quad (2)$$

As the linear speed of beads ( $v_s$ ) remains constant, the vector sum of all forces acting on a bead is zero as shown in Fig. 2b. Therefore, the normal force  $F_N$  can be calculated as follows:

$$F_N = (2F_T + \Delta F_T) \sin \alpha + F_G - F_C \cong (2F_T + \Delta F_T) \frac{\beta}{L_{bl}n_L} + F_G - F_C \quad (3)$$

where  $F_T$ ,  $F_G$  and  $F_C$  are wire tension, weight of wire per bead and centrifugal force per bead, respectively.

As the wire tension force  $F_T$  and wire linear speed  $v_s$  are directly set on the sawing machine, the other two forces can be calculated from the following equations:

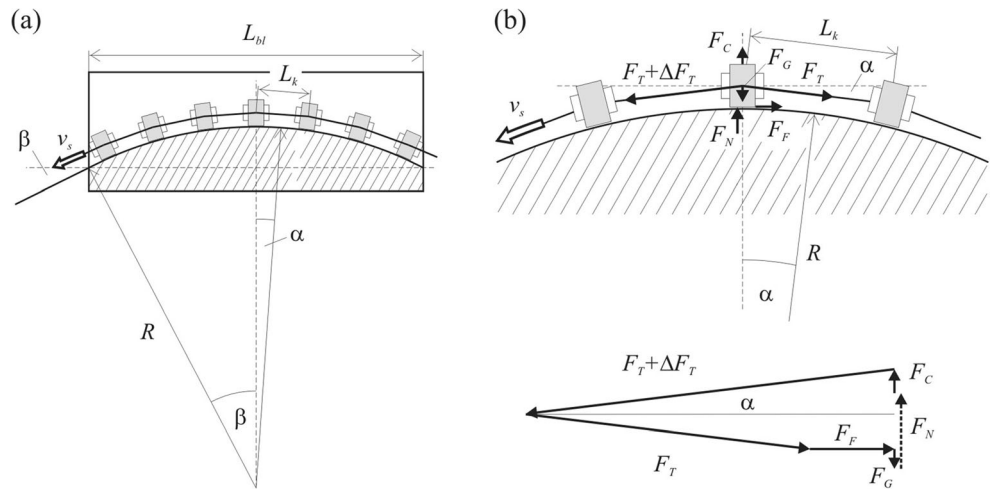
$$F_G = \frac{m_L g}{n_L} \quad (4)$$

and

$$F_C = \frac{m_L v_s^2}{n_L R} \cong \frac{2m_L v_s^2}{n_L L_{bl}} \beta \quad (5)$$

where  $m_L$  is mass per unit length of diamond wire and  $g$  is standard gravity. The wire tension increment  $\Delta F_T$  can be expressed as

**Fig. 2** Bead arrangement in the cut (a) and array of forces acting on an individual bead (b)



$$\Delta F_T = \frac{F_F}{\cos \alpha}$$

where  $F_F$  is friction force per bead.

Putting

$$\cos \alpha = \cos^2 \frac{\alpha}{2} - \sin^2 \frac{\alpha}{2} \cong 1 - \frac{\alpha^2}{4}$$

and using Eqs. (2) and (1) in order to substitute  $\alpha$  and  $R$ , respectively, yields

$$\Delta F_T = F_F / \left( 1 - \frac{\beta^2}{4n_L^2 L_{bl}^2} \right)$$

For  $L_{bl}$ ,  $n_L$  and  $\beta$ , ranging from 2 to 3 m, 36 to 40 beads/m and 2 to 8 deg, as known from the industrial practice, it can be assumed that

$$\Delta F_T \cong F_F \tag{6}$$

As proposed in Ref. [8], the friction force  $F_F$  can be approximated empirically by measuring the power drawn by the motor while cutting

$$P = \sqrt{3}UI \cos \varphi$$

where  $U$  is the electric potential and  $\cos \varphi$  is the power factor.  $I$  is calculated as a difference between current consumption readings recorded during sawing and idle running.

