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A new technology for the tunneling machinery; Part I: Decreasing cutting forces due to rock fatigue

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***Abstract*— This study is technology research to make the mechanical cutting process more efficient and sustainable in tunnelling by using lower forces and energies due to the rock fatigue effect using cyclic loading. This fatigue-based technology research was done at the University of Queensland, Australia for the first time in literature. Comparative experiments between the dynamic cutting tests using the Dynamic Cutting Discs (DCD) fatigue technology and the traditional (non-oscillating) hard rock cutting process are determined as the main objective of this research. When the DCD rock cutting test results are compared with the TBM disc test results working with the vibration-free conventional discs, the cutting forces, and the Specific Energy (SE) were found to decrease by 30% with the increased amount of excavated material by 200%. The cutting test results showed that the average normal force FN was attained approximately to be 43 kN at 3 mm vertical distance of cut and 54 kN at 5 mm vertical distance of cut for vibration-free conventional cutting. It was attained in particular that the magnitude of the average normal force FN decreased more than the average cutting force FR when the disc vibrated at 45 Hz. It was concluded that the cutting forces decreased significantly as the cyclic loading frequency increased. In conclusion, it is believed that this high energy saving rate obtained from the research results will be sustainable in scientific, economic, commercial, and social areas.**

***Index Terms*— DCD dynamic rock cutting technology, tunnelling, and rock fatigue, TBMs and energy efficiency, oscillating disc cutters and TBMs, sustainability and tunnel boring**

I. Introduction

In general, the research concerns experienced in mechanical hard rock cutting are grouped under two main headings: excessive chisel wear and vibrations in the machine and breakage of the retaining units. These two problems shorten the life of the chisel and thus make the mechanical excavator uneconomical. The huge and heavier machines have been produced to overcome these problems by using larger cutters. Moreover, more durable artificial materials have been developed that can replace tungsten carbide, which is usually used in cutter manufacturing (SmartCUT, CSIRO). In addition to the cutter types and machine developments in mechanical excavation in the last decade, research have been changed in terms of the new cutting technologies. It has been seen in the new cutting technologies that it is not sufficient to consider the machine parameters independently of the rock, which is the material to be cut, and its properties [1], [2], [3].

The main difference between the two types of cutters comes from the way they attack the rock surface to cut the rock. Peak cutters move parallel to the rock surface and cut by a kind of dragging. Disc chisels, on the other hand, apply forces perpendicular to the rock surface and cut with a penetrating action (Fig.1) [4], [5], [6], [7], [8]. Three-dimensional forces act on the cutters during excavation with the machine. These are shear force (FC), normal force (FN) and lateral force (FS).

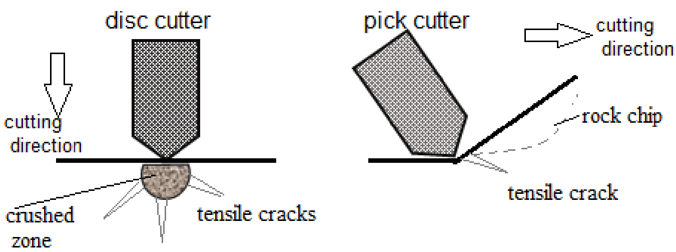

Fig.1. Rock cutting directions of disc cutters and pick cutters

A mechanical cutter usually indents into the rock surface, creating crushed and cracked zones in the rock. These cracks are then combined with increasing force to form the main crack. There are crushed, cracked and finally elastic regions are formed in the rock under a disc cutter respectively [9], [10] (Fig. 2). Most of the applied energy (85-95%) is spent creating this crushed region. Therefore, drill bits consume more energy than pick cutters.

