Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2017, 4(9):146-151

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Application of Basic Principles of Stone Cutting on Experimental Studies

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Abstract The systematic and rigorous study of the cutting process in natural stones, using diamond abrasives, to provide an understanding of the relationships between machine, tool, workpiece and cutting parameters and naturally the resultant and evaluation factors comprising geometrical forces, wear, machined face and chips of the blade, offers the possibility of optimising stone sawing operations. In this study, some empirical formulae and chip removal model were developed which takes into consideration the distribution of synthetic diamonds on the tool surface and also the different mechanisms of cutter-edge wear. Besides, the influence of diamond grit size and concentration were investigated in order to provide facility and practical view for frame and circular stone sawing processes.

Keywords Stone, sawing, Cutting Process

1. Introduction

The term “sawing” generally refers to the operation of cutting the stone by tools, equipped with diamond grit, geometrically at an infinite edge. According to their working principle, the stone sawers can be subdivided into frame saws, circular saws and wire saws, separately. In all these sawing processes, the most important criterion to be considered is the optimal width of the slot formed within the piece of rock prior to cutting [1]. The cutting operation should be expected to represent a combination of both physical processes and chemical reactions as depicted in Figure 1, which would facilitate us to build a model link between these parameters and their effects [2].

2. Description of the Fundamentals for Cutting Process

The main interests to be taken account for researching cutting technology and optimization of cutting process are tool wear, cutting forces and the support stability. Among those factors, cutting force is accepted to be the most vital one, not only for the prediction of lifetime, fatigue, capacity and the stability of the machine but also for the eligible construction of the stone sawing machines [3]. With regard to the cutting forces, we can summarize the questions asked both by manufacturers and users of these machines as the condition of the tool absorbing high forces and torque without creating a layout for the critical working boundaries, the condition of the tool enduring the forces in case of running improperly, the characteristics of the diamond grit to fulfil its function, the setting of the whole machine for yielding high performance with rather low costs at the same time. The most common way to respond to the questions mentioned above is carrying out in-situ tests and taking practical measurements creating optional permutations of each parameter assigned to the cutting machine. However, this way of solution seems a time-consuming, expensive task and only gives approximate results. Instead of this, a manner of linking of different factors of the sawing operation is studied and from this approach, we can obtain answers to the aroused questions more theoretically. Moving on from this point, it useful to explain some of the technical terms regarding optimization attempts. The term “chip thickness” is similarly also applicable to the cutting of indeterminate edges as in with the geometrically determinate edges.

An "equivalent chip thickness" for a saw can only be calculated dependent to quantitative factors such as the circumferential velocity, feeding rate, length of the cut and depth of the cut. This quantity named as chip thickness is both applicable to linear movements as in frame saws and cyclic movements as in circular saws. Figure 2 clearly illustrates the plan and cross-sectional view of the cutter head under the guidance of such empirical equations.

