Diamond wire cutting: failure modes, risks for safety and workers' protection

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ABSTRACT: Despite the fast development and diffusion of diamond wire cutting, the intrinsic risk of death caused by the ejection of diamond beads in case of wire breakage is still an open problem.
This project, sponsored by Italian Carrara manufacturers, aims to evaluate and improve the safety of diamond wire saw machines. This paper describes the phenomena occurring immediately after wire breakage during squaring operations of marble blocks. The results of a systematic series of full-scale experiments with provoked breakage and of laboratory wire testing are provided.
Over 30 experiments have been documented by high-speed imaging and analyzed in two conditions: without protections, to examine the behaviour of a free diamond wire (which has been also simulated by a numerical model) and with various protection equipments, to assess their effectiveness in eliminating all or at least drastically reducing risks for workers.

1 INTRODUCTION

The introduction of diamond wire cutting in the early eighties has produced a tremendous increase of productivity in quarrying (Tantussi, Lanzetta & Romoli 2003). Unfortunately, this new extraction method has also caused a crucial increase of risks for workers. Risks are due to the presence of a diamond wire looped partly around the drive pulley of the wire saw machine and in a kerf in the material to be cut. The wire loop itself, up to tens of meters long, runs at high speed, up to 40 m/s, and presents a risk of contact for workers. A much higher threat is represented by the wire breakage (Chaplin 1995, Huang & Xu 2006), for the projection of its active elements (diamond beads) and parts (springs and/or spacers) that are closer to the broken ends. In some conditions, they can reach very high speeds, higher than the speed of sound, causing even risk of death, also for workers at tens of meters of distance from the cutting machine.

To reduce risk factors, machine and diamond wire manufacturers from the Italian leading Massa-Carrara stone district have pointed out restricted

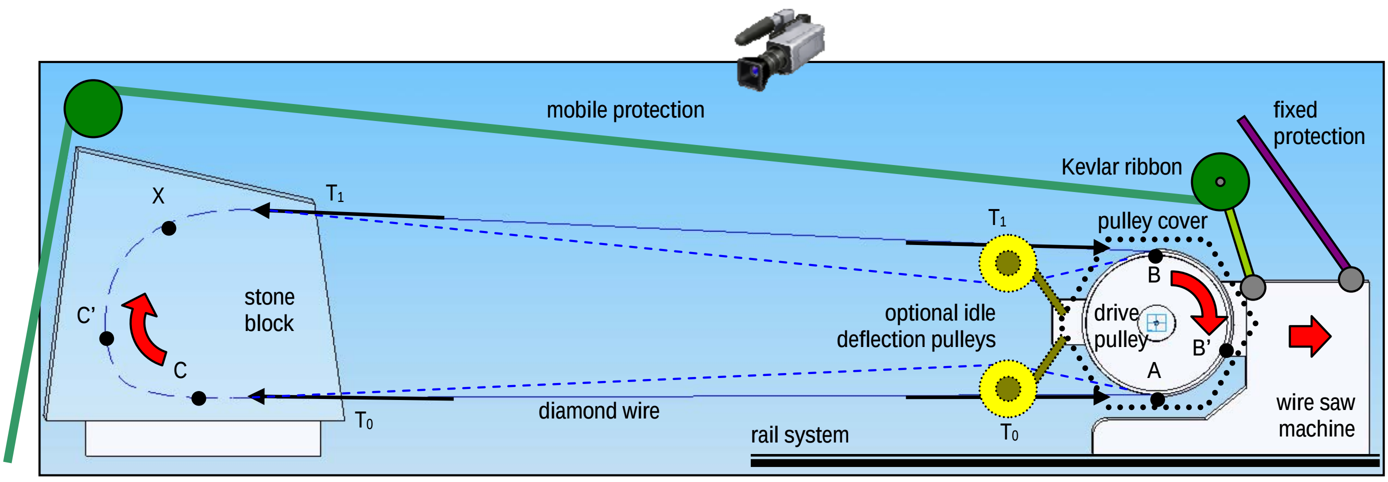

Figure 1 Configuration of the wire saw machine, forces in diamond wire cutting and protection equipment: drive pulley cover, fixed and mobile protections.

areas around the machine, and propose the adoption of fixed and mobile protections on the machine and over the wire loop (Figure 1).

