Concept of the CLEAN-CUT project

The stone industry is of strategic importance for the European Union economy, particularly for its Southern member states including Italy, Spain and Portugal. A large proportion of the 60 million tons world production can be attributed to EU countries, representing an estimated market of 20 billions Euro, and of this 81% is produced in the three Southern European countries mentioned above. However, the figures on world trade in the stone sector show that the market share of the EU countries has been decreasing steadily over the last few years in favour of relatively new stone producing countries (China, India). Although the prospects for the future development of the sector appear to be promising, there is a number of problems which have to be addressed in order for the sector to remain competitive and maintain its leading position in the global market. These problems are particularly relevant when considering stone processing and particularly granite slab production, being faced by low productivity, huge quantities of waste material, high energy consumption and environmental management of wastes produced.

Literature reports that in Europe every year 12 million tons of granite are cut into 150 million square meters slabs (average thickness 15 mm) by some 10,000 SME companies with an overall energy consumption of 4.5 billions kWh and generation of 3.5 million tons of waste. There is therefore a need for a new concept of granite slabbing machine with high energy saving per square meter, a low environmental impact, high versatility in work programming, high productivity, high quality surface finishing, as well as reduction in foot print. The solution to this need represents a huge opportunity for the SME participants and more in general for the competitiveness of the overall stone industry, employing some 500,000 people in 60,000 companies, whose majority has less than 50 people. The availability of highly flexible and cost-effective equipment will allow small workshops to afford for the purchase, allowing the installation in small areas further increasing the market perspectives with respect to traditional gang saws.

Within this framework, our partner Tesimag has patented an innovative stone slabbing machine, shown in Figure 1, which is based on a set of diamond wires operated vertically and not horizontally, thus reducing their length and overall machine foot print, while enabling the processing of both regular and irregular sized blocks. The system does not use grits as for current gang-saws and therefore the processing waste is fully recyclable.

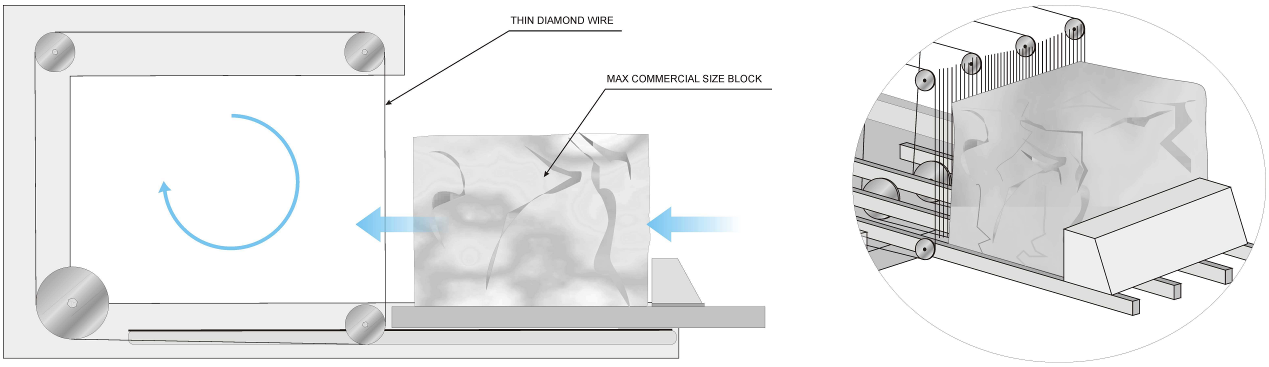

Figure 1: Scheme of the working process with the innovative stone slabbing machine

However, there are still some bottlenecks preventing the direct exploitation of the concept, namely:

- the larger kerf caused by available diamond wire based on stainless steel strands (10-12 mm) when compared to 5-6 mm with steel blades (basically each slab cut means a lost slab if targeting 1 cm thick slabs),
- the reduced life-cycle of the wire due to failures of the joints of the steel strands,
- the lack of a proper control system able to constantly monitor anomalous stresses and deformations, thus guaranteeing the correct functioning of up to 50 wires singularly subject to different stresses because of the variable geometry of the block across the cutting plane (high down time because of the time needed to replace single broken wires).

