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Evaluation of cutting forces in granite treated with microwaves on the basis of multiple linear regression analysis

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ABSTRACT

The current study is focused on the evaluation of cutting forces in granite treated with high-power (24 kW) microwave radiation based on a multiple regression analysis. As a result, dependencies of forces acting on a conical cutting pick on the irradiation time (up to 45 s), the spacing between cuts and the distance from the treated surface (in depth) were established. The values of obtained correlation coefficients are in the range from 0.90 to 0.98. The analysis of the regression models show that the noticeable reduction in cutting forces for granite used in cutting tests is achieved after its irradiation with a minimum of approximately 34 s. Cutting forces increase linearly with increasing distance from the initially irradiated surface (in depth). For an irradiation time of 45 s, the influence of cracks induced by microwaves is levelled out at the depth of 32 mm, so the treatment of the rock used in cutting tests should be repeated after cutting of some 30 mm in order to initiate a new set of cracks for subsequent layers. Representation of cutting test results in form of regression dependencies allow a more detailed analysis of the influence of irradiation and cutting parameters on the cutting forces as well as more convenient re-use of the obtained empirical data by researchers and engineers.

1. Introduction

Over the last quarter of the twentieth century, many investigations worldwide were focused on the development of non-blasting hard rock excavation technologies. It resulted in the emergence of a number of new rock fragmentation methods, such as activated (i.e. impact and oscillating) cutting, high-pressure water jet assisted cutting, and thermal rock fragmentation methods (with the use of microwaves, lasers, electropulse discharges, plasma heating, and others). Some of them were successfully implemented in mining machines (for example, impact rippers CAT D9L, D10N and D11N,[1] excavators with activated buckets EKG-5V and EKG-12V,[2] roadheaders Dosco Mk2A, RH22 and RH25L[3] utilizing high-pressure water-jet assisted cutting technology). Other technologies were tested in industrially relevant environments (e.g. Sandvik Reef Miner ARM1100/MN220 equipped with undercutting discs[4]) or remain to be developed at lab scale until now.

The main advantages of mechanical excavation methods over the drill-and-blast ones consist in continuous operation, minimum ground disturbance, safer and more environmental-friendly operation, uniform particle size of excavated material, selective mining/excavation capability, and higher production/excavation rate in favourable ground conditions.[5] The inability to cut very hard and abrasive rock, however, limits the application of mechanical excavation methods. So far, point-attack picks are capable to cut in economically acceptable way non-abrasive rocks with the uniaxial compressive strength (UCS) of up to 150 MPa and highly abrasive rocks of $<$ 70 MPa UCS.[6] For rolling cutting tools, this value is limited to 250–300 MPa UCS for highly abrasive rocks. Energy consumption and wear of cutting tools increase dramatically with increasing the strength and abrasiveness of rocks.

To increase operational performance of hard rock excavation equipment, the main part of manufacturers focus on the improvement of cutting tools to make them generally stronger and more wear-resistant.[7] Another approach consists in providing more energetically efficient interaction between the working tool and rock massif (for example, utilization of tensile failure of rock cut with undercutting discs instead of compression one, which is typical for rocks cut with V-type cutting discs[4]). The improvement of rock cuttability by optimizing physical influences remains to be primarily in the focus of researchers. Investigation results demonstrate a great potential for the use of microwaves for the purposes of weakening hard rocks.[8–10] For instance, the UCS of granite samples irradiated with microwaves is reported[11] to be decreased by up to 40%. Despite encouraging results, however, there is still a long path to be overcome prior to the wide implementation of microwave-assisted hard rock excavation technologies in industry. The

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development of mathematical models based on empirical data is expected to facilitate the understanding of effects observed during cutting of rocks irradiated with microwaves, establish knowledge about the influence of irradiation parameters on cutting parameters and find ways for further improvement of the technology to make it a technically sound and economic alternative to conventional excavation methods. This paper is aimed at establishing and analysing dependences of cutting forces in granite treated with high-power microwave irradiation on the irradiation time, the distance from a treated surface (penetration depth in the rock) and the distance between cuts (spacing) using a multiple linear regression analysis. This study is a follow-up to the experimental procedure and results previously described by the authors[12] and aims at further analysing the parameters influence considered in that publication.

2. Material and methods

Three granite blocks with dimensions of 500 × 500 × 300 mm were used for the cutting tests. The top surface of the first and second block was treated with microwaves in a "chessboard"-like spot pattern for 30 s and 45 s per spot respectively. The distance between the spots was 90 mm. The third block was left untreated. Hereafter, these blocks are referred to as B30, B45 and B0 respectively. The properties of the granite used for the tests are as follows: density of 2670 kg/m^3, UCS of 210 MPa, Cerchar abrasivity index of 4.2. The treatment of the blocks with microwaves caused the occurrence of surface and subsurface cracks up to a depth in the range from several millimetres up to approximately 100 mm (Fig. 1).

