23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

DEVELOPMENT OF A LABORATORIAL DIAMOND WIRE STONE CUTTING MACHINE PROTOTYPE

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Portugal is, after Italy, the largest stone exporter per capita in the world. In the first quarter of 2012 increased 28%, the largest increase considering the previous 5 years. In spite of European market contraction, this industry exported in 2012 more than 86.8 million that compare to 68 million in the same of 2011. In 2013 and 2014 exports of Portuguese natural stone continued to grow at a remarkable pace.
When analyzing the main Portuguese natural stone importing countries, it should be noticed that among the top 30 there was no growth in only 4 destinations, and the other markets showed significant growth. Quality, beauty and reputation are the key attributes of Portuguese stones. They are products with high interest worldwide because of its natural properties, aesthetic and structural behavior. Recent technological developments in stone treatment from the quarry to final finish, demand high investments in new equipment and require more research in the domain. It seems clear however there is a need to better characterize the new cutting processes, in particular diamond wire cutting technique. This technique allows a wide variety of cutting operations, gives versatility, higher cutting speed, and an average reduction of cut thickness, and so with lower raw materials waste, very regular cutting stroke, resulting in a great surface finish. Diamond wire cutting is achieved by abrasion between stone and tool, a steel cable with diamond beads mounted, which is drawn by means of a system of pulleys. The approach has been empirical, justifying a systematic study of key parameters, not only to improve the operating conditions, but also to allow the development of more effective, robust and economical equipment. In this paper a diamond wire stone cutting machine prototype under development at UMinho in Portugal is described. A numerical controlled cutting lab machine is being built, to test the process parameters. The ultimate purpose is to be able to conduct controlled studies for optimization of cutting parameters to reduce raw materials waste, streamlining the process to increase productivity, improve energy efficiency, equipment robustness and development of innovative tools. Since most of the equipment used in Portugal is totally or partially imported, there is a huge potential for national machine development and construction. Also, by Increasing the quality of final equipment and products of the national stone industry this sector will drive up the manufacture and exportation, reducing the national dependence and increasing the skilled labor and its competitiveness. This area is also of particular interest considering the case of Brazil, not only because it presents an extractive expanding industry, being currently one of the majors destinations of Portuguese made machinery, but also because of the appreciation of the finished product reachable by technological development of the equipment associated with the stone cutting.

Keywords: *Stone cutting, Diamond wire, CNC, Testing machines*

1. INTRODUCTION

Quality, beauty and reputation are the key features of Portuguese stone whose exports recorded an increase of 28% in the first semester of 2012, the largest in the 5 previous years, since the European market contraction. During this period, the sector exported over € 86.8 million comparing to the € 68 million from the same period of 2011. However, in 2011, the signs of vitality of this sector were proving positive: the exports recorded an increase of 1.7%, representing a business volume of € 301 million. Portugal is, right after Italy, the leading stone exporter *per capita*. China, France, Spain and Saudi Arabia are the leading importers (Portugal Global, 2012). In 2013, despite losing ground in China but focusing more on the European market, the exports on the sector resulted in nearly € 340 million (Jornal de Negócios, 2014), about 0.2% of the country's GDP that year.

Since 2001, Brazil has risen from 12th to 4th in the stone consuming ranking, with only China, India and USA ahead (XXIV Report Marble and Stones in the World, 2013, cited by Vitória Stone Fair, 2015). Brazilian ornamental stone exports hit 2.55 billion tons in 2014, resulting in US$ 1.22 billion. Regarding stone cutting technology, Brazil is the 3rd top importer of machinery and other equipment hitting US$ 148.1 million in 2013, of which US$ 93.2 million (62.9%) were from Italy, making Brazil the largest importer of Italian stone cutting technology, especially regarding diamond wire machinery (Vitória Stone Fair, 2015).

Diamond wire stone cutting stands out in comparison with other technologies due to its versatility, costs, low cutting thickness, lower waste rate (also resulting in a lower environmental impact), and an excellent surface finishing, an important feature for the stone ornament sector (Founti, *et al*. 2010; JDK Diamond Tools CO., Ltd, 2011; and Regadas, 2006). It also requires lower manpower and provides higher work safety conditions due to the lower vibrations, noise and dusting (Ayim, 2011 and Vuoritekniko ry, 2013).

Considering the present favorable conditions for the Portuguese and Brazilian stone sector, research and development on advanced ornamental stone cutting equipment that may provide accuracy, quality and execution speed is an opportune requirement to reinforce leadership, both internally and externally in this sector.