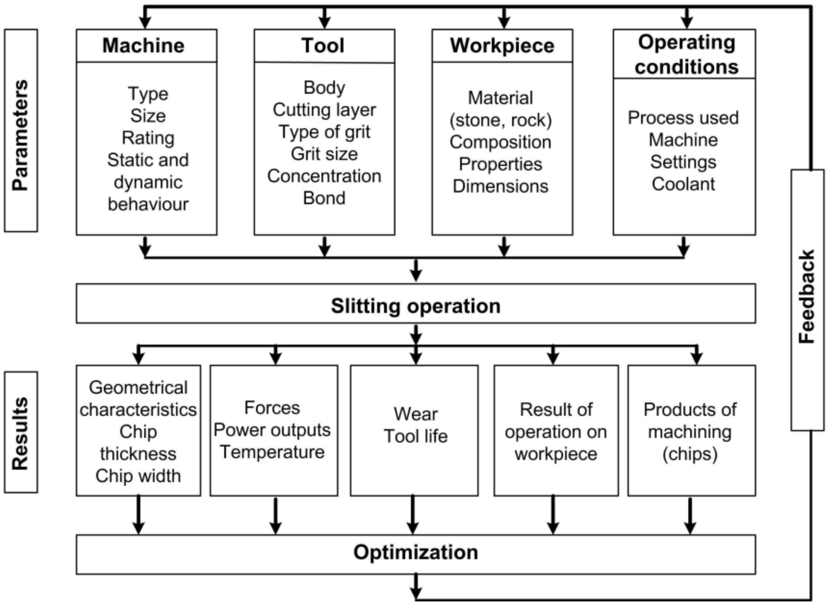

Figure 1: Proposed Optimization System for Stone Sawing

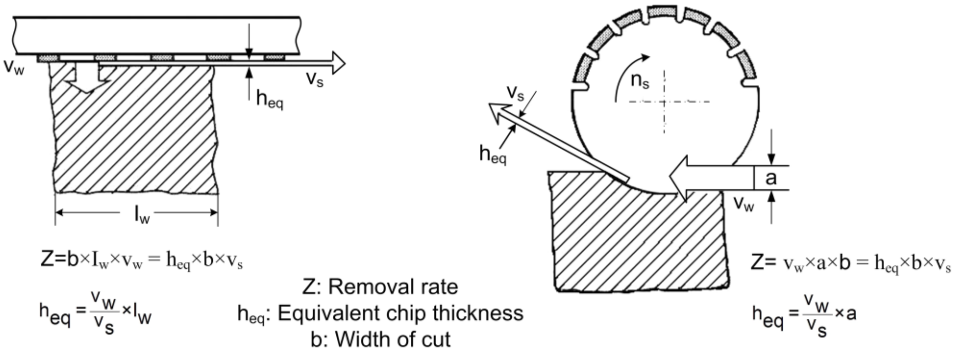

Figure 2: The Definition of Equivalent Chip Thickness Both for Linear and Cycloidal Movements [2]

Nevertheless, its one disadvantage is that it takes no account of the macro and microstructure of the cutting tool and does not give comparable results for different contact lengths. For this reason; it is more useful to define the chip thickness quantity as the mean chip thickness, h_c. Figure 3 and 4 explicitly put forward the diagrams of the mean chip thickness for linear and cycloidal tool movements, successively.

The internal removal rate, which is the same with the external rate in the equations above, is found by the mean chip section per cutting edge, by the number of grains and by the tool velocity. The shape of the grains is denoted as r and defined as the ratio of mean chip width to mean chip thickness, known as the "chip ratio". Table 1 offers us the practical parameters for 3 different sawing processes encountered in the industry. Here, the chip ratio has been assumed constant (r = 10) for simple outlining of these 3 applications.

Table 1: Practical Characteristics of Tool Data for Different Sawing Operations

Method	V_W (mm/min)	V_S (m/s)	a (mm)	C (mm^{-2})	h_c (µm)
Wire saw	10	20	-	10	0,57
Frame saw	10	2	-	2	4,4
Circular saw	1800	30	5	2	2,8

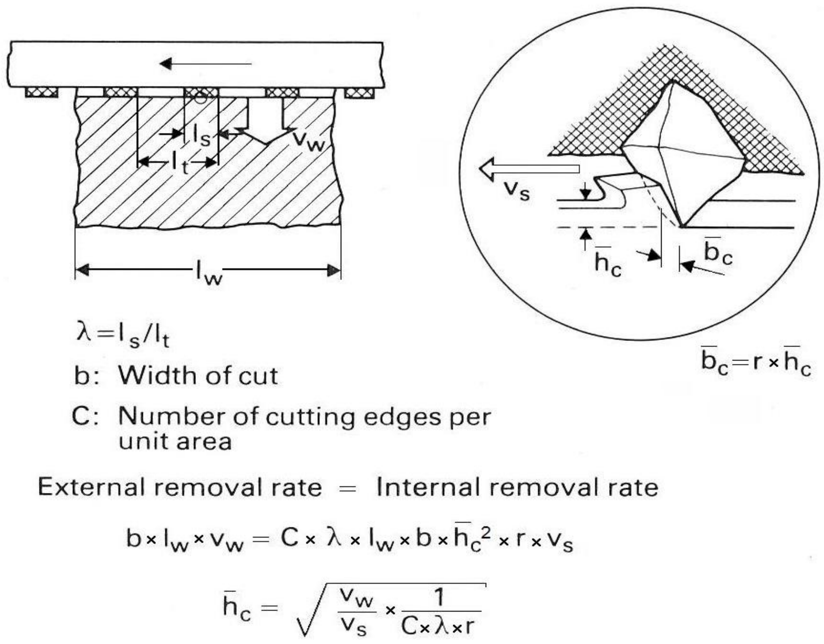

Figure 3: Definition of Mean Chip Thickness with Linear Tool Movement [2]