This work has been sponsored by a Consortium of manufacturers from the same district in order to understand the phenomena occurring immediately after the wire breakage and to assess the effectiveness of current protection measures.

2 PROBLEM STATEMENT

Modelling the "whip cracking" effect, which occurs after breakage to an elastically tensioned wire free to deform in space, has been approached by various researchers (Goriely & McMillen 2002, Torkar & Arzensek 2002). This work examines with an eminently experimental approach, the specific case of diamond wire breakage in order to consider the element ejection problem too.

In this initial work, the common case of vertical cutting in block squaring is examined. The sense of rotation is the one generally used in quarry, with the machine pulling the top wire segment. Tests have been carried out in a closed environment with screens and protections for the investigators' and equipments safety against the projected elements.

Two series of tests have been carried out respectively with and without various protection equipments, to assess their performance and to measure the wire path (due to the whip cracking effect).

Both traditional and gummed wire have been used. With the former, beads and spacers are free to rotate about the steel rope, while pressers generally positioned at intervals of five diamond beads, limit the number of projected elements in case of breakage. With the latter, beads are locked and spaced by high-pressure injected resin.

3 MODELLING OF DIAMOND WIRE CUTTING

Based on the analysis of the forces involved, according to the belt transmission theory, breakage may occur mainly in three segments (Tantussi 2008) shown in Figure 1:

1. inside the block (segment C'-X);
2. in the upper tighter segment between block and pulley (X-B);
3. over the pulley (B- B').

4 EXPERIMENTAL CONDITIONS

The acquisition system used to monitor breakage tests is based on three cameras positioned in order to allow a complete view of the wire. High-speed imaging is required because phenomena occur in a fraction of a second. A high-speed camera (1280x1024@240 Hz) is positioned perpendicularly to the cutting plane, viewing the area in the back of the machine as in Figure 2. Two high-resolution (1024x768@60 Hz) digital matrix monochrome cameras have also been used. One of them is positioned with a view from the top to detect the wire motion out of the cutting plane, if any.

Two 55 kW commercial cutting machines from different manufacturers have been used. Both are driven with inverter to adjust the cutting speed and the moving back speed (to keep the wire tension constant). A current limiter set at 120 A stops the machine to limit the wire tension.

At machine setup, the diamond wire is looped over the drive pulley and the block, and the two wire ends are clamped.

The mechanical properties of both the steel rope and of the (cupper or steel) end clamps have been measured by laboratory tensile tests and are reported in Table 1.

The rope and clamp resistance is two to eight times higher than that, which can be exerted by the machine before the intervention of the current limiter.

To provoke the loop opening during cutting, two methods have been experimented:

1. weakening the wire rope by cutting some of the strands;
2. clamping the loop ends with a lower load than the nominal one.

The first method has been quickly abandoned because it required cutting almost all the external strands and successive breakage did not occur as a clean cut but as unthreading of the central strands from the clamp. The second method has produced some dispersion of the breakage tension values caused by the dispersion in the weakened (manual) clamping load, as shown in Table 1.

5 RESULTS

Over 30 full-scale experiments are documented in detail in (Tantussi 2008).

Breakage occurred in all cases in the segments with the highest tension, as predicted in § 3. The most significant cases are discussed here. In figures, the wire is enhanced in red.