This paper resumes the study under development in the University of Minho, intending to revise the knowledge regarding diamond wire stone cutting, to devise specifications for the development of a laboratorial diamond wire stone cutting machine prototype. With the machine, tests can be conducted in order to verify the knowledge available, possibly obtain new data, and optimizing the cutting process.

2. DIAMOND WIRE

Technological development, particularly with the diamond wire technology, has increased the efficiency of stone extraction and shaping. Each type of rock used its own technique but the diamond wire's versatility made some of those techniques obsolete. The clearest examples are the marble and granite extraction that were accomplished by steel cable and jet-flame respectively (Vidal, 1999 cited by Regadas, 2006). A study conducted in the Cagliari University (Tab. 1) presents a list of results obtained from different techniques used in stone quarrying.

Table 1. Stone cutting techniques technical and economical comparison (for marble quarrying) (Regadas, 2006).

Operational and performance feature	Technical parameters					
	EXPL	SC	FD	CS	CD	MHW
Cutting speed (m^2/h)	-	2-3	10-12	5-7	-	-
Cut width (mm)	-	9-10	11-12	40-50	-	-
Roughness (cm)	5-8	1-2	2-4	0-1	2-3	4-8
Waste zone thickness (cm)	10-15	-	-	-	-	-
Commercial deduction (cm)	15-23	1-2	2-4	0-1	2-3	4-8
Cost per unit (US$/$m^2$)	20-25	30-40	18-24	23-32	28-38	19-24
Lost value (*)(US$/$m^2$) according to stone quality:						
200 US$/$m^3$	30-46	2-4	4-8	0-2	4-6	8-16
400 US$/$m^3$	60-92	4-8	8-16	0-4	8-12	16-32
800 US$/$m^3$	120-184	8-16	16-32	0-8	16-24	32-64

Legend:
EXPL – Explosive quarrying; DW – Diamond wire; CD – Continuous drilling
SC – Steel cable; CS – Chainsaw; MHW – Mechanical or hydraulic wedge
(*) Usage coefficient for 50% cutting area.

Diamond wire is composed of a galvanized steel cable which acts as a supporting structure for diamond beads. These beads are separated along the cable by metal springs, for marble block extraction, or by plastic or rubber, for silica stone (fig. 1).

Figure 1. Diamond wire types from KEEN TOOL. From left to right: coated with rubber, spring and plastic (Lululoso.com, 2012).

The assembly of the beads on the steel cable varies in accordance with the diamond wire's purpose. The spring cable assembly is accomplished by introducing alternately the beads and the springs and it is often performed at the quarry. The wire's ends are connected by steel brushings pressed into place by hydraulic clamps, which must be replaced after 8 to 12 hours of use or when the wire ruptures. Plastic and rubber cable spacers are assembled by injecting the polymeric material into the spaces between beads (Regadas, 2006; Diamant Boart, 2008 and Vuoritekniko ry, 2013).

Although diamond wire saw is mostly used in stone mining and shaping, it is also used in other endeavors: it is used in urban environments in the building of subway tunnels, cutting of pipelines or underwater structures, in delicate and dangerous demolitions (namely decommissioned nuclear power plants), in dismantling large steel structures (such as decommissioned ships) and it is the most suitable solution when vibration or noise are completely prohibited (Engineers Edge, 2010 and Vuoritekniko ry, 2013).

2.1 Diamond beads

Diamond beads are ring segments of 6.3 to 12 mm diameter and 6 mm length. The amount of beads in a diamond wire may range from 32 to 40 per meter and that are kept apart from each other by different coatings or casings around the steel cable, depending on the application (Regadas, 2006; de Oliveira and Figueira, 2008, Ayim, 2011; Diabü Diamantwerkzeuge, 2013 and Vuoriteknikot ry, 2013). These beads are composites made by diamond particles embedded in a binding matrix (usually tungsten, cobalt, cobalt-bronze, iron-cobalt) forming a composite with diamonds. These materials are usually produced at large scale by powder metallurgy, covering a wide variety of applications, such as stone shaping, civil engineering, etc. Currently, the majority of diamond tools (diamond slitting wheels, blades, grindstones, etc.) is produced by hot press molding which can be finalized, in some cases, by metallic infiltration but some of these tools can be manufactured by cold press molding, conventional sintering or electrolysis and these last two are the most used in diamond wires (Regadas, 2006 and de Oliveira and Figueira 2008). During the process, the diamond particles are bounded to the metallic matrix by a combination of chemical and physical reactions and a strict control is necessary in order to avoid attack, dissolution and/or graphitization of the diamond, which can compromise the cutting's final performance (de Oliveira and Figueira 2008).