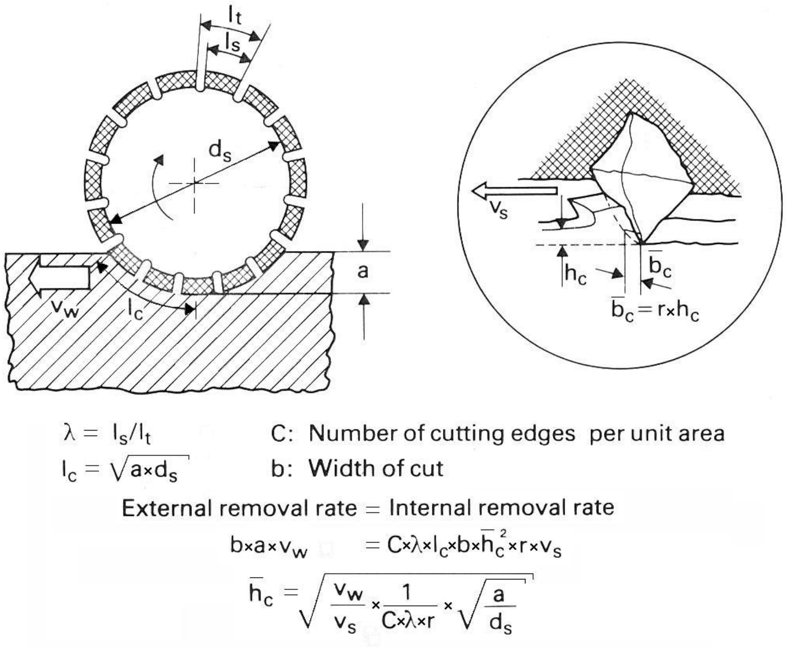

Figure 4: Definition of Mean Chip Thickness with Cycloidal Tool Movement [2]

The most determining factor affecting the mechanical aspects during the stone sawing operations happens to be the chip thickness. Therefore, the mean chip thickness can also be used for the quantitative description of the operation, which then can be applied to the initial phases of optimizing machine settings. For stone sawing too, we should find a similar relation to the Taylorian Equation below, between the G-ratio, that is the quotient of the volume of stone cut, the volume of tool wear and the mean chip thickness;

$$G = G_0 \cdot h_c^{-2g}$$

where G_0 and g are the coefficients which depend on the pairing of the tool and the material of the workpiece. This equation does the analysis of optimization process for cost-effective purposes. It is accepted that the total amount of costs per cut consists of two parts, machine cost which is determined by the loading of the machine and the tool cost determined by the tool wear. The graph showing combinations of these costs are given in Figure 5.