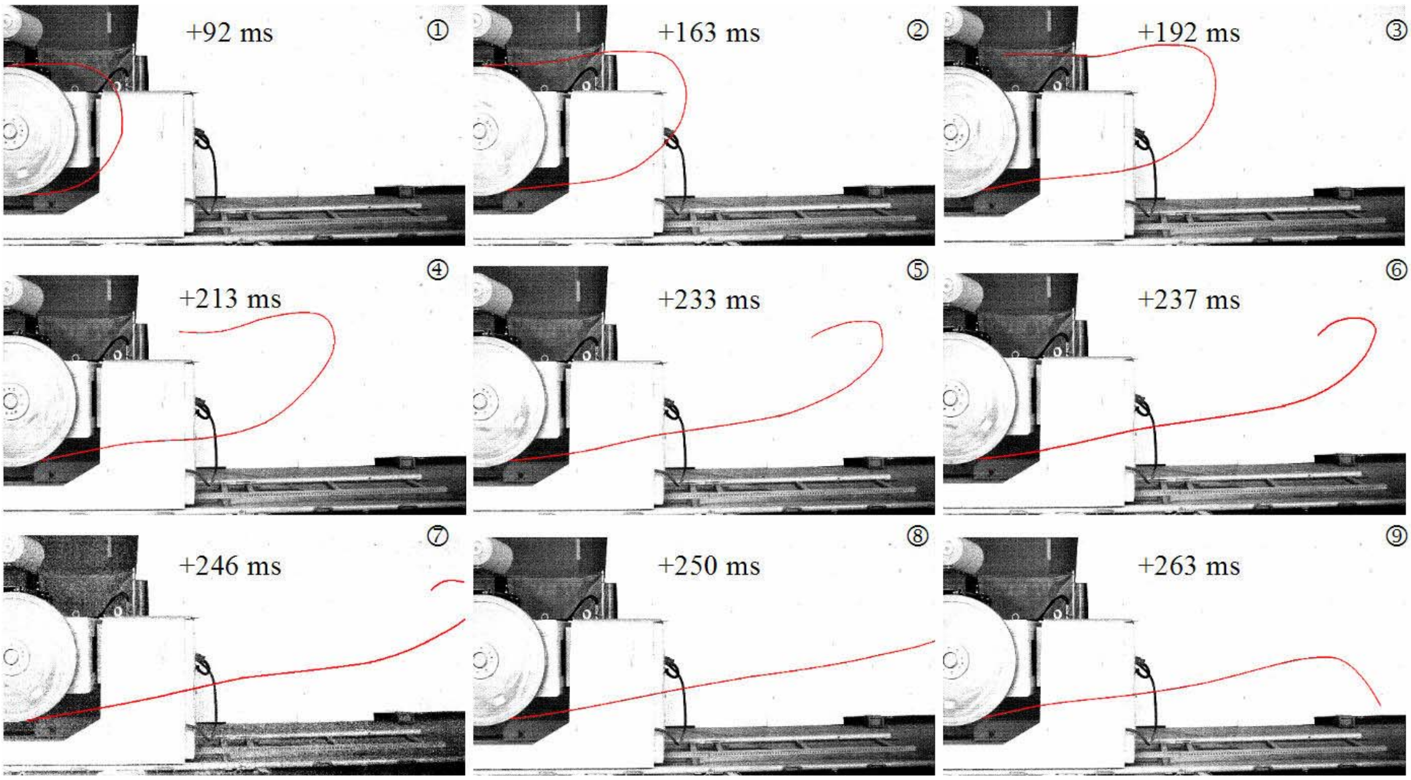

Figure 2 High-speed images. A typical example of free (without protections) diamond wire path after (provoked) breakage between block and drive pulley.

5.1 *Path of a free diamond wire*

The example shown in Figure 2 represents a significant phenomenon occurred in the same way during 11 breakage tests under the same conditions.

With reference to Figure 2, immediately after the breakage, the tension T_1 in the upper segment drops to zero, while the potential elastic energy released accelerates that wire segment in the right direction.