Electroplated beads (fig. 2) diamond wire was the first type introduced in the market. The beads are made by a metallic ring support upon which are plated, through galvanic dipping, the diamond grit with roughly 0.30 to 0.40 carats of synthetic diamond with 40 to 60 mesh of particle size distribution. These tools are known by their sturdiness, penetration, cutting capacity at startup and high speed cutting. This diamond wire type is the most suited for low hardness stone (preferably marble), for small cutting and block cutting (small radius of curvature), due to the diamond protuberance, and therefore cutting more effectively, even with greater wear (roughly twice more wear) than sintered beads. These beads are the most recommended when greater cutting speeds are desired however, it decreases regularly with time, but on the other hand, depending on the application, they allow the usage of low powered machines (~18,4 kW) and low cooling (between 10 a 20 l/min) (Regadas, 2006 and Diamant Boart, 2008).

Sintered beads (fig. 2) were designed to cut every type of stone (including the hardest and the most abrasive) and to improve the wire's durability. This process consists in the mixture of diamond powder with metallic powder, shaped into a cylindrical body and submitted to high temperature and high pressure in a sintering machine. This method is the most appropriate for cutting hard and abrasive stone, due to the homogeneous distribution of diamonds throughout the bead's paste, which, by the wearing process, new diamonds are revealed until the bead is worn out. . The use of this type of beads demands a minimum power of approximately 30 kW and normal cooling, that is, from 20 to 50 l/min according to the cut's dimensions (Regadas, 2006 and Diamant Boart, 2008).

Figure 2. Electroplated bead (left) and sintered bead (right) (Diamant Boart, 2008).

3. DIAMOND WIRE STONE CUTTING MACHINES

Diamond wire stone cutting machines for quarrying are mobile (moved on rails) and their movement follow the cut's progression in order to keep the wires stress optimal (fig. 3). In comparison to conventional tools these devices require less manpower, have increased cutting speeds, are easily installed (Founti, *et al*. 2010) and are a good example of the diamond wire's versatility as a cutting tool, for it is possible to mine stone both vertically and horizontally as well as difficult access zones (Marcon, *et al*., 2012).

Figure 3. Mobile diamond wire stone cutting machine (Weiku.com, 2011).

Diamond wire machines for stone shaping are also known as "stationary" for, unlike the ones used in quarrying, they remain in the same place while operating. The diamond wire is held by a cantilever or an arch that may be fixed or mobile, and the target stone may also be fixed or mobile, whereas at least one of these elements must move in order to perform the cut. There are two types of machine in this category: multi-wire (plate cutting) and mono-wire (squaring and shaping) (Regadas, 2006 and Monteiro, 2014). This kind of equipment allows a broader range of shapes (fig. 4) by harnessing the tool's flexibility and numerical control, which is expected to prove as an useful concept in investigation of the cutting parameters, conditions and tools to tackle some of the loopholes on the diamond wire stone cutting process

Figure 4. Stationary diamond mono-wire stone cutting 4 axes machine *Poker 4 axes* by *Breton* (left) and a helix shaped stone staircase built by it (right) (Breton UK, 2012).

4. DIAMOND WIRE STONE CUTTING STUDY

4.1 Cutting parameters, efficiency and diamond bead wearing

According to studies by Ozcelik and Yilmazkaya, 2010, Marcon, *et al.*, 2012, and Monteiro, 2014, diamond wire stone cutting is affected by controlled and non-controlled parameters. Controlled parameters regard cutting tool and equipment properties and also working conditions. Non-controlled parameters are related to stone properties.

Table 2. Efficiency affecting parameters on diamond wire stone cutting (from Ozcelik and Yilmazkaya, 2010; Marcon, *et al.*, 2012 and Monteiro, 2014).