Assuming that

$$P = F_F v_s L_{bl} n_L \text{ and putting } \cos \varphi = 1$$

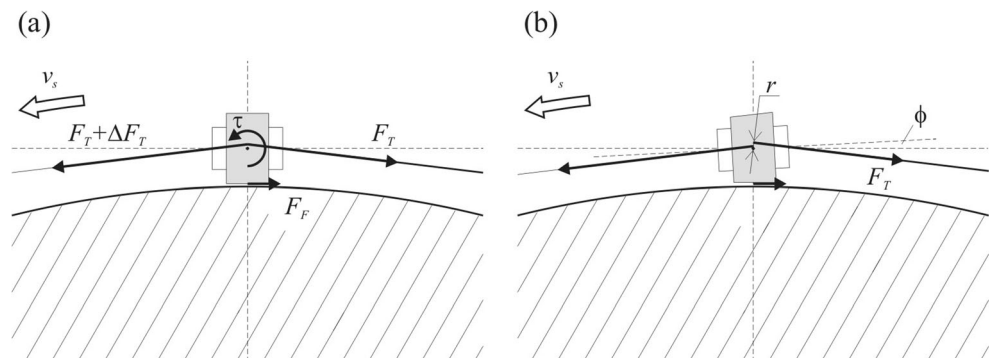
The maximum friction force per bead ( $F_F$ )<sub>max</sub> is then

$$(F_F)_{\max} = \frac{\sqrt{3}UI}{v_s L_{bl} n_L} \tag{7}$$

From Fig. 2a and Eq. (6), it becomes evident that the tension of the steel rope gradually increases over the cutting zone from its set value  $F_T$  on the tension side to  $F_T + F_F \cdot L_{bl} n_L$  on the motor side of the granite block (see Fig. 1). Using the data given in Ref. [8] for sawing class 1 granite at 0.66 m<sup>2</sup>/h with 7.4 mm diameter diamond wire saw, i.e.  $U = 380$  V,  $v_s = 28.8$  m/s,  $L_{bl} n_L = 108$  and  $I = 3.31$  A, the maximum increase in tension is 75.6 N, whereas  $(F_F)_{\max} = 0.7$  N. Since  $F_T$  typically ranges from 2000 to 2400 N, the total increase in tension reaches approximately 3.5% of its pre-set value.

This latter variable can be a major concern with wire sawing of granite. The preceding equations ignore torque ( $\tau$ ) produced by friction at the bead-workpiece interface. As

**Fig. 3** Bead torque produced by friction (a) and torque balance due to bead rotation (b)



**Fig. 4** Excessive friction (torque) leading to conical wear of beads



presented in Fig. 3a, the friction force ( $F_F$ ) is offset relative to bead centre. Therefore, it tends to rotate the bead at an angle ( $\phi$ ), thus increasing the lever arm ( $r$ ), as shown in Fig. 3b.

The torque balance requires

$$F_F \frac{d_b}{2} \cong F_T r \quad (8)$$

where  $d_b$  is the bead diameter and  $r$  is the lever arm directed perpendicularly to the tension force vector.

Precise assessment of  $\phi$  is practically impossible. However, as  $r$  is proportional to  $\phi$ , by decreasing friction forces and bead diameter, it is possible to prevent visible conical bead wear. In practical terms, faster bead wear at its leading edge that is observable by the naked eye, as demonstrated in Fig. 4, is unacceptable and indicates faulty bead formulation or improper sawing conditions or both.

Table 1 provides information on sawing class 1 granite block on MDW machine which enables evaluation of the normal force ( $F_N$ ).

The data included in Table 1 indicates that during sawing class 1 granite at  $0.98 \text{ m}^2/\text{h}$  ( $163 \text{ cm}^2/\text{min}$ ), the normal force ( $F_N$ ) and friction force ( $F_F$ ) per bead are 3.28 and 0.35 N, respectively, which yields a mean bead surface pressure of 58 kPa. Interestingly, the total increase in rope tension is only 1.5% of the pre-set value, which effectively prevents conical wear of beads.

The above data well coincides with both field and laboratory test results recorded on class 1 granite [9]. Interestingly, no meaningful effect of diamond quality on 12-mm diameter

wire/bead performance was found in Ref. [9] for normal loads ranging between 3 and 9 N. At the lowest applied load (3 N), the beads containing higher-grade diamonds showed noticeable reduction in cutting rates. This was associated with progressive wear flattening of diamond crystals on the surfaces of the beads.

## 2.2 Wire vibrations

Contrary to circular and frame diamond saw blades, where the cutting segments are attached to rigid steel holders, the diamond wire has no clearly defined shape and is considered to be completely flexible. Therefore, it is particularly prone to detrimental vibrations resulting from a variety of tool-, workpiece- and machining-related factors. A number of these factors were studied while sawing a medium hard granite on a laboratory test machine and have been reported in Ref. [10]. Although the sawing conditions differ from those commonly used in a production environment, some relationships are evident.

