The mechanics of sawing granite with diamond wire

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Abstract

A theoretical model of sawing granite by means of a diamond wire saw, composed of a multitude of diamond-impregnated beads mounted onto a steel rope, is presented. The wire sawing process has been contrasted with circular sawing with respect to diamond loading conditions. The analytical treatments have been supported by industrial quantitative assessments and qualitative observations. The evaluation of cutting forces as well as identification of system characteristics affecting wire vibration and wire rotation are instrumental in both machine design and tool formulation. This knowledge is also useful to diagnose and prevent problems inherent in diamond wire sawing of granite, such as the high incidence of wire breakage, unsatisfactory tool life and cutting capability, eccentric bead wear, etc.

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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 MDW machines utilise 6.3–8.3 mm beads although wires 4.5 mm in diameter have recently been targeted to minimise kerf widths and consequently to maximise the yield of slabs per block.

2. Process description

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. Depending on the granite sawability class and number of wires installed on the machine, typical cutting rates range from 0.6 to 1.5 m²/h.

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

Figure 1 Schematic representation of block cutting with a diamond wire saw

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 off-set and angled pulley arrangements in the machine usually yields 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 [1]. It has also been found that too high cutting forces resulting from the increasing downfeed rate may eventually overcome the torsional force induced by the machine pulley off-set leading to eccentric wear (ovalisation) of beads [1].

3. Force analysis

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.

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

As the wire exit angle β can be directly measured on the sawing machine it becomes possible to estimate the radius of curvature R and α from equations

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

where L_{bl} is length of block and n_L is number of beads per unit length of diamond wire saw. For small angles it can be assumed that

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

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 ΔF_T can be expressed as

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

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 equations (2) and (1) in order to substitute α and R , respectively, yields

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

For L_{bl} , n_L and β , 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

$$\Delta F_T \cong F_F \quad (6)$$

The friction force F_F can be approximated empirically by measuring the power drawn by the motor while cutting

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

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

Assuming that

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

The maximum friction force per bead $(F_F)_{max}$ is then

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

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 $F_T + F_F \cdot L_{bl} \cdot n_L$ on the motor side of the granite block (see Fig. 1). Using the data given in Ref [2] for sawing class 1 granite at 0.66 m²/h with 7.4 mm diameter diamond wire saw, i.e. $U=380$ V, $v_s=28.8$ m/s, $L_{bl} \cdot n_L=108$ 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 (τ) produced by friction at the bead-workpiece interface. As 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 (ϕ) thus increasing the lever arm (r), as shown in Fig. 3b.

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

The torque balance requires

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

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

Precise assessment of ϕ is practically impossible. However, as r is proportional to ϕ , 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 improper bead formulation or sawing conditions or both.

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

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

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

The data included in Table 1 indicates that during sawing class 1 granite at 0.98 m²/h (163 cm²/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 [3]. Interestingly, no meaningful effect of diamond quality on 12 mm diameter wire/bead performance was found in Ref [3] 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.

4. 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 [4]. 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 lowered from 1.6-to-0.6 mm at the ends of block to 0.8-to-0.4 mm at its centre. It has also been found that the amplitude markedly decreases with increasing the wire linear speed, downfeed rate, tension and length of block (shorter distance between block and guide wheels).

5. 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.

Figure 5 Schematic representation of slab cutting with a diamond circular saw blade

The blade rotates in a constant direction at a peripheral (linear) speed ranging from 25-30 to 30-40 m/s for class 4-5 and class 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. [5]. 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.

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

$$l_c \cong R_p \sqrt{aD} \quad (9)$$

where R_p is 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.

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

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 [6]

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

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 ω , changing angular position of working diamonds in the cut (γ) as demonstrated schematically in Fig. 7.

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

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

$$h_{\max} \cong \frac{v_f}{v_s n_L} \quad (11)$$

Eq. (11) holds for statistically uniform distribution of crystals over the surface of beads [5].

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

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

Hence

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

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

$$l_c = L_{bl} n_L l_b \quad (13)$$

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

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

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 $C_s=63$ [7] for 40/50 mesh (297-420 μm) diamond at 25 concentration (6.25% by volume). Bearing in mind, however, that the empirical figures provided in Ref [7] represent the total number of diamond and pullouts per unit area of wear surface of the tool, the h_{max} figure 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 [8]. 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.

Table 3. Saw blade forces recorded in a range of saw tests;
segment dimensions 51×6.3×12.7 mm; $v_s=31 \text{ m/s}$

6. Conclusion

A good synergy between the diamond wire, machine design and cutting parameters guarantees an efficient and cost-effective production of defect-free granite slabs. The growing prices of granite exerted pressure on the diamond wire manufacturers to decrease the wire saw diameter from typically 7.3 to below 6.3 mm, in order to minimise kerf widths and maximise the number of slabs per block. Such a small bead diameter poses a great risk of wire breakage due to high forces acting on the 3.2 mm diameter steel rope.

Cutting rates varying from 1 m^2/h for class 5 granite to around 3 m^2/h for class 1 granite were earlier recommended for both single and multi-wire stationary machines [9]. The recent trend has been, however, toward lower cutting rates of between 1.5 to 0.9 m^2/h on single-wire machines [10] and 1 to 0.6 m^2/h on multi-wire machines [11]. The obvious advantage of slower downfeed rates is enhanced wire rotation, 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, which adversely affects the wire life. This trend is more pronounced as rock becomes more difficult to cut [9].

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, although the effects of wire vibration and impact loading of beads still need to be quantified. Under such conditions, more-irregular in shape and more-friable crystals seem the preferred form of diamond due to their improved retention in the matrix and free-cutting characteristics, not to mention cost competitiveness. Other advantages of free-cutting behaviour of diamond beads include improved dimensional accuracy, good surface quality and higher production rates that markedly reduce the tool-independent costs [12].

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.

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Competing Interests: The author reported no potential conflict of interest.

Availability of data and materials: The data presented in this study are available on request from the author

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Figures

Figure 1

Schematic representation of block cutting with a diamond wire saw

Figure 2

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

Figure 3

Bead torque produced by friction (a) and torque balance due to bead rotation (b)

Figure 4

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

Figure 5

Schematic representation of slab cutting with a diamond circular saw blade

Figure 6

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

Figure 7

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