Non-controlled parameters (related to stone properties)	Controlled and partially controlled parameters	
	Cutting tool and equipment properties	Operability
• Hardness	• Machine power	• Technical personnel
• Abrasiveness	• Peripheral speed	• Machine vibration
• Stress	• Pulley size	• Cutting direction
• Degree of alteration	• Number of beads per meter	• Wire's cutting angle on the stone
• Discontinuities	• Number of beads in contact with the stone	
• Mineralogical properties	• Wire's radius of curvature on contact with the stone	
• Textural characteristics	• Amount of water used	
	• Cut's dimensions	

A study by Marcon, *et al.*, 2012 indicated that the wire's efficiency increases with cutting area, which is believed to be explained by the lower efficiency at the beginning and at the ending of the cutting operation. It was also observed that the efficiency increases with the wire's dragging dimension (length of wire in contact with the stone). Huang and

Xipeng, 2013, studied the performances of sintered and electroplated beads and concluded that the latter are sharper, which is explained by their lower cutting force and by their ability to cut into the work piece more easily, thus consuming less power (up to 5 times less than sintered beads). The general performance of electroplated beads may have proven superior, but according to work from Caranassios and Pinheiro, 2004 (cited by Regadas, 2006), that performance decays progressively. The authors concluded that this is due to the fact that there's a single layer of diamonds on the surface in electroplated beads, whereas in sintered beads the performance is roughly constant and their life span is largely superior, though slightly more expensive (Diamant Boart, 2008).

On a study conducted by Jain, *et al.*, 2013, bead wearing and cutting rates were analyzed according to certain values of wire stressing and peripheral cutting speed in marble stones. The study concluded that the optimal wire peripheral speed varies little relatively to the hardness of the marble type used (varying from 27 to 29 m/s) and the bead wearing does not only increase with the wire's linear speed (which matches the drive wheel's peripheral speed) but also with the marble's hardness. However this study does not address important cutting parameters, as well as textural characteristics, such as particle size distribution, hardness or texture. These have been established qualitatively without the indication of quantitative reference values that can be used as a basis for comparison studies. The controlled parameters, such as cutting tool configuration, machine power, wire's cutting angle on the stone and also water pressure and flow rate are also not referred (Monteiro, 2014).

Studies by Turchetta, *et al.*, 2014 and Monteiro, 2014 address the forces and tensions at work on the diamond wire and diamond beads during the cutting operation. Mathematical analysis shows that for a maximum value of tension on the wire, the pressure of the beads on the cutting surface increases along with increasing wire's curvature (fig. 5).

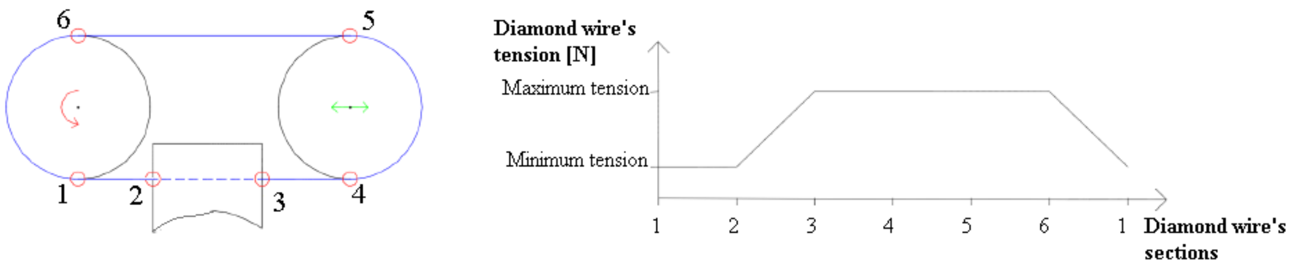

Figure 5. Diamond wire stone cutting schematic representation divided into specific zones (left) and graphical representation of tension variation in those zones (right) (Monteiro, 2014).

Residual strain and hysteresis loop are largely connected to temperature fluctuation; also friction between the wire and the stone and between the wire and the pulleys produce heat. So it is necessary a proper flow of coolant, namely water, to bathe the wire in order to keep the machine at optimal performance (Masood, *et al.*, 2012 and Marcon, *et al.*, 2012). If the flow of water is too low, there may still occur wire overheat, higher bead wear and possible rupture, bead stacking due to the melting of the polymeric coating or even complete wire stripping and higher dusting. On the other hand, if the water flow is too high, there may be less cutting efficiency due to aquaplaning of the wire, water over spilling, warbling, and ovalization (localized bead wear) (Ayim, 2011 and Diamantcer, 2014).

In a study by Ozcelik and Yilmazkaya, 2011, the effects of the cutting angle between the wire and the horizontal direction were tested. The tests revealed that on the horizontal, the wire vibrates in such a way that the stone's surface finish was compromised, which is an important requirement in the ornamental stone industry. They also revealed higher bead wear and cutting rate in that cutting position.

