A new technology for the tunneling machinery; Part II: Rock fatigue damage mechanism by the DCD cutting technology

Nazife Erarslan

Izmir Democracy University, Civil Engineering Department, İzmir, Turkey

***Abstract*— : 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 purpose of this study to develop a novel hard rock cutting technology. 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 25-30% with the increased amount of excavated material by 200%. It was attained that the magnitude of the average normal force FN decreased more than the average cutting force FR when the disc vibrated at 45 Hz. Moreover, it was determined that the cutting forces decreased significantly as the cyclic loading frequency increased. More cracks occurred with the rock fatigue mechanism and the FPZ resulting in more rock chips than with the non-oscillating conventional 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. The experimental and numerical analysis results showed that there are two effective damage mechanisms in the rock/tool interaction zone that cause these cutting force reductions and obtaining more cut material: rock fatigue damage mechanism and cyclic indentation damage mechanism. 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

Excavation mechanics is a science that studies the relationship between rock or ground and mechanical cutter during excavation, and its purpose is to investigate the suitability of rock or ground for mechanized excavation. Excavation mechanics also covers some specific topics such as machine selection, performance estimation and feasibility [1],[2], [3]. The cutters are divided into two categories according to their excavation principle. These are drag cutters and roller cutters (Fig.1a). 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 cutters, 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.1b).

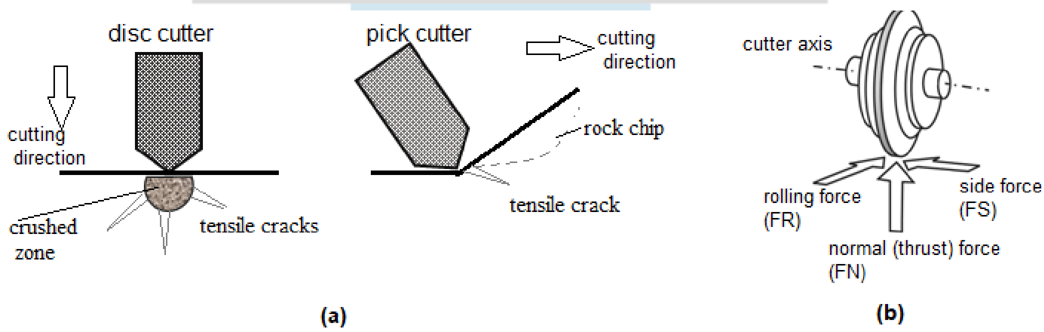

Fig.1. (a) Rock cutting directions of disc cutters and pick cutters, (b) cutting forces acting on a disc cutter

A dis cutter 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.