The CLEAN-CUT project aims at **developing a cost-effective small diameter diamond wire with increased life cycle based on superelastic nichel-titanium alloys (Nitinol)**. In order to overcome the previously mentioned technical barriers, the following **scientific and technical objectives** have been defined, associated with the main innovations expected from the project:

- Definition and optimisation of the thermo-mechanical sequences and training procedures which are needed to obtain a superelastic Nitinol wire with the required mechanical performances with respect to the specific application as well as with a stable mechanical behaviour along its whole life cycle and an improved fatigue behaviour;
- Development of a proper joining methodology for SMA-SMA and characterization of the mechanical and fatigue behaviour of the joint (laser welding, butt welding, ultrasonic soldering, halogen-based flux soldering, Ni plating, mechanical joining, etc. will be taken into account);
- Development of a complete model which integrates different properties of the wire, the beads and the plastic in order to define a proper set of algorithms for process control via the implemented control apparatus.

The impact of the project on the competitiveness of the SME participants is strictly related to the market perspectives of the CLEAN-CUT system, expected to generate 13 million Euro increase in turnover by the second year after project completion. The impact of the project on the competitiveness of the SMEs outside the project consortium is related to the licensing and joint-venture opportunities arising in the medium term from the exploitation of the CLEAN-CUT system in the stone processing sector. In fact, whilst the initial demand is expected to be satisfied by the SMEs participants, the expected growth in the demand will be far beyond their joint capability to satisfy. Hence the consortium recognise the need to transfer the technology to a wider industrial community by offering manufacturing and distribution licensees and establishing joint-venture agreements both throughout Europe and world-wide to expand supply capabilities whilst generating royalty revenues. This will have a positive impact to optimize the European granite slabs production, thus enhancing the competitiveness of European SMEs within the global market.

Participants to the project

The list of the participants to the CLEAN-CUT project is provided in Table 1, together with their origin country and the role accomplished within the Consortium to carry out the project tasks.

Table 1: Project Consortium

Beneficiary number	Beneficiary Name	Beneficiary short name	Country	Identity
1	Tesimag S.r.l.	TESIMAG	Italy	SME
2	Master Tre S.r.l.	MASTER3	Italy	SME
3	Mc Diam Sp. z o.o.	MC DIAM	Poland	SME
4	Steinmets- und Steinbildhauermeister Kohlhoff & Raatz GmbH	K&R	Germany	SME
5	Centro di Progettazione, Design e Tecnologie dei Materiali	CETMA	Italy	RTD
6	Centre de Ricerca I Ivestigacio de Catalunya S.A.	CRIC	Spain	RTD
7	Tevan S.r.l.	TEVAN	Italy	RTD

CLEAN-CUT advancements

The starting point of the CLEAN-CUT project has been a deep analysis on the state of the art manufacturing processes and procedures commonly utilized in granite quarrying, performed also involving the expertise of end users and machines/diamond tools developers, which has highlighted the numerous advantages and the few limitations related to the use of cutting diamond wires with respect to other traditional cutting methods. The focus of the analysis has been then addressed to an introductory study on both the properties of the cutting diamond wire and the control parameters which address cutting operations on single/multi wire machines. Figure 2 shows the view of a single wire and a multi-wire machine together with a schematic view of the cutting diamond wire employed on board.