Another method used to increase the wire's lifespan is by twisting it (Diaquip Sales & Service, 2004; Regadas, 2006 and Ayim, 2011). By twisting the wire, the wearing progresses evenly through the whole surface of the diamond beads and overheating is prevented. The twisting operation must be performed before uniting the wire's ends and it depends on the wire's length and on its amount of connections. The twists must be made in the same direction as the steel cable's filaments are twisted in order to prevent the tool's malfunction. For each meter of wire it must be twisted one turn and for each connection along the wire, additional twists must be added. However these additional twists vary according to the number connections (Diaquip Sales & Service, 2004).

The wire driving on diamond wire stone cutting machines is carried out by a drive pulley and it is necessary to have enough friction between the pulley and the wire to avoid slipping. A study conducted by .Dunda, 1998, concluded that the friction coefficient for optimal performance is μ=0.32.

4.2 Other studies and concepts

Although diamond wire technology offers many advantages in comparison with other methods, it has its limitations. The major drawbacks are the complex architecture of the machine with a system of pulleys and wire tension-control system (tensioner) to avoid wire failure. Wire tension is the functional parameter determining the correct progression of the cut. If the wire fails before the cutting operation ends it is a serious issue: recovery of the machine is necessary, the diamond beads are projected at high speed in the surroundings and repositioning the cable in the cutting path to complete the cut is generally difficult. Passive tensioners (such as springs on axles of pulleys) are at times used; however they are not reactive to the wire slack when the beads jam suddenly in the material. The best approach is an active (actuated) tensioner, which is the most used solution. These active tensioners are complex to design and control, requiring electronics and actuation, increasing the machine's complexity. Part of these issues may be solved by the so called "softwire technology" in which the core steel cable is replaced by a single or few wires made of a superelastic alloy (usually a Ni-Ti alloy due to market availability and cost). The major advantage of a softwire, besides simplifying the machine's architecture with a single or a few strands, is its adaptability to the cutting conditions, keeping its tension constant without a tensioner (Masood, *et al.*, 2012).

All these studies allowed some insights about stone cutting by diamond wire, but they don't show the possible influence of other variable characteristics of the diamond wires. There are many types of diamond wires (bead length and diameter, bead spacing, wire coating, etc.). Manufacturers often recommend a specific type of diamond wire in accordance with applications, which means that each wire will have a certain performance (Diaquip Sales & Service, 2004). Some manufactures even go further, altering the shape of the beads (conical, for instance), of the coating (bullet shaped) or even combining types of coating (polymer and springs) (Diamantcer, 2014; Tyrolit, 2012 and Winterstone, 2012). Therefore, an extensive study is necessary in order to evaluate the performances of those types of wires.

Process Research Products, 2012, has developed a concentrated coolant for diamond wire cutting which is applied in bricking and wafering operations of silicon carbide and sapphire. It improves the wire's performance, precision and surface finishing. In addition, it does not foam, and then can be recirculated after centrifugation of the effluent. This coolant is applied in a different type of diamond wire, which is thinner, not beaded and used in smaller types of machinery and applications (Clark, 2001). Although the applications and the tools are very different, both are referred to as "diamond wire" or "diamond wire saw" and there does not seem to exist a proper disambiguation.

5. PROTOTYPE MODELLING AND CONSTRUCTION´

Considering the importance of the ornamental stone cutting industry (both in Portugal and Brazil) and the apparent lack of knowledge in the field, the development of prototype machine is justified, not only to foster machine making industry but also to enlarge the set of data on cutting characteristics and conditions. Both CNC and manually operated machines should be considered, envisaging the spreading of technology namely towards low skilled operators.

The lack of study in some of the parameters, methods and tools in diamond wire stone cutting reinforces the necessity of the development of the laboratorial prototype in order to fill that gap and optimize the process. However, some basic parameters must be established to conduct tests and the studies by Ozcelik and Yilmazkaya, 2010; Marcon, et al., 2012, and Monteiro, 2014, will be the start point.

It is vital that the pulleys be correctly positioned and aligned in order to prevent oscillations of the wire, variations on the wire's speed, undesired abrasion of the pulleys and uneven wear of the beads. Rubber on the pulleys' outer diameter smooths vibration when the cable reaches and leaves them (Masood, *et al.*, 2012) and gives the wire enough friction so the machine operates properly (Dunda, S. 1998).

From the studies by Ozcelik and Yilmazkaya, 2011, it can be concluded that, in order to improve the wire's lifespan and productivity and also to improve the stone surface finish, the working piece should be placed in such a way that minimizes the number of horizontal cutting operations.