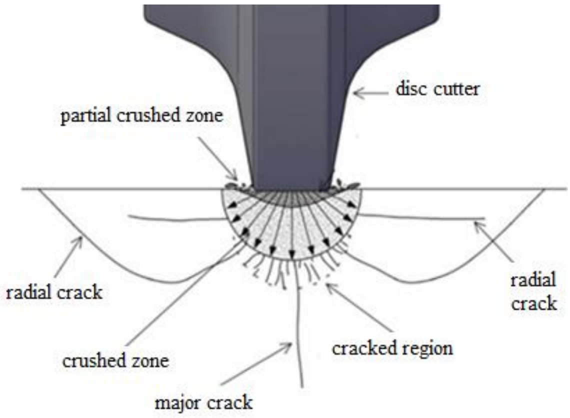

Fig.2. Crack and crushed zones under a disc cutter

There are basically two types of machine groups in hard rock cutting: full-face and partial-face machines. The full-face machines are the same size as the head-to-head on full-face (e.g., Tunnel Boring Machines (TBM) (Fig.3-a)). On the other hand, the activated head is more powerful on the partial face machines, and they cut the rock surface by several sweeping paths complete (Road headers). TBMs are the most widely used hard rock cutting machines in the tunneling machinery. However, they are huge energy-hungry machines. Another development in hard rock cutting is the use of mini discs. An important mechanical cutting technology using undercutting method, that cuts hard rock parallel to the surface, is the Sandvik Tamrock ARM 1100 (Fig. 3b), developed by Sandvik Tamrock Voest Alpine. Hard rock is cut with free rotating discs with a diameter of 30 cm and cutting parallel to the surface. Another novel technology is Oscillating Disc Cutter (ODC), Fig.3-c) designed in Australia using the rock-cutting technique with rock fatigue. Joy Mining Machinery and later Komatsu companies made new machine designs by using the ODC technology.

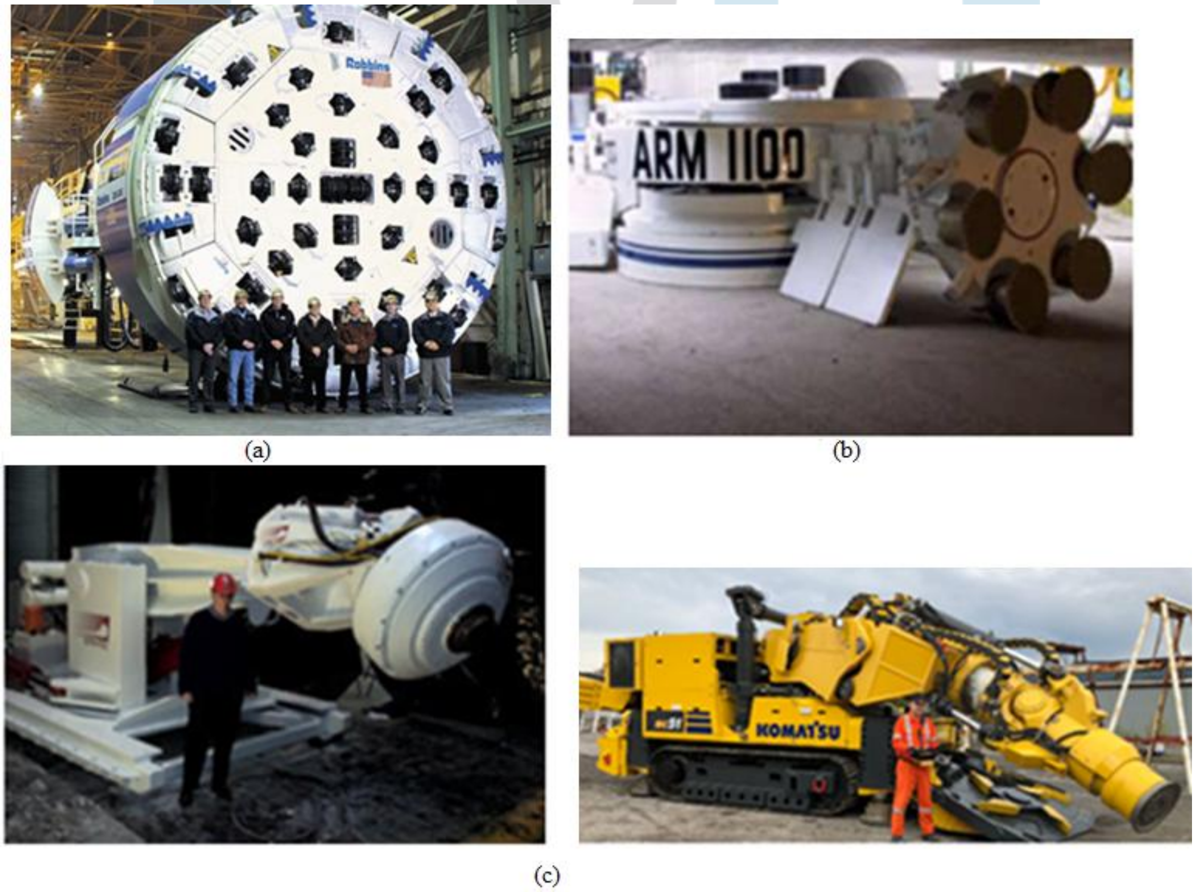

Fig. 3. Hard rock cutters developed in recent years (a) TBM (b) mini discs Sandvik Tamrock ARM 1100, (c) ODC (left) and Komatsu MC51 (right)