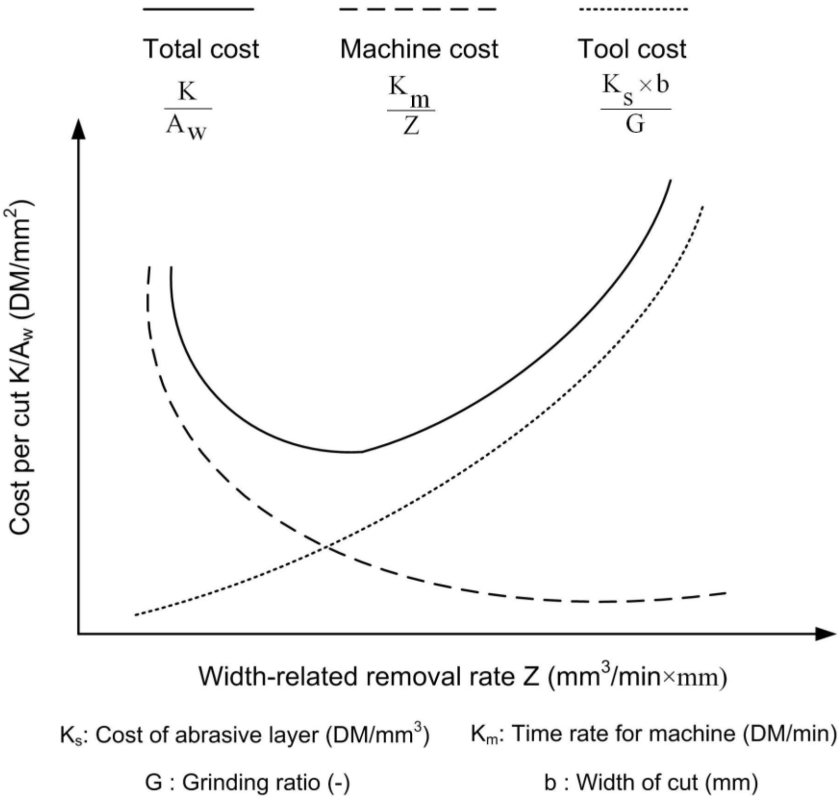

Figure 5: The Diagram of Sawing Costs versus Removal Rate

From the figure, It can easily be perceived that as the removal rate increases, the machine and tool costs travel in opposite direction, at different average slopes though. This fact remarks that, in optimization machine setting attempts from the economical point of view, we should point out a degree that we should reach at which an optimal rate of removal exists [4]. If we keep the volume cut constant, the internal removal rate according to the width of cut could be related to the mean chip thickness as the following equation, whose scheme had been explained before;

$$Z' = (C \cdot \lambda \cdot \mathrm{I}_W \cdot r \cdot V_S) \cdot h_C{}^{-2}$$

Since the constant values within the brackets are same for a certain kind of machining operation, we can cumulate them under a new coefficient, M. So, we have;

$$Z' = M \cdot h_C{}^{-2}$$

$$\Rightarrow G = G_M \cdot Z'^{-g}$$

where; $G_M = G_O \cdot M^g$ obtained as the sawing ratio.

The function of total cost (K/A_W) now depends only on Z'. The optimal point is sure obtained by taking its first rank derivative and making it equal to zero.

$$d(K / A_W) / dZ' = 0$$

$$Z'_{Optimal} = \left[\frac{K_M \cdot G_M}{g \cdot K_S \cdot b} \right]^{1+g}$$

From the eventual equation formed for the optimization of stone sawing operations; it is concluded that the optimal removal rate is directly proportional with the costs of the machine per unit time and sawing ratio while inversely proportional with the costs of abrasive layer and the width of cut.

3. The Study of Forces and Wear in Cutting Process

During the cutting operation, the tool is exposed to diverse mechanical and thermal stresses, namely the diamond grains and the various portions of the bonding medium at the operating face go through many forces and extreme heat which gives birth to rapid fatigue. For genuine optimization both economically and technically, a sawing tool should fulfil the requirements of maximum cutting rate, minimum tool wear and additionally, minimum tool thickness also providing stability along the cut. These plotted features minimize the amount of material that is removed and generate optimal results. The most crucial factor here is the forces acting on the tool, which are aroused from individual diamond grains. Therefore it is necessary to study the relation between the forces applied and the chip and the diamond grain geometry, simultaneously. On the contrary, it is essential too to investigate the linkage between the circumstances affecting a single diamond grain and the whole tool under the connection of applied operation parameters.

Another point of research regarding cutting technology is that while the specific cutting forces such as the forces acting over per unit area of the chip cross-section gradually diminish as the chip thickness per cutting edge increases; the cutting surprisingly keeps on inflating with the increase observed in the chip section. This contradictory phenomenon might be overcome by considering the geometry of the chip and the cutting edge of the individual grain separately. The sharpness, a term which corresponds to cutting capacity of a diamond grain is defined with the location of the edges and corners that contributes another factor to be involved for the chip thickness. Figure 6 is created to depict the chip geometry formed taking into care the effects of chip thickness and edge rounding. For instance; at a small chip thickness and at a large edge radius, the material moves in a rather firm cutting wedge, which causes plastic deformation even in brittle rock [5]. As the chip thickness is enlarged or the edge radius is decreased, this time the irregular chips are chopped off with insignificant deformation ahead of the cutting edge and beneath the ideal line of cut.