Wire tension was also addressed repeatedly, so the prototype must include a tensioner. This will allow the setting of different values of wire tension which in turn will grant the opportunity to compare the wire's performance with the results obtained by Jain, *et al*., 2013, Turchetta, *et al.*, 2013, and Monteiro, 2014.

Regarding the diamond wire's peripheral cutting speed, some of the tests were undertaken relying solely on one or two values suggested by the manufacturers, like the tests by Turchetta, *et al.*, 2014, or not mentioning values at all, like Ozcelik and Yilmazkaya, 2011, and many cutting conditions were not taken into account. In order to fully ascertain which is the optimal peripheral speed value to use according to the cutting conditions (such as wire's cutting angle, water flow, stone type, bead type, wire type, coating type and so on), the prototype will must include a feature that to allow the variation of the drive wheel's speed.

Several manufacturers have tested their diamond wires and analyzed malfunctions. There are many types of malfunctions that may originate from many causes and each of them seems to have a different solution (Diabü Diamantwerkzeuge, 2013, and Diamantcer, 2014). These procedures are listed and serve as support for trouble shooting during the machine's and wire's test phase.

Wire twisting is another topic that may be explored regarding bead life span. There seems to be consensus between manufacturers and some researchers on the procedure before operation. Having that in mind, tests will take place and their results will be compared with the work of Jain, *et al*., 2013, for bead wearing analysis.

As previously mentioned, there are several types of wire, so in later stages of this research, some of the machine's components will have to be replaced so that many kinds of wires can be tested.

Water will be used as the wire's coolant during the cutting tests and its flow will follow the recommendations of Diamant Boart, 2008 and other manufacturers.

The specifications for the prototype were then established in accordance with the data gathered and are as follows:

- Compact machine for laboratorial testing;
- 2 vertical axles (gateway), 1 horizontal axle (base) e 1 rotational axle (base);
- Manual and CNC control;
- Adjustable drive wheel speed (peripheral wire speed);
- Wire tensioning system (active tensioner);
- Replaceable pulley system for different wire usage (bead size and shape, number of beads per meter, types of coating, etc.);
- Adjustable cooling flow system (adjustable water flow);
- Stone clamping system;
- Wire maintenance equipment;
- Equipment and environment safety.

The prototype 3D CAD model is shown in Fig. 6

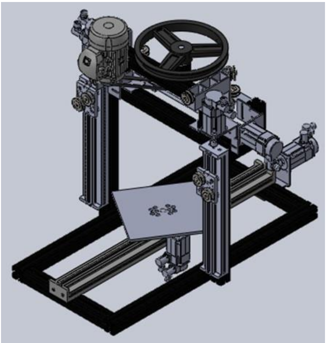

Figure 6. Prototype model on *SolidWorks*.

The prototype is currently being built at the University's Department of Mechanical Engineering Laboratories and upon its completion the testing phase will take place. Whenever test results deem it necessary, adaptations to machine's design will be taken into account.

6. CONCLUSION

Diamond wire is proving to be a superior and the wisest choice for stone cutting. Compared with other methods, it offers higher cutting speed, flexibility, accuracy and surface finish. The process produces lower waste, pollution, vibration and noise which in turn guarantees better working safety. It also requires lower investment and maintenance costs, reduced manpower and the cutting tool is easily changed or repaired, often on site.

Given the absence of a structured model of procedure and parameters on diamond wire cutting, at times, some of the available information on the subject is contradictory or ambiguous. The efficiency affecting parameters are also ambiguous due to the lack of consensus between authors regarding which (controlled parameters) are relevant or not. There is also lack of distinction between the diamond wires with and without beads (which are quite different in size and application) both being referred to as "diamond wire" or "diamond wire saw", and in spite few authors refer to the wire type without beads as "spool diamond wire", almost every study regarding those refer them simply as "diamond wire". Therefore, much (but not all) of the information about these "spool diamond wires" does not have relevance for this study and has been disregarded. Thus, it seems imperative to undertake a detailed study on this technology to establish a knowledge database. The development of a laboratorial prototype will allow advances on standardizing the process, as well as its posterior optimization and the upgrading of the equipment itself.

7. ACKNOWLEGMENTS

.We would like to express our gratitude to the company D2 Technology for the experience opportunity, to technician Vítor Neto for his assistance on fabricating some of the components for the prototype and our colleague Lucas Feliciano from Instituto Federal de Santa Catarina for his support suggestions and for sharing his knowledge.

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