Dynamic Cutting Disc (DCD) technology has been developed in the research project and its design and manufacturing, calibration studies, rock characterization tests, numerical analysis and rock cutting experiments have been carried out (Fig.4) Comparative experiments between dynamic cutting tests using with DCD technology and traditional (non-oscillating) hard rock cutting process are determined as the main objective of this project. ODC (Oscillating Disc Cutting, Australia) technology, which is one of the latest technologies in the world that makes dynamic cutting like DCD technology, rock cutting forces and specific energy values are reduced by 45%. The rock cutting direction of DCD technology is not parallel to the surface like ODC technology. DCD technology cuts rock by applying vertical dynamic loads normal to the surface like traditional disc cutters.

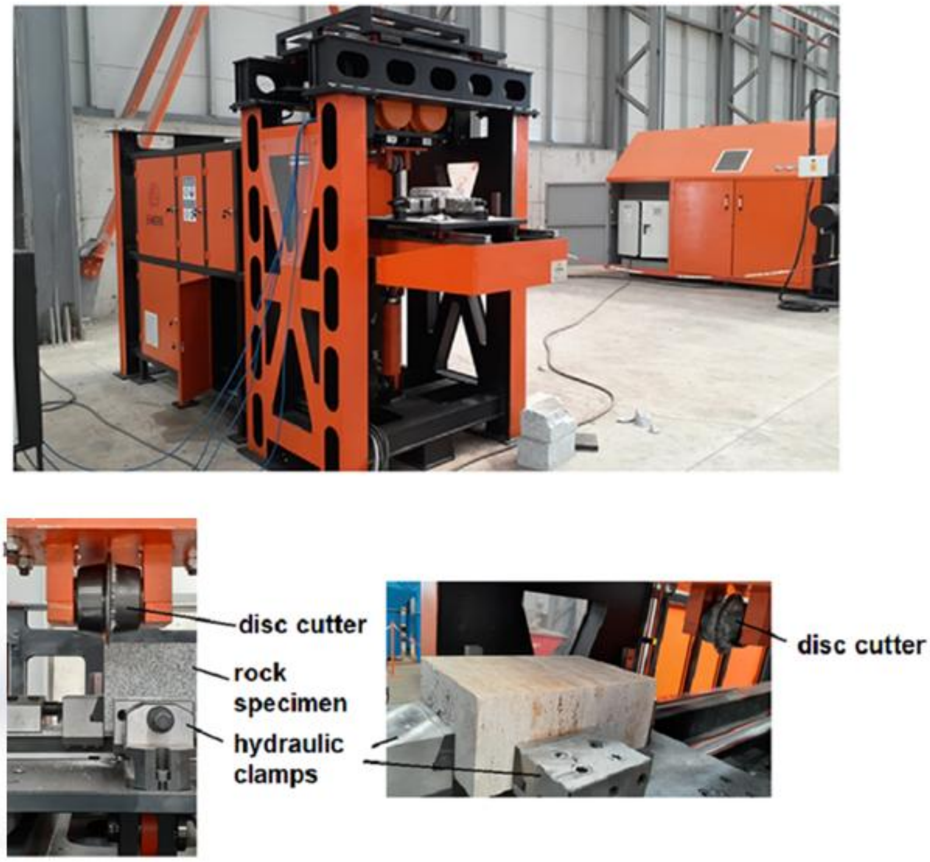

Fig.4. General view of the DCD technology prototype and a single oscillating disc cutter

The reduction of monotonic rock strength under cyclic loads is named for 'rock fatigue'. Although the effect of periodic loading on metals, composites, concrete and ceramics is well known, however, its effect on rocks has only attracted attention in recent years.