An energy balance has been estimated using experimental parameters (tensile tests reported in Table 1 for T_1), the traction of the machine calculated from the absorbed current, and the belt transmission theory for the trend of T_1 on the segments C-X and B-A. This analysis has shown that the kinetic energy is about twenty times higher than the potential elastic energy produced by the wire tension. This latter is estimated as about 2800 N from Table 1.

The wire detaching from the pulley cancels the friction that produces the wire traction. The lower wire segment stays in touch with the pulley in the tangency point A of Figure 1. It remains under strain because of the unthreading resistance exerted by the part of wire trapped within the block on one side, and by the traction exerted by the upper wire segment continuing to move towards the right, along the original trajectory.

The limited wire flexibility and its displacement towards the right (③ and subsequent of Figure 2) determines the formation of a U-shaped curve starting from ①.

From the observation of the top camera and for the absence of forces in the transverse direction, motion takes place mostly in the cutting plane.

The wire segment between the breakage point and the U-shaped curve gets progressively shorter (② to ⑤) and the free end increases its speed. When the length of this wire segment becomes zero, the whip cracking effect takes place: the curved segment pivots extremely fast about the lowest point of the U-shaped curve, the wire stretches completely and the curved segment finally completes its pivoting toward the bottom, hitting the floor (⑦ to ⑨). During pivoting, the elements closest to the free end that are not perfectly secured to the wire are projected "fanwise" at high speed.

Table 1. Results of laboratory tensile tests on rope samples of 493 mm.

	Ultimate or unthreading load [N]		Maximum elongation [mm]	
Weakened cupper clamp	3207 3069 2194	2804 4272	6.0 6.5 3.7	5.3 6.3
Normal cupper clamp	4529 4704 4827	4776 4199	6.8 8.7 6.8	8.5 4.9
Normal steel clamp	10192	10246	7.0	6.1
Rope without clamp	19287	19389	17.1	18.4