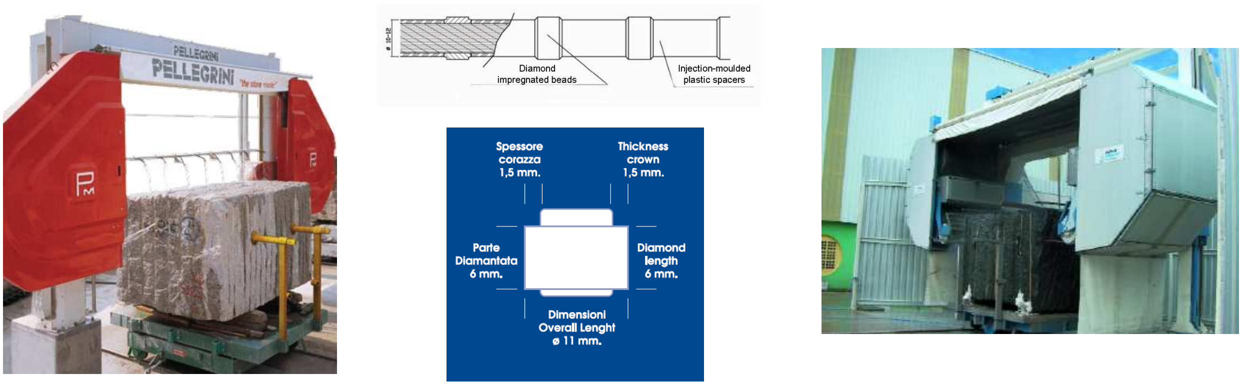

Figure 2: View of a single wire machine (left), a cutting diamond wire (centre) and a multi-wire machine (right).

The above mentioned study together with the preliminary study of the overall stresses and applied loads which act on the wire during cutting operations have allowed the proper functional requirements and technical specifications definition for the superelastic wire core, the integrated diamond cutting wire and the control system, in order to address the project and grant it the maximum effectiveness. Within CLEAN-CUT activities, a conceptual design has followed, as illustrated in Figure 3.

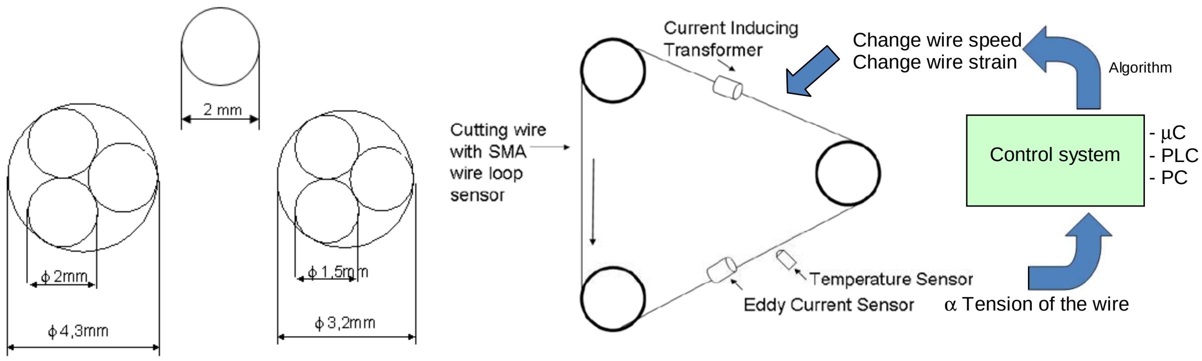

Figure 3: Wire conceptual design (left) and control system conceptual design (right).

The set specifications and conceptual designs have been introductory to the definition of a detailed design of the superelastic core wire implying the selection of the appropriate Nitinol material to employ, the investigation of thermo-mechanical processes and training procedures needed to achieve a superelastic wire with appropriate characteristics. An extensive experimental characterization activity has been successively performed whose aim has been to fully characterize and optimise the Nitinol thermal and fatigue behaviour in order to meet the specific requirements of the CLEAN-CUT system, especially in terms of life cycle. Several wire diameters and layouts have been analysed, and some results are illustrated in Figure 4. The best suitable wire core has resulted to be the one realised with 3 superelastic wires with 1.5 mm diameter.