In the rock indentation technique, especially in sharp-tipped cutting picks, the main rock chip formation is not during the loading of the rock, but the unloading movement in the rock, which occurs when the force applied by the cutter is suddenly reduced or the cutter is completely removed from the rock surface (e.g., loading strokes such as percussive drilling). These cracks move to the surface during this unloading action and form the rock chips. Therefore, the effect of indentation and unloading cycles on rock cutting mechanics and cutting mechanisms of many rock cutting machines has been scientifically investigated by many researchers [11]. The basic principle of rock fatigue mechanism is related to these load-unloading cycles. If a load-unload cycle can be created under the cutter, the ability to break rock more easily with less energy comprised the basis of this study. In the literature, it has been observed that more cracks and particles are formed in a rock with periodic loading, but the basic mechanism That causes this increase has not been found yet [12], [13], [14], [15], [16].

II. MATERIALS AND RESEARCH METHODS

Since rocks are natural and heterogeneous materials, they are formations that can vary per meter. While the suitability of the selected rock type to the DCD set in terms of hardness was checked, attention was also paid to its abrasiveness. Since the cutter type used in DCD is a disc cutter and the wear resistance of the discs is higher than the peak cutters, especially the rock type with high abrasiveness was chosen. In this project, the granite type rock supplied from Bergama region in Turkey is referred to as 'Bergama Granite' in this study and has been determined as the type of rock to be used in all cutting tests. Granite is an intrusive igneous rock. The general composition and approximate percentage values of Bergama granite are quartz (25%), orthoclase (20%), biotite (6-8), chlorite (% 1-2), and opaque minerals (%2). The average UCS strength value of Bergama granite is 135 MPa, the Elasticity modulus is 53 GPa and the fracture toughness is 1.45 MPa.m$^{1/2}$. According to International Society of Rock Mechanics (ISRM) (ISRM 2015) classification, the average CAI value of the samples was found to be 4.50. Cutting experiments were carried out using 144 mm diameter CCS (Constant Cross Section) type mini disc cutters having fixed cross section.

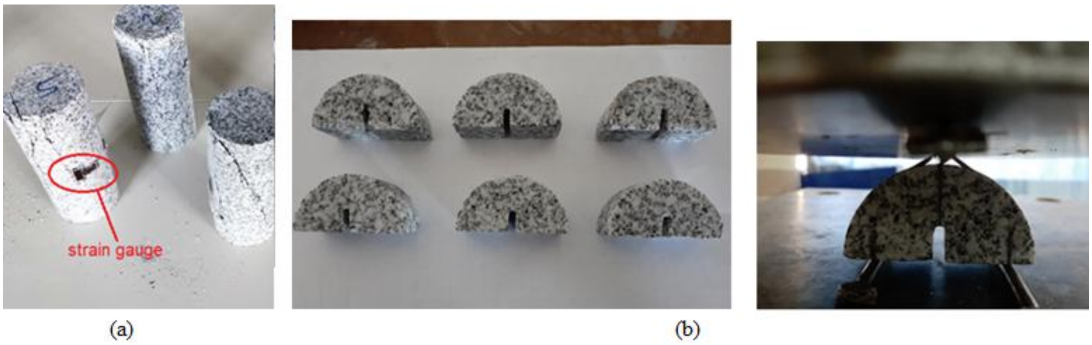

Fig.4. Prepared Bergama granite specimens (a) USC test samples (b) fracture toughness test samples

The design of the DCD cutting set using a mini disc cutter allowed data to be obtained under different test conditions by easily changing the cutting parameters such as the distance between the cutters and the cutting depth, as in the full-size linear excavation test sets. Since the main purpose of this research was not to determine the optimum cutting conditions with the DKS set, frequency, cutting depth and specific energy, which are important parameters in dynamic cutting process, were the determining parameters of the cutting program in this research. In order to comparatively examine the effect of frequency on cutting forces and specific energy, vibration-free, that is, conventional cutting, were included in the cutting program and experiments were started with the conventional cutting tests. Three frequency values were determined in the cutting experiments: 0Hz, 20Hz and 45 Hz. The cutting depth values were determined as 3mm and 5mm. The cutting speed was kept constant in all experiments and was determined as 3 cm/s. After placing the sample in the sample box, the cutting depth (d) and the distance between the chisels (s) values were adjusted by moving the cutting head with the sample table and the disc in both vertical and horizontal directions with the help of hydraulic cylinders that provide movement in different directions.