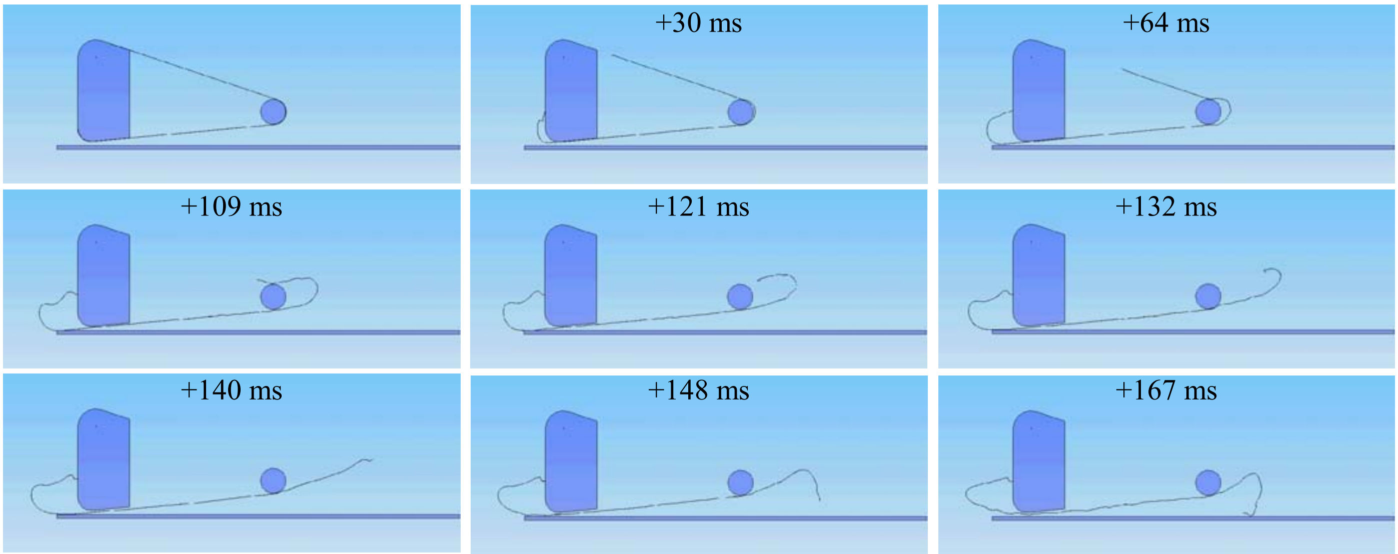

Figure 3 Graphical output of the numerical simulation of the free (without protections) wire breakage between block and pulley (closer to the block) in the case of vertical cut.

The projection speed has been estimated from images over 500 m/s and depends on the instant of release during pivoting, and consequently also on the actual elements position relatively to the wire end. Because of the big threat of the whip cracking effect, it must be prevented by interposing obstacles (like fixed and mobile protections) before it occurs.

In the final phase, the wire end violently hits the floor, with high deformations. The wire spring back recalls the wire toward the machine and the phenomenon is exhausted.

The whip cracking takes place in a few milliseconds, while the whole phenomenon from the breakage instant to the floor hitting can be estimated in about 0.3 s.

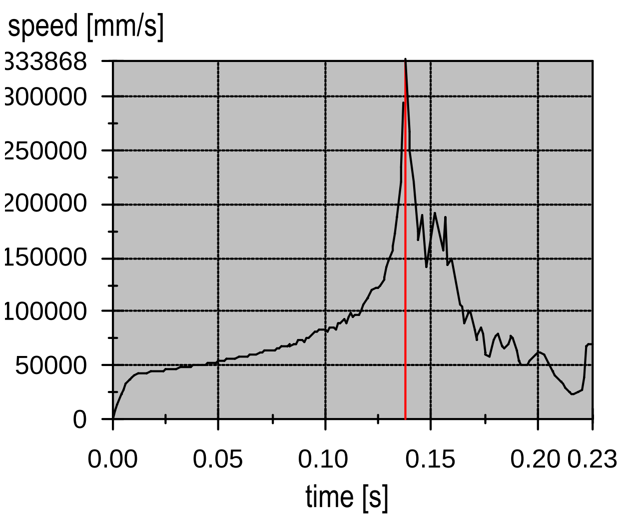

Figure 4 Numerical simulation. Absolute speed of the wire end.

5.2 *Numerical simulation of whip cracking*

The whip cracking phenomenon has also been simulated using a commercial multibody software (Solid Edge – MSC.ADAMS.solver). The diamond wire has been modeled using a concentrated mass system, with beads ∅ 10 mm, 5 mm thick and links 5×5 mm, 150 mm long. Constraints are of type “hinge” without friction both for bead to link and link to link.

A three dimensional contact has been defined with the stone block, the drive pulley and the floor. This has strongly affected the simulation processing time.

No self generated elements or constraints have been used.

The component material has been assigned in order to fulfill the actual 0.3 kg/m wire density. The wire length is 15 m. As required by the software, the wire has been modeled as an open loop with coincident ends.

Other simulation parameters: integrators GSTIFF, time interval 0.0001 s (initial), 1 E-07 s (minimum), 0.01 s (maximum), accuracy 0.01. The number of iterations depends on the breakage type and is in the order of 2 E+05.

Forces and reactions at the wire ends are such to drive all components at 40 m/s speed at the breakage instant, e.g. when the wire ends start separating.

Gravity has been taken into account. The evolution has not been conditioned, the only approximation has been neglecting air drag.

Figure 4 shows the graph of the wire end speed. The maximum simulated speed is of the same order of that experimentally detected.