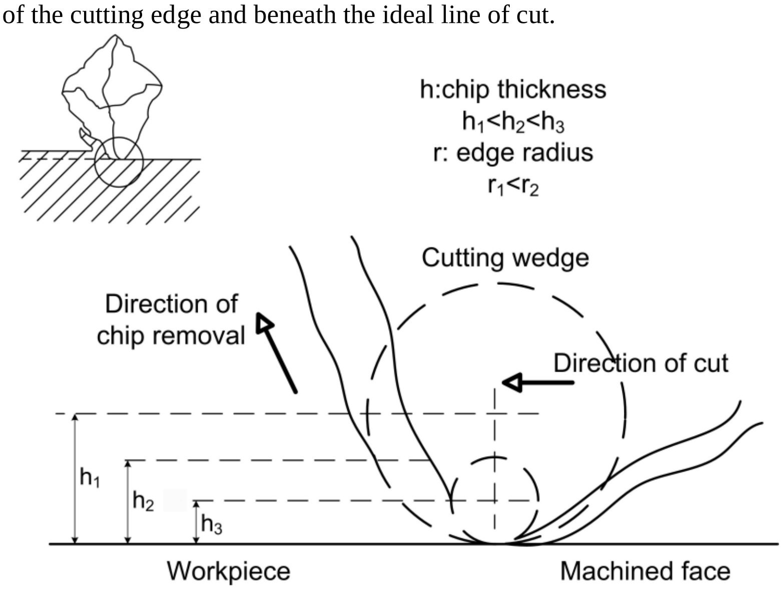

Figure 6: The View of Chip Geometry at a Cutting Edge [2]

Up to now, the parameters and the interactions between them have been studied for optimal operating condition of frame sawing. The other versatile means of cutting through rock masses is the circular saw process. In analogous manner, according to a recent research carried out in circular saws on concrete samples by Bienert (1978) [6], it has been focused on the large number of parameters that are directly or indirectly effective over the power requirement and degree of wear and graphs considering the relation between the grit size, the concentration on the radial and normal forces and especially on the radial wear, which definitely determines the lifetime of a circular saw blade at several feeding velocities with a given width of the cut have been plotted . As seen in Figure 7 and 8, at high cutting rates, a moderate grit size and high concentration, whereas at low cutting rates, a relatively smaller grit size and low concentration are in favour of supplying a more stable tool structure and getting more economical results. The graphs illustrated by Bienert (1978) [6] fortunately form the initial basic steps in the way of obtaining an optimal sawing technology in case all the relevant factors shown in those graphs are taken into account and inquired rigorously, which is indeed considerably a tough task to do.

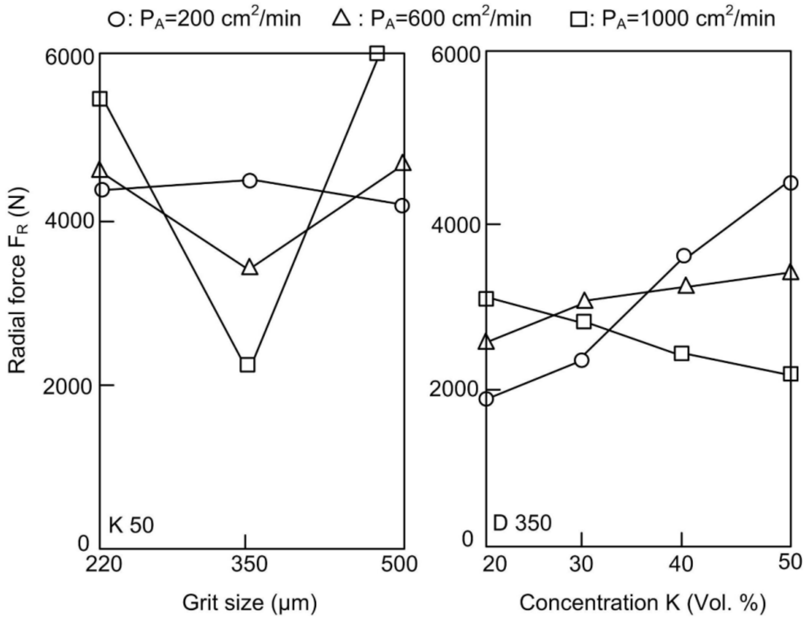

Figure 7: Effect of Grit Size and Concentration on the Radial Forces in Circular Sawing [2]

4. Conclusions and Recommendations

Despite the effort of researchers on optimization, even today progress in the machining of stone masses comes from practical experience of the users and not built on a strong base. However, this practical knowledge seems to differentiate even in the same type of sawing processes with almost identical operating conditions. Unless an insight into the fundamental processes taking place at the point of action between the abrasive grain and the stone and unless necessary adjustments are applied to working parameters that interfere with each other, the sawing operation of the stone will continue to be vague for the future [7]. This unlucky divergence indicates the benefit of developing state-of-the-art empirical formula for the optimization of stone sawing. In order to serve this purpose, all the parameters related either to the workpiece, or the tool or the grit size and concentration have been tried to be put in relation with each other sustained frequently with graphs and diagrams for better optimization.

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