The cutting tests were carried out with the use of the linear cutting test rig HSX-1000–50 of TU Bergakademie Freiberg equipped with a conical cutting bit BETEK BSR112. The cutting parameters were set as follows: cutting depth of 4 mm, cutting speed of 0.1 m/s, spacing of 8 and 12 mm, attack angle of 45°, tilt angle of 0°.

The cutting forces acting on the cutter in three mutually perpendicular axes were measured during the tests with a frequency of 10 kHz. As a result, the graphical dependences of cutting forces on spacing, distance from the initial top surface and the duration of treatment with microwaves were established.[12] The regression models describing the obtained results are given below in this paper.

3. Calculations

3.1. Data processing

A scheme of forces acting on the cutter and a typical force-time oscillogram obtained during cutting tests are shown in Fig. 2. The processing of each oscillogram was performed in a sequence as follows:

a) determination of the mean value of a considered force,
b) determination of force peaks exceeding the mean value,
c) statistical analysis of the peak force distribution,
d) determination of the mean value and confidence interval of the force peaks.

Afterwards, the regression models describing dependencies of the mean and peak forces on spacing, duration of treatment, and distance from the initial top surface were developed. Herewith, each individual cut made within a layer cut with the same cutting parameters was considered as a replicate test. The first cut was disregarded for the following calculation as it is as "blocked cut" without an additional free face.

The determination of peak forces was carried out with the use of the peak count method.[13] Here, peaks on the force-time oscillogram located above the mean value were counted. The mean value of a force F_{Qmean}, where index Q denotes an appropriate axis of the force direction (X, Y or Z), was determined as a sum of force values F_{Qi} (i = 1, 2, …, n) divided by a number of the data points n measured within a cut. Elimination of small variations caused by force oscillations due to electrical noises was realized with the use of the following conditions: $F_{Qpeakj} = F_{Qi}$ if $F_{Qi} > max\,[F_{Q(i-m)}; F_{Q(i-1)}]$ and $F_{Qi} > max\,[F_{Q(i+1)}; F_{Q(i+m)}]$, where F_{Qpeakj} is the peak force (j = 1, 2, …, k), m is a number of data points determining the width of intervals from the left and right sides from the value F_{Qi}, within which the force $F_{Qi} > F_{Qmean}$ is maximal. Analysing the obtained oscillograms, the value m was selected to be 10 points (the number of data points per cut was equal to approx. 43,000). A fragment of an oscillogram $F_X(t)$ (1000 data points) with determined mean and peak forces is shown in Fig. 3. It should be pointed out, that the free swinging of the cutting head after the separation of a larger chip fragment caused negative force values.

The further processing of the peak forces F_{Qpeakj} was conducted in a sequence as follows[14]: determination of a mean value and a variance of a series, ordering the series, data categorizing, creating the frequency histogram, formulation and verification (on the basis of the chi-square test) of a probability distribution. Since the physical essence of the stochastic process during the cutting of one block is the same, the statistical analysis of peak forces distribution was conducted for 1 cut (selected randomly) for the second layer of each block. The second layer was selected as the one, which is primarily effected by microwaves (the first layer was not taken into account due to the uneven initial surface, which is caused by the sawing and installation inaccuracy as well as by the rise of surface within irradiated spots).

The series of peak forces F_{Xpeakj}, F_{Ypeakj} and F_{Zpeakj} for the blocks B0, B30 and B45 were analysed. The peak forces F_{Xpeakj} were verified to conformity to the Gaussian distribution (Cauchy distribution was

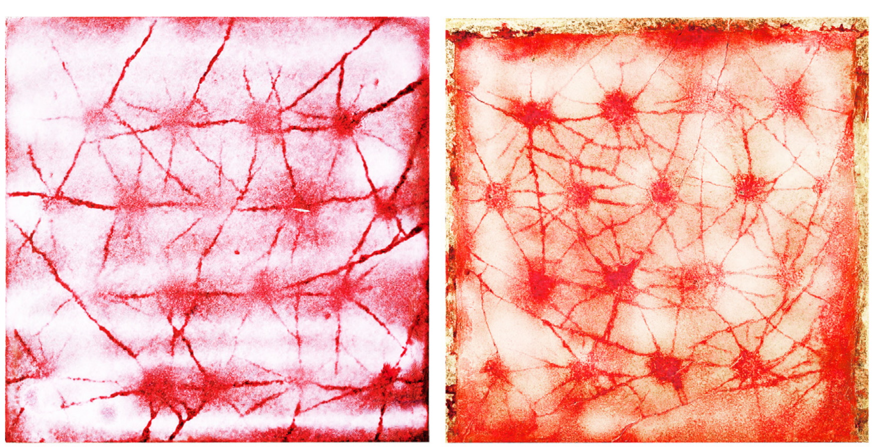

Fig. 1. Granite blocks radiated with microwaves for 30 s (a) and 45 s (b) per spot (coloured with a pink penetrator).