First, the vibration frequency well corresponds to the product of the number of beads per unit length of diamond wire and its linear speed ( $n_L \cdot v_s$ ). This implies that beads are subjected to successive impact loads as they enter the stone block.

Second, the vibration amplitude is higher at the ends of block (0.6–1.6 mm) than at its centre (0.4–0.8 mm). It has also been found that the amplitude markedly decreases with increasing the wire linear speed, down-feed rate, tension and length of block (shorter distance between block and guide wheels).

## 2.3 Wire sawing versus circular sawing

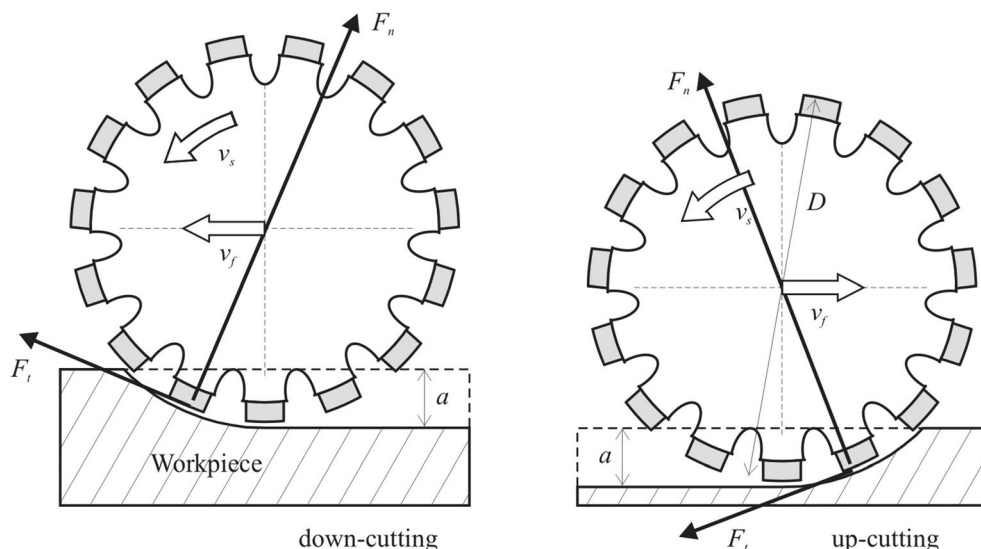
As presented in Fig. 5, a slab of granite is sawn with a circular diamond saw in many passes with a reciprocating movement of the blade, which alternately operates in the up-cutting and down-cutting modes.

The blade rotates in a constant direction at a peripheral (linear) speed ranging from 25–30 to 30–40 m/s for classes 4–5 and classes 1–3 granite, respectively. The depth of cut ranges between 1 and 20 mm, whereas the feed rate is chosen according to the rock sawability class, machine rigidity and power, surface finish, etc. [6]. High feed rates (15 m/min) combined with shallow depths of cut (1 mm) result in a short length of contact between the tool and the workpiece and favour a free-cutting action of the tool, which becomes a priority in sawing granite on multi-blade machines for the production of modular tiles.

**Table 1** Conditions of MDW sawing Blue Night class 1 granite (J. Konstany, unpublished results)

Parameter	Recorded value
Length of block ( $L_b$ )	2.8 m
Wire tension force ( $F_T$ )	2358 N
Linear speed ( $v_s$ )	29 m/s
Down-feed rate ( $v_f$ )	0.35 m/h
Number of beads per unit length ( $n_L$ )	$37 \text{ m}^{-1}$
Mass per unit length ( $m_L$ )	0.15 kg/m
Bead diameter ( $d_b$ )	8.1 mm
Bead length ( $l_b$ )	7 mm
Mean wire exit angle ( $\beta$ )	4.3 deg
Net current consumption for sawing ( $I$ )	11 A
Number of wires	7

**Fig. 5** Schematic representation of slab cutting with a diamond circular saw blade



For shallow cuts, the length of contact can be calculated from the following equation:

$$l_c \cong R_p \sqrt{aD} \tag{9}$$

where  $R_p$  is the rim partition ratio calculated as the total length of diamond segments divided by the blade circumference.

Diamond loading conditions change dramatically when reversing the saw blade rotation as illustrated in Fig. 6.