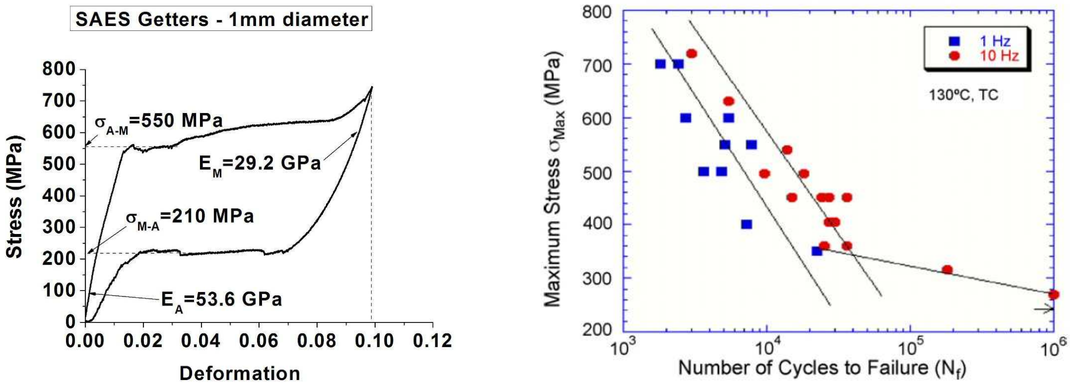

Figure 4: Stress-strain curve for 1 mm diameter SAES wire (left) and S-N curve of austenitic wire loaded at two different frequencies (right).

In order to numerically simulate the working process and the overall behaviour of both the wire core and the whole cutting diamond wire comprising of beads, joints, springs etc., it has been necessary to perform an extensive survey of existing one-dimensional constitutive models for modelling the Superelastic and Shape Memory behaviours of Nitinol. The most appropriate model has been then chosen with respect to the simulation requirements and embedded into a finite-element scheme. Subsequently, once validated the implemented scheme with case studies, FEM-based simulations have been performed. Since the connection among the strands and the epoxy matrix is indeed the weakest point of the wire, the main focus has been on the evaluation of the joint influence on the overall wire behaviour under working conditions. Some results are reported in Figure 5.

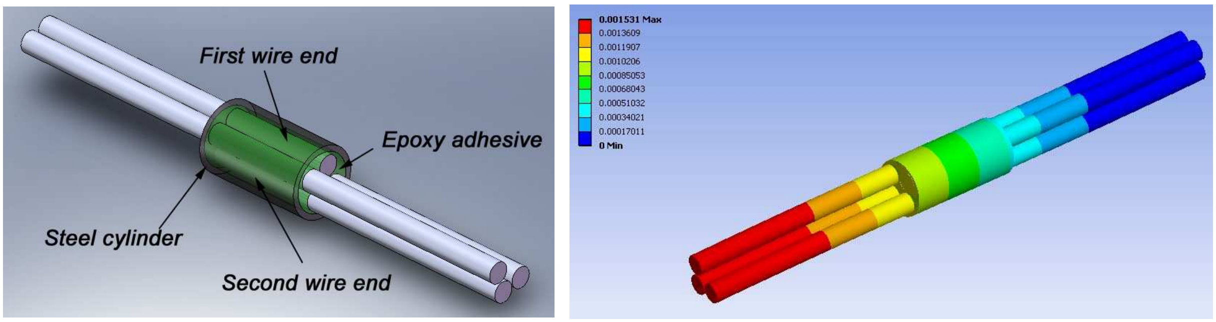

Figure 5: Schematic view of the joining geometry (left) and view of its deformed shape (right).

The evaluation of the shear stresses on the interface between each wire core and the epoxy matrix of the joint has resulted to be too high for the selected wire configuration. An optimization process has then started, coming out with a new wire made up of three superelastic wires with 1.5 mm diameter.

A novel control system was successively developed to evaluate if the new Shape Memory Alloy (SMA) wire is working in the right conditions with applied loads and to allow the monitoring of its behaviour in order to undertake corrective actions in case. The control system is composed by sensors which monitor four parameters (wire speed, current consumption, wire vibration and temperature). The data collected during all the cutting process are processed by a microcontroller and sent to a PC via a serial port, where all information is saved in a file, as shown in Figure 6.

