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Cutting force monitoring of chain saw machines at the variation of the rake angle

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1. Introduction

In the recent years many scientific efforts have been devoted to deeply investigate the quarrying of marble blocks since this operation can induce geometrical defects, which significantly reduce the effective economical value of the stone. The commonly used technique makes use of wire cutting machines based on the abrasive effects of diamond grains on the natural stone. This process shows high proficiency and good quality of the obtained surface but needs for preliminary drilling on the bulk stone in order to insert the diamond wire. The presence of coolant is also needed in order to remove marble powder from the groove and reduce the high temperatures developed by friction on the stone.

A complementary technique for stone cutting is represented by chain saw machines, especially when bottom horizontal cuts have to be operated or in case of reduced cooling fluid. Chain saw machines for stone cutting eliminate collimation problems encountered with diamond wire cutting machines, reduce production and time losses to enter a new bench, produce directly saleable blocks with less waste material. Conversely, chain saw machines cannot be used for cutting very hard stones and highly fractured deposits. The cutting performance of a chain saw machine depends on geological and geotechnical conditions of the quarry, mechanical features of chain saw machines, and operational parameters.

The stone is cut by multiple carbide or PCD inserts bolted or brazed respectively on tool holders fixed at a chain which moves around an adjustable arm of 5–7 m length, visible in panel (a) of Fig. 1. The abrasive inserts, acting as cutting tools on the stone, are located along the rim of the chain and are fixed in a jig composed by the chain grid and the tool holder, as shown in the sub-assembly of panel (b) of Fig. 1. As the chain moves along the edge of the arm each insert deepens the track made by the preceding one, and the arm movement turns this track into a real cutting plane over which the chain keeps on excavating further into the rock. Tool holders have a design which can host tools with various geometries according to their position into the sequence. The geometries to be used in the sequence have different tasks (e.g. preliminary engraving, deepening, enlarging, etc.) so that their precise position is fixed by the direction of rotation of the chain. Moreover, the layout is chosen on the basis of rock mechanics which rules the material removal.

The tools which constitute a sequence are designed symmetrically with the objective to counterbalance the sideways forces acting perpendicularly to the arm plane. This enables avoiding uneven wear of the tools and arm plate, as well as deviations of the arm which may stuck it into the engraved track. The cutting action of tools sequence, is obviously repeated by the following sequences, which have the same cutting pattern. The spacing between the tools and their angular positions, determining the cutting profile, may vary: usually smaller at the external borders of the cut profile and larger at the centre.

As it can be expected, the cutting mechanics changes significantly as the rock properties change and consequently the cutting conditions and tool wear rates will show large variations. Therefore, the design of a tool holder might be different for different stone types to improve cutting rate and reduce tool wear rate. The aforementioned optimization problem is rather complex since it should involve all the parameters mentioned above, at the same time. Nevertheless, the knowledge of rock cutting mechanics suggests to solve this problem by the superposition of effects using the combination of linear rock cutting tests, which makes it possible to simulate the cutting action of chain saw machines.

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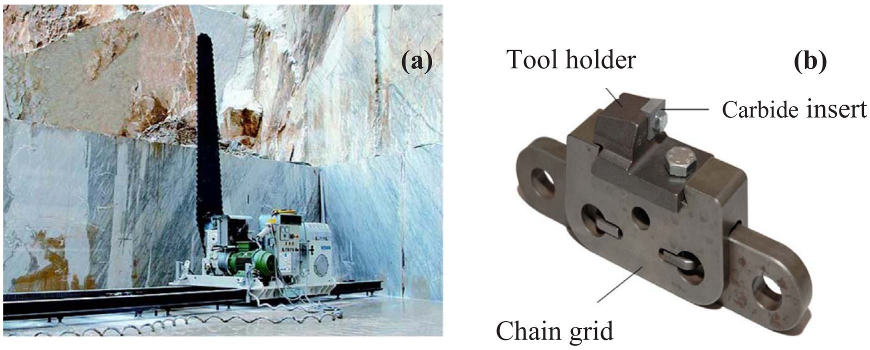

Fig. 1. (a) Chain saw machine; (b) detail of a basilar element of the chain.

A few researches exist in literature on stone cutting and especially on how stone cutting mechanics could be applied to the complex case represented by chain saw machines. Copur[1] suggested a simplified model to evaluate the operational depth of cut and feed rate to be then implemented in the calculation of cutting forces. The dependence of cutting forces to the process parameter was estimated by means of linear cutting tests. At this purpose, Jerro et al.[2] showed a mathematical approach to define and derive theoretical chipping geometries for stones. From the knowledge of the theoretical chipping geometries, chip area and mean chip thickness relations were obtained. The relationship between tangential cutting force and obtained chip thickness was empirically investigated. Brach et al.[3] studied the problem of converting dynamometer measurements of specific cutting energy into the power consumed, while Asche et al.[4] showed the empirical results of the influence of process parameters on tool wear. In very preliminary studies, Tönshoff and Warnecke[5] and later Tönshoff et al.[6] developed a model on stone cutting by circular saw blades which could be considered as an orthogonal cutting process not far from the linear cutting. According to the aforementioned studies, Turchetta[7] presented a mechanism of material removal during the cutting with a single diamond grit.