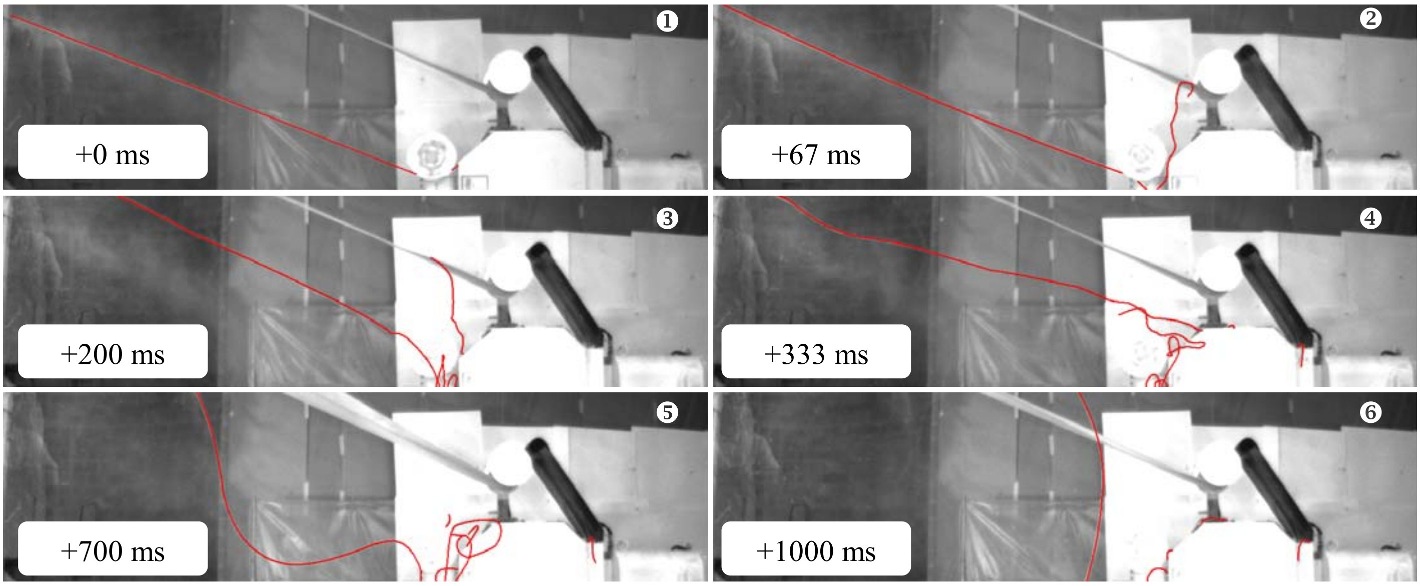

Figure 5. Sequence of images of a typical example of diamond wire path after (provoked) breakage on the drive pulley, with idle deflection pulleys, drive pulley cover and with both fixed and mobile protections.

The simulated speed and the good agreement between the sequence in Figure 3 and experiments (Figure 2) validate the numerical model proposed.

5.3 *Effect of protections*

Among 20 experiments with at least one protection type (drive pulley cover, fixed or mobile protection), the 8 cases, where all protections were present as shown in Figure 5, are discussed here. In the other experiments individual protections have been selectively removed to better understand their effect.

In some tests, two optional idle deflection pulleys have been installed to increase the wire wrap angle over the pulley (Figure 1 and Figure 5).

The following three cases have been observed.

1. Breakage inside the block. In this case the wire end immediately afterwards the breakage point moves up for conservation of linear momentum, dragging up also the rest of the wire. In some cases it hits the Kevlar protection over the block, which dissipates the kinetic energy and prevents any whip cracking risk.

2. Breakage between block and pulley. The wire afterwards the breakage point continues its motion along the same direction it had before breakage and hits the drive pulley cover or other protections nearby, dissipating its energy. As for the path of the wire segment before the breakage point, two sub cases are available: breakage point close to the block or to the pulley. In the first case, the wire fragment remains inside the block and may or may not hit the upper Kevlar protection. In the second case, the energy owned by the wire segment between the block and the breakage point may determine a partial or total unthreading of the wire from the block, colliding the upper protection and even the machine. The friction between wire and block partially dissipates energy so collisions occur at lower speed. With worn out diamond wires, because of the lower friction between diamond beads and block, the wire unthreading is increased.