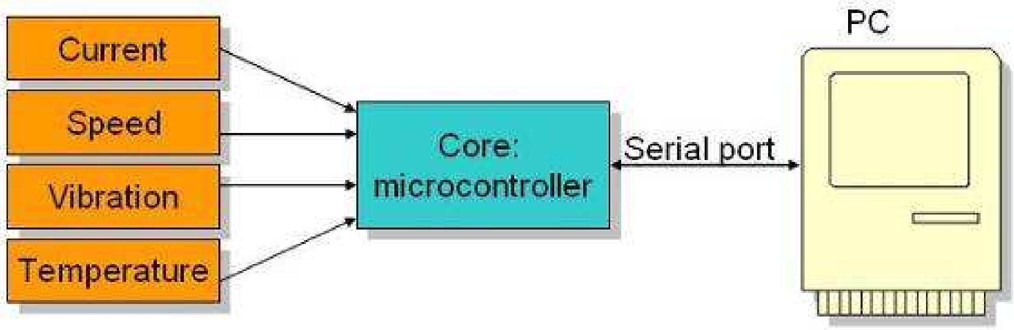

Figure 6: Control system diagram

All these data is used to study the behaviour of the wire in order to improve its cutting conditions. The control system has been installed in a single wire machine.

Figure 7: Single-wire machine

Attention was then focussed on the characterisation of the joining of the wire ends. The fatigue behaviour of scaled rings, reproducing the behaviour of the real diamond wire, was investigated. Experimental activities such as pull-out tests to characterise the joint of the integrated diamond cutting wire were carried out in order to find the proper structural adhesive for the bonded joint. Starting from the analysis of the joining of two wire ends, and after having tested little portions of the entire joint, the last tests regarded the final joint that was successively used for the integrated cutting wire. Both static and fatigue tests were carried out on the joint. From fatigue tests two solutions were found able to bear the expected exercise loads at laboratory conditions:

- three SMA wires with 1.8 mm diameter jointed with three joining cylinders;
- four SMA wires with 1.5 mm diameter jointed with four joining cylinders.

Figure 8: View of the wire while working

The integration of the control system prototype and the wire prototype on board of a single-wire cutting machine was then performed. Experimental activities were carried out to test three novel wire prototypes as in Figure 8 (one made by steel and two made by SMA with different design) in real working conditions and to get deeper knowledge on the process parameters and loads acting on the wire. The steel wire showed a proper behaviour, while the SMA prototypes got into failure due to the locally high peel stresses achieved when the wire passes by the small upper wheel at a certain speed. Modifications of the joining were proposed, and a hybrid combination of bonding-mechanical fixing was identified as the most promising. Further full-scale tests with the single wire machine and common operating conditions led to final prototypes. Last trials carried out with the full-scale prototypes showed the final solution of the cutting wire could work well in real conditions, allowing good surface finishing and showing important perspectives that will be made concrete in the next industrialization phase.

Conclusions

At the end of the project a cutting wire with SMA core and with diamond beads with an external diameter of 7 mm was produced, with better performances in terms of fatigue resistance, damping behaviour, easiness of manufacturing and suitable for cutting machines characterized by lower manufacturing and maintenance costs. The innovative design of the joint will allow to further decrease the diameter of the core, and thus the bead diameter: in fact in this case there is not the need of a high number of thin wires that have to be threaded in order to make the joint, like for traditional strands. To do this new diamond beads have to be manufactured and tested, and some significant changes have to be done on traditional machines, in order to make these ones adapt to be equipped with the new wires.

The Consortium has managed in developing all the tasks with success. Project objectives and the main public domain results are available on the project website, at the address http://www.project-cleancut.eu. For further details and description, please contact Mrs. Sara Vannucci, CLEAN-CUT Coordinator:

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Tesimag has patented an innovative stone slabbing machine which is based on a set of diamond wires operated vertically and not horizontally as in Figure 9, thus reducing their length and overall machine foot print while enabling the processing of both regular and irregular sized blocks. The system does not use grits as for current gang-saws and therefore the processing waste is fully recyclable.