In down-cutting, diamond crystals penetrate into the workpiece to full depth while coming in contact with it, whereas in the up-cutting mode, diamonds gradually increase the depth of penetration to achieve the maximum values while leaving the kerf. Consequently, the diamond breakdown is facilitated by downward rotation of the blade, and the maximum chip

thickness, quantifying diamond loading conditions, can be calculated as follows [7]:

$$h_{max} \cong \frac{v_f a}{w C_s v_s} \sqrt{\frac{1}{aD} - \frac{1}{D^2}} \tag{10}$$

where  $w$  is width of a diamond crystal and  $C_s$  is surface concentration of diamonds.

In contrast to circular sawing, in wire sawing, the beads rotate around the steel rope at an angular speed  $\omega$ , changing angular position of working diamonds in the cut ( $\gamma$ ) as demonstrated schematically in Fig. 7.

At  $\gamma=0$  deg (see Fig. 7b), a sufficiently protruding diamond engages the workpiece increasing the depth of penetration until  $\gamma=90$  deg, when

$$h_{max} \cong \frac{v_f}{v_s n_L} \tag{11}$$

Equation (11) holds for statistically uniform distribution of crystals over the surface of beads [6].

For  $0 < \gamma < 180$  deg, when the surface diamonds are able to cut, the average chip thickness may be approximated as

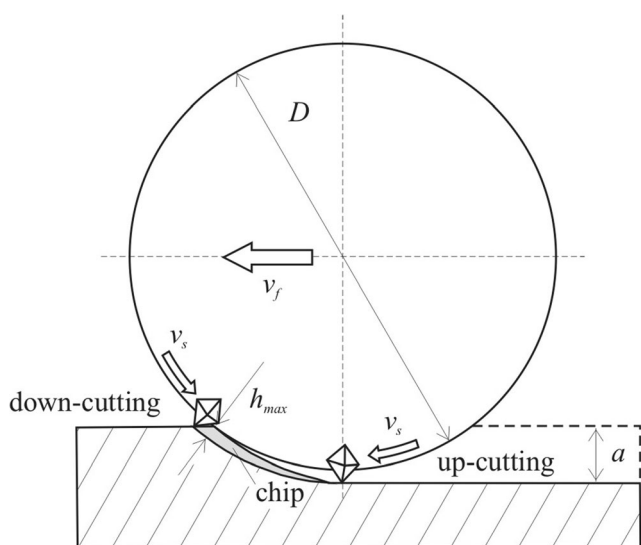
$$h_{avg} \cong h_{max} \frac{\int_0^\pi \sin \gamma d\gamma}{\int_0^\pi d\gamma} = h_{max} \frac{2}{\pi}$$

Hence,

$$\text{and } \begin{cases} h_{avg} \cong 0.64 \frac{v_f}{v_s n_L} & \text{for } 0 < \gamma < 180 \text{ deg} \\ h_{avg} = 0 & \text{for } 180 \leq \gamma \leq 360 \text{ deg} \end{cases} \tag{12}$$

Because the length of contact between the diamond wire and stone is

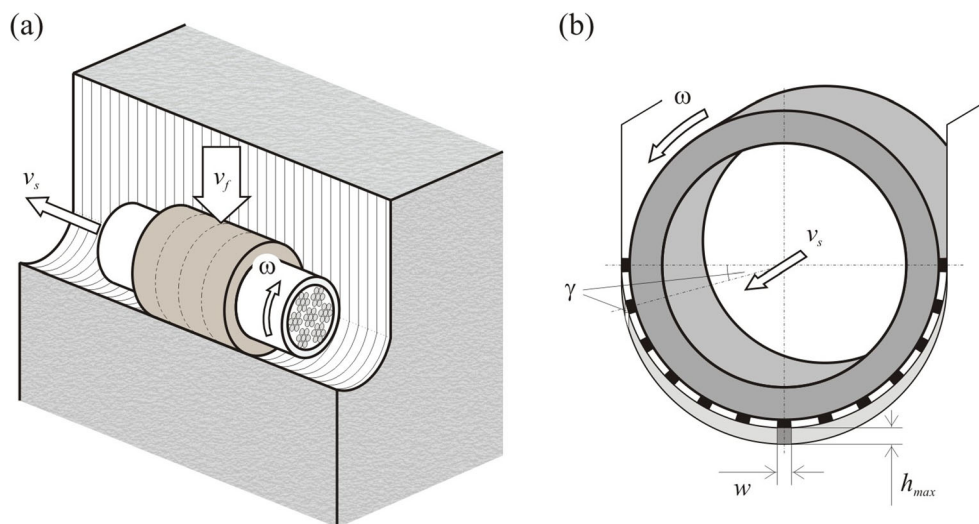
$$l_c = L_b n_L l_b \tag{13}$$



**Fig. 6** Kinematic diagram of diamond crystals that come in contact with a workpiece in down-cutting mode and up-cutting mode