3. Breakage over the pulley (more probable in the presence of idle deflection pulleys causing rapid path changes, 4 events on 13 experiments). In this case (Figure 5), the lower wire segment continues its motion towards the block and in some cases, it can also rises the block. This motion is supported by the traction of the top segment, which continues to move towards the pulley, dragging also the wire segment still inside the block. With idle pulleys, the wire end between the top idle pulley and the breakage point slides up hitting the fixed protections (❷ and ❸ of Figure 5) and falls in the space between the drive pulley and its cover. The rest of the wire following the breakage point, if able to slide up, continues its motion towards the drive pulley, as shown by the tangles in ❸ and ❹. In ❹ it slips in the gap between drive pulley and its cover. In ❺ the other end 0.7 s after breakage hits with low energy the mobile protection (partially rotated) and overcomes as in ❻. Because of the chaotic wire movement and of rotating pulleys, the wire can get entangled and break further: a short wire segment is visible near the fixed protection in ❹ to ❻.

5.4 *Benefits of protections*

Rigid protections (drive pulley cover and fixed protections) behind the drive pulley are necessary to stop the wire motion towards the back of the machine. The fixed protection must hang upward and merge to the ribbon (mobile protection) not to leave gaps.

The relatively tight gap between the pulley and its cover may provoke wire clamping with machine parts causing further breakage risks and consequent projection of elements in addition to heavily damaging the wire, which cannot be reused as is. Drive pulley covers must be smooth, without overhangs (e.g. sharp edges, brackets, bolts, etc.) that may interfere with the normal wire trajectory inside the pulley cover after breakage. In addition, the pulley cover should be shaped in order to contain the wire and dissipate its energy after breakage.

The top Kevlar protection is necessary to limit the wire motion upward, particularly in the case of breakage close to the block outlet. Such protection should stay as close as possible to the wire and should wrap the block back and be secured to the floor to prevent the motion of the wire passing down the block and proceeding behind it, as occurred during some experiments.

6 CONCLUSIONS

This extensive experimental work represents an initial systematic analysis of risks caused by breakage in diamond wire cutting and the first approach to investigate the effects of diamond wire breakage and the ejection of elements.

The main failure modes have been documented and reviewed in the paper.

The case of block squaring in vertical cutting, both with free wire cutting and with standard protections has been examined.

High-speed imaging has been used to characterize the behavior of a diamond wire during the most critical 0.3 s after breakage occurs.

Experiments have shown that

- without protections, the ejection of elements (diamond beads, springs and/or spacers) at speeds up to 500 ms is caused by the whip cracking effect;
- traveling at 40 m/s, the elastic potential energy of the wire is negligible with respect to its kinetic energy;
- after breakage, the wire remains in the same plane.

The beneficial effect of protections in preventing the whip cracking effect has been demonstrated. Consequently, the projection of elements in the case of gummed wire with protections is practically absent because elements are secured. With traditional diamond wire, projection occurs in the space between machine and block or in small neighbour lateral areas; the energy of the projected elements is anyway very low because the phenomenon takes plane mostly in the cutting plane. In the presence of detrital rocks on the floor, bounces in unpredictable directions are possible, so some lateral safety limits should be defined. Larger mobile and fixed protection would provide increased safety.

A numerical model to simulate failures has been described. An analytical model of the wire path and of diamond bead bounce is under study.

The mechanical properties of the steel rope and end clamps have been tested to be included in the model and to design the experimental conditions. Based on that and considering the risk of fatigue cracking, minimizing the number of clamps on a wire and wire assembly in controlled conditions is strongly recommended.

Current experiments include: cutting in different configurations, e.g. investigating the reverse rotation (pulling the lower wire segment) and the case of horizontal cut.

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