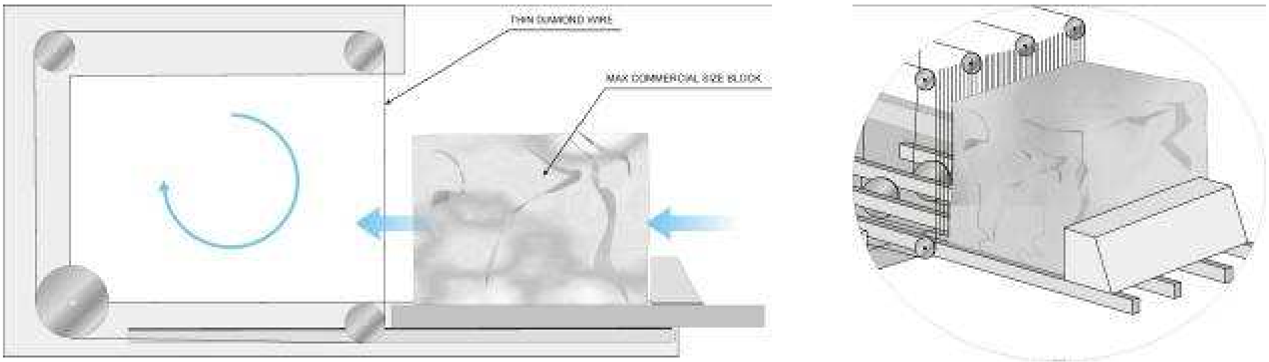

Figure 9: Scheme of the working process with the innovative stone slabbing machine

However, there are still some bottlenecks preventing the direct exploitation of the concept, namely:
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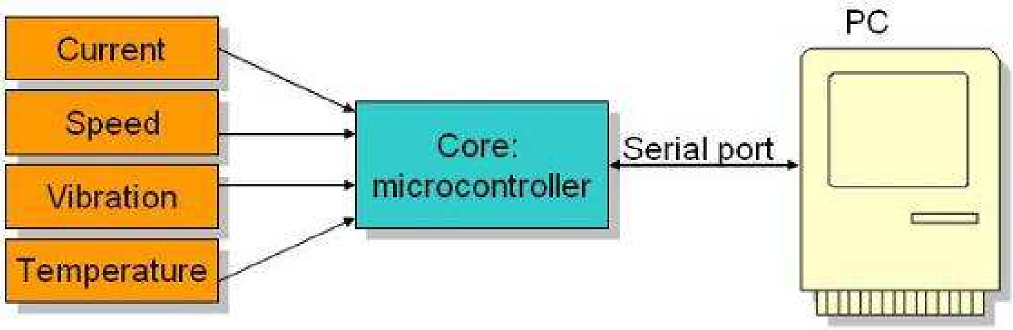
- the reduced life-cycle of the wire due to failures of the joints of the steel strands,
- the lack of a proper control system able to constantly monitor anomalous stresses and deformations, thus guaranteeing the correct functioning of up to 50 wires singularly subject to different stresses because of the variable geometry of the block across the cutting plane.

To solve these bottlenecks, the CLEAN-CUT project proposes to develop a cost-effective small diameter diamond wire with increased life cycle based on superelastic nichel-titanium alloys (Nitinol).

Starting from the results of the first period of the project, the CLEAN-CUT consortium has developed a control system to evaluate if the new Shape Memory Alloy (SMA) wire is working in the right conditions with applied loads and to allow the monitoring of its behaviour in order to undertake corrective actions. The control system is composed by sensors which monitor four parameters (wire speed, current consumption, wire vibration and temperature). The data collected during all the cutting process are processed by a microcontroller and sent to a PC via a serial port, where all information is saved in a file, as shown in Figure 10.



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