**Fig. 7** Kinematic diagram of a diamond bead cutting the stone block (a) and effect of diamond angular position on its penetration depth (b)



**Table 2** Comparison of typical sawing parameters for diamond wire and circular saw

Parameter	Wire sawing	Circular sawing
Length of block ( $L_{bl}$ )	2 m	-
Depth of cut ( $a$ )	-	1 cm
Linear speed ( $v_s$ )	30 m/s	30 m/s
Down-feed rate/feed rate ( $v_f$ )	0.5 m/h	166.7 cm/min
Cutting rate	1 m <sup>2</sup> /h	1 m <sup>2</sup> /h
Bead length ( $l_b$ )/segment length ( $l_s$ )	7 mm	24 mm
Number of beads/segments ( $n_L$ )	37 per m	70 per blade
Blade diameter ( $D$ )	-	1 m
Diamond size	40/50 mesh	40/50 mesh
Diamond concentration	25	25
Max chip thickness ( $h_{max}$ )	0.13 $\mu$ m	0.81 $\mu$ m
Average chip thickness ( $h_{avg}$ )	0.08 $\mu$ m	-
Length of contact ( $l_c$ )	518 mm	53.5 mm

it becomes evident that due to a huge difference in the length of contact, for the same cutting rate, tool linear speed and tool specification (diamond size and concentration), diamond crystals involved in circular sawing must deeper penetrate the workpiece in order to remove more material compared to diamonds involved in wire sawing. This has been exemplified in Table 2.

**Table 3** Saw blade forces recorded in a range of saw tests; segment dimensions  $51 \times 6.3 \times 12.7$  mm;  $v_s = 31$  m/s [11]

Cutting rate ( $v_f a$ ) cm <sup>2</sup> /min	Depth of cut ( $a$ ) mm	Cutting force ( $F$ ) N	Normal force ( $F_n$ ) N	Tangential force ( $F_t$ ) N	Surface pressure <sup>#</sup> kPa
150	7.5	468	466	43	1903
300	7.5	222	218	44	904
300	10	330	326	52	1162
450	15	284	276	68	817

<sup>#</sup> Calculated ignoring rim partition ratio

Although it is unfeasible to find exact values of  $w$  and  $C$  in Eq. (10), a rough estimate of  $h_{max}$  for circular sawing can be obtained by taking  $w = 360 \mu\text{m}$  and  $C_s = 63$  [6] for 40/50 mesh (297–420  $\mu\text{m}$ ) diamond at 25 concentration (6.25% by volume). Bearing in mind, however, that the empirical figures provided in Ref. [6] represent the total number of diamond and pullouts per unit area of wear surface

of the tool, the  $h_{max}$  figure given for circular sawing in Table 2 seems underestimated.

By analogy with diamond penetration depths, there is also a marked difference in forces acting on wire beads and blade segments. Forces involved in circular sawing class 4 granite have been reported in great detail in Ref. [11]. The sawing tests were performed using 203-mm blade containing segments impregnated with medium-grade 40/50 mesh diamond at 20 concentration.

The results are presented in Table 3.

### 3 Conclusions

The theoretical analysis of sawing granite supported by quantitative assessments of tool performance in an industrial environment has led to the following conclusions:

1. Forces/pressures acting on diamond beads are by an order of magnitude lower compared to circular sawing.
2. The operating conditions encountered by diamond crystals in wire sawing are mild compared with circular sawing when judged by maximum chip thickness.
3. Under such conditions, more-irregular in shape and more-friable crystals seem to be the preferred form of diamond in wire sawing. Their improved retention in the matrix and free-cutting characteristics should result in better stone surface finish, higher production rates and longer tool life due to less pronounced conical wear of beads.
4. Processing of longer stone blocks is preferred because of two reasons. First, the shorter distance between block and guide wheels reduces wire vibration amplitude. Second, the lower down-feed rate, needed to maintain the required cutting rate, promotes wire rotation.

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**Data availability** The data presented in this study are available on request from the author

### Declarations

**Ethical approval** This research did not involve human participants or animals; thus, an ethics approval is not necessary.

**Consent to participate** Not applicable.

**Consent to publish** Not applicable.

**Competing interests** The author declares no competing interests.

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