This mechanism, summarized in Fig. 2, shows the mechanical interaction of tool and workpiece as caused by the elastic and plastic workpiece deformation of the cutting grits, the friction between stone and diamonds, stone and matrix, slurry (a mixture of marble powder and water) and matrix. The plastic deformation and fracture deformation are influenced by the cutting conditions such as the depth of cut, tip shape of the cutting tool and the properties of the stone. In front of a grit that is engaged in the process, stresses are affected by tangential forces. In this zone, the slurry is forced out through grooves in front and beside the grit. While the rock shows elastic characteristics up to its ultimate compressive stress (about 30–40 MPa for white marble and travertine, 80–90 MPa for beige marble) it is necessary for the cutting edge to reach a certain minimum grinding thickness. The material to be cut is deformed by compressive stresses under the tool. When the load is removed, an elastic reversion leads to critical tensile stresses which cause brittle fracture. This mechanism ruled by tensile stresses is termed secondary chip formation. Factors influencing this mechanism are numerous: physical material properties of the stone, forces between the diamond and the material, stress distribution in the rock, temperatures at the tool-workpiece interface. As a result, it suggests the use of tools which favour compressive stresses and the sudden propagation of cracks underneath the surface skin-depth of the workpiece.

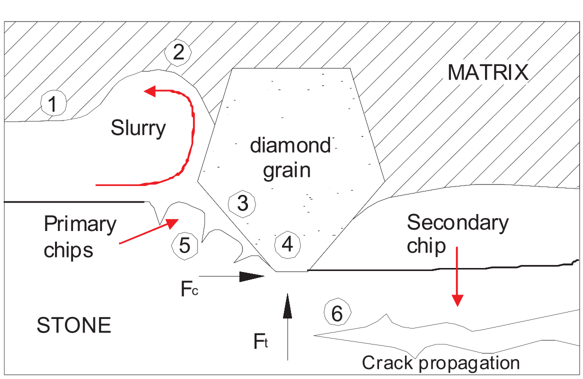

Fig. 2. Chip formation during stonecutting: (1) friction between slurry and matrix, (2) matrix erosion by slurry and chips, (3) primary chipping zone, (4) friction between stone and grain, (5) plastic deformation (6) elastic deformation.

Concepts related to the mechanism of material removal were further implemented in simplified conditions, like the use of single cutters. Konstanty[8] presented a theoretical model of natural stone engraving by means of diamond-impregnated tools for both circular and frame sawing. Pai et al.[9] collected and observed cracked chip samples under a scanning microscope and related them to the specific grinding energy. Unfortunately, these investigations did not reach a whole comprehension of the phenomena happening at the tool-workpiece interface during stone cutting due to the extreme large variety of stones and the related anisotropy. Buyuksagis[10] presented a study to examine the effect of cutting mode on the sawing performance of some selected granites. Two cutting modes, up-cutting and down cutting referring to the cutting direction, were employed in the experiments. Turchetta et al.[11] presented a study on the use of single CVD diamond inserts instead of traditional tungsten carbide ones looking for a faster cutting speed and a longer life of the tool. Dagrain et al.[12] performed tests by using rectangular tools whose effects on the stone can be modelled as two independent processes: pure cutting and frictional contact at the interface. Authors suggested the existence of a 3D effect, linked to the cutter geometry, which influences the magnitude of the energy required to cut a unit volume of rock.

If the literature efforts on the mechanism of stone machining using single cutters represent a niche topic, as pointed out in the review done so far, the research on chain saw machines and/or continuous belt-type machines offers an even more restricted number of contributions. Anyhow chain saw machines are increasingly used in quarries and relevant questions arise from the point of view of setting up the best operating conditions. This is the reason why the few contributions dealing with the cutting process monitoring of such machines belong obviously to the field of mining engineering but sometime lack of relevant aspects related to manufacturing. An example of this being the definition of standardized cutting forces and cutting angles and the identification of important parameters like the depth of cut and feed rate per single tool.

Whittaker[13] investigated the effect of the rake angle and blunting of wedge-type tools on cutting performance. Dalziel[14] analyzed the effects of blunting of wedge-type cutting tools on performance (cutting force, torque, haulage force, energy consumption, dust generation) of a 1/3 scale model coal cutter. The results indicated that blunting had a slight effect on cutting force and energy consumption while increasing normal force as much as three times, especially at lower depth of cut. Mellor[15] analyzed kinematically the working principles and design parameters of

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