The numerical analysis series have been done by using FRANC2D (Fracture Analyzes Code) program and XFEM (Extenden Finite Element Method) analyzes. The quassi-static analyzes were performed with the FRANC2D program first. Since FRANC2D is a crack analysis program, very useful results were obtained in rock mechanics and rock failure mechanics analysis [7], [12], [16]. Since FRANC2D is a program that works both according to the principles of crack mechanics and discrete fracture analysis, especially in the investigation of the cutter\rock interaction area, very successful results was obtained with FRANC2D in this research. In numerical models, before starting the analysis with FRANC2D, the tip shape and rock sample to be modeled were modeled with a mesh generator named CASCA (Fig. 5). The rock sample used in this mesh modeling was modeled in dimensions of 200x80 mm and the cutting depth was 5mm. The modeled rock sample mesh model is fixed in x and y directions (x, horizontal direction and y, vertical direction). The Young's modulus of the rock material is 25GPa, the Poisson ratio is 0.24, and the KIC value is 1.45 (MPa√m) as material parameters in the model. The force applied by the cutter was applied as distributed loading along the cutter-rock interaction profile.

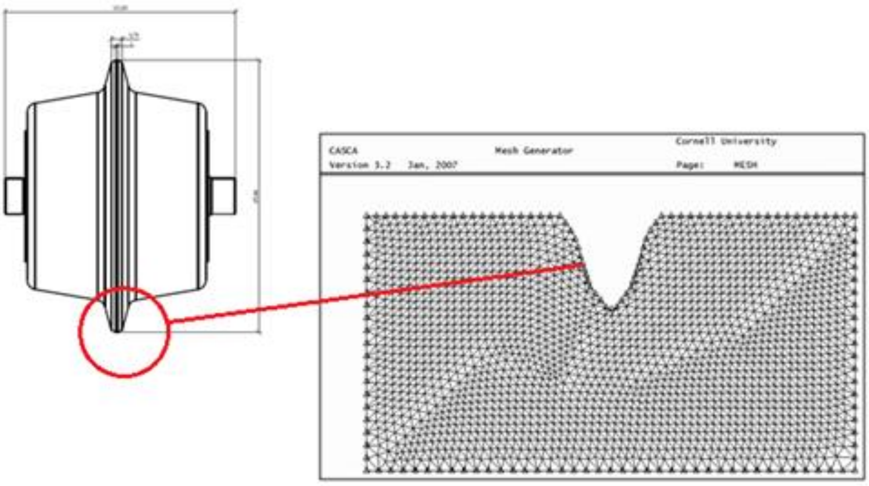

Fig.5. Cutting test geometry and disc tip profile made with the CASCA mesh generator

III. RESEARCH RESULTS AND DISCUSSION

The results of DCD cutting tests are given in Table 1 in detail. The FN is 44 kN at 3 mm depth of cut and 56 kN at 5 mm depth of cut for vibration-free and assisted cutting. When dynamic cut was made with DKS at 3mm and 5 mm depth with 20 Hz, these values decreased to 35.3 and 44.03 kN, respectively. Likewise, a decrease was observed in the average FC values. In general, the reduction in cutting forces is approximately 25% with 45 Hz while the decrease obtained with 20 Hz is 20%. The average normal force FN is approximately 44 kN at 3 mm depth of cut and 56.5 kN at 5 mm depth of cut for vibration-free cutting. When dynamic cut was made with DKS at 20 Hz, these values decreased to 35.3 and 44.03 kN, respectively. Likewise, a decrease was observed in the average cutting force, FC, values according to the results of dynamic cutting with DKS. According to the results obtained in general, the reduction in cutting forces obtained with 45 Hz vibration is approximately 25%, while the decrease obtained with 20 Hz is 18% - 20%. It was observed in particular that the average normal force FN decreased more than the average shear force, FC, with a frequency of 45 Hz (Fig. 6). It is concluded that the cutting forces, especially FN, can be significantly reduced as the cyclic loading frequency increases. Accordingly, it is concluded that the cutting force components, especially FN, can be significantly decreased as the cyclic frequency increases.

Table 1. Results of rock cutting tests

Frequency, Hz	Cutting forces			
	FN (N)	**FN'**	**FR (N)**	**FR'**
0	43621	45112	9970	10102
0	56543	58025	11602	12327
20	35317	42838	8361	9802
20	44032	52219	9439	11417
45	33743	37507	8041	8731
45	43325	49401	9118	10251

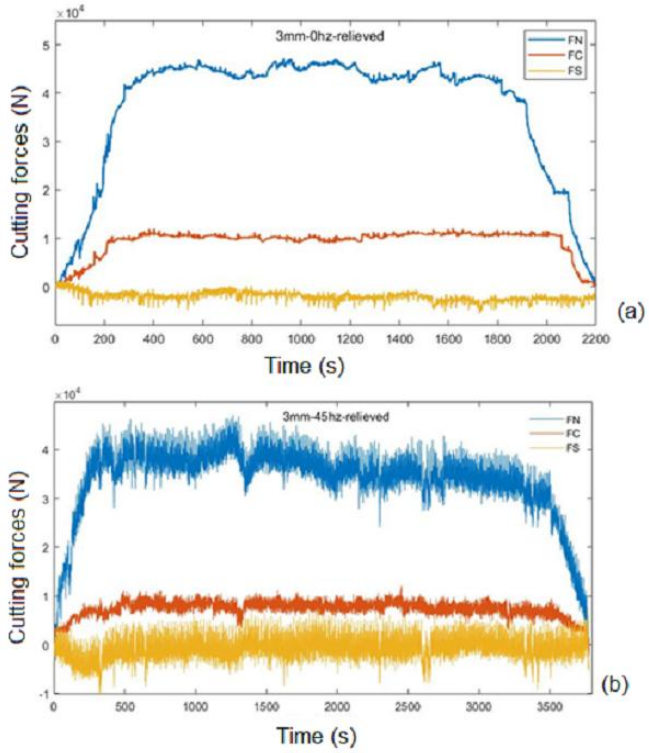

Fig.6. Comparison between (a) cutting forces of disc cutting without oscillation and (b) oscillating cutting with 45 Hz frequency

An example of the graphs of the dynamic cutting tests performed at 20 Hz at d=3mm cutting depth are given in Fig.7.

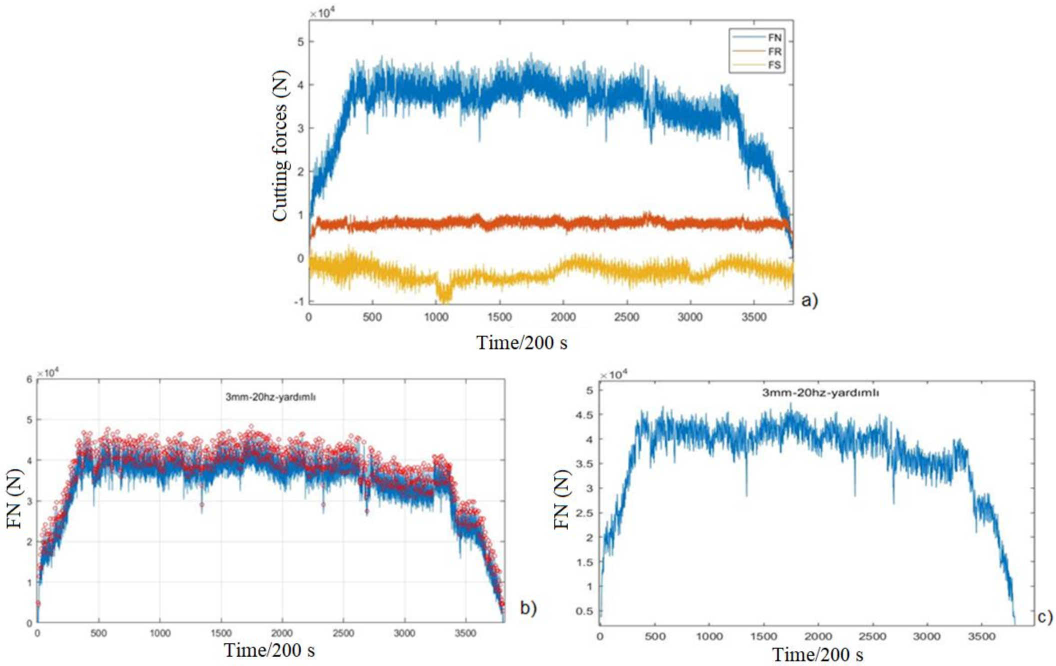

Fig.7. (a) Cutting forces of oscillating cutting with 20 Hz frequency at 3mm (b) Peaks of FN and (c) plot of FN peaks

Since the rock cutting process with DCD is a dynamic cutting process, the rock chip formation mechanism is different from the cutting theory and findings of the traditional rock cutting (without cyclic loading). The cutting grooves and the obtained rock chips after cutting with DCD and after cutting with a conventional vibration-free disc are given in Fig.8. Much more and larger rock pieces were obtained in the cutting made with DCD than in the cutting e with the vibration-free conventional disc. When the cut pieces was carefully removed from the groove, it was determined that the groove widths formed after the two cuttings were quite different.

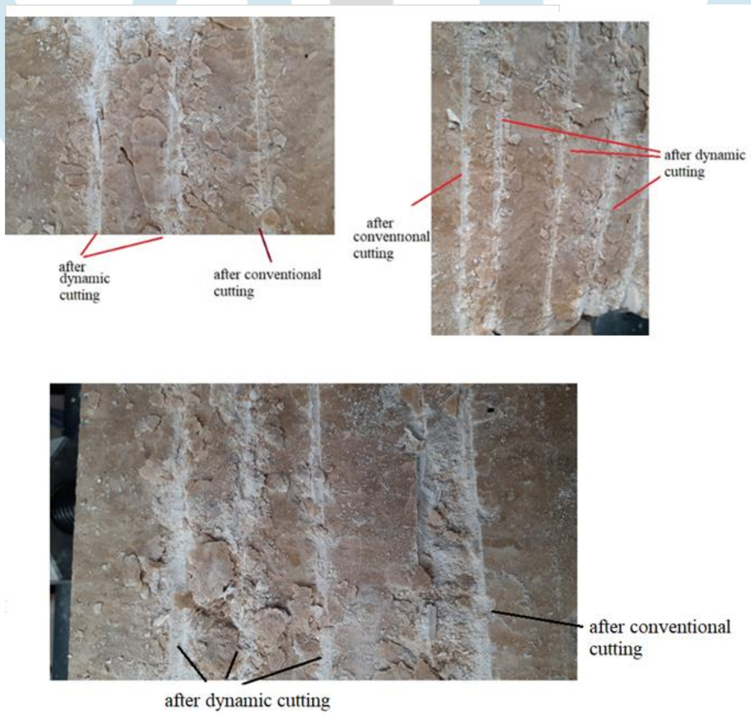

Fig.8. Comparison between the cutting grooves obtained with the DCD and conventional disc cutter

As seen in different machine designs using ODC technology until today, the cutting mode of the machines is in the form of cutting parallel to the surface called undercutting. However, cutting with a vibrating disc perpendicular to the rock surface with the DCD set is the basic cutting method used in this study. Loading the rock surface with cyclic cutting forces with DCD technology is a kind of dynamic cutting method. However, it is a well-known fact in the literature that the strength of rocks increases under impact loads [17], [18], [19], [20]. It should be questioned for this reason why the reduction in cutting forces is obtained in rock cutting with DCD and ODC. At this point, the differences of the terms oscillation, dynamic load and impact loading should be well defined. The reason for this difference between these loading is the stress-strain rate. In the cyclic loading, the loading speed

increases or decreases at a certain amplitude and frequency by acting according to a certain function. In dynamic loading, all kinds of static and quasi-static loading are in the dynamic loading type. In impact loading, the loading is done at a rate almost equal to the blasting loading rate. Technologies such as DCD and ODC can be considered in dynamic loading or oscillatory loading class.
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IV. CONCLUSIONS

The cutting forces data obtained from the non-oscillating rock cutting tests and oscillating disc cutter tests performed with the DCD set at 3mm and 5mm depth of cut, 20 Hz and 45 Hz frequencies were obtained clearly. The average normal force FN was attained approximately to be 43.6 kN at 3 mm vertical distance of cut and 56.5 kN at 5 mm vertical distance of cut for vibration-free conventional cutting. These values decreased to 35.3 and 44.03 kN at 3mm and 5mm depth of cut respectively. A decrease likewise was observed in the average cutting force, FR, values. In general, the reduction in cutting forces attained with 45 Hz oscillation is 25%, while the decrease is 20% with 20 Hz. It was observed that the magnitude of the average FN decreased more than FR when the disc oscillated at 45 Hz. It can be summarized that the cutting forces were found reduced significantly as the cyclic loading frequency increased. It has been determined that the amount of removed rock material obtained by cutting with DCD is about two times higher than the yield of cut material obtained with a conventional non-oscillating cutter. This is a very effective finding because the most generally accepted parameters for evaluating excavation efficiency in mechanical rock cutting research are the cutting forces and the Specific Energy (SE) values calculated from the amount of rock material removed. With an increase in the amount of cut material and a decrease of approximately 23% in cutting forces, considerable decrease in the specific energy values were obtained in DKS cutting compared to conventional vibration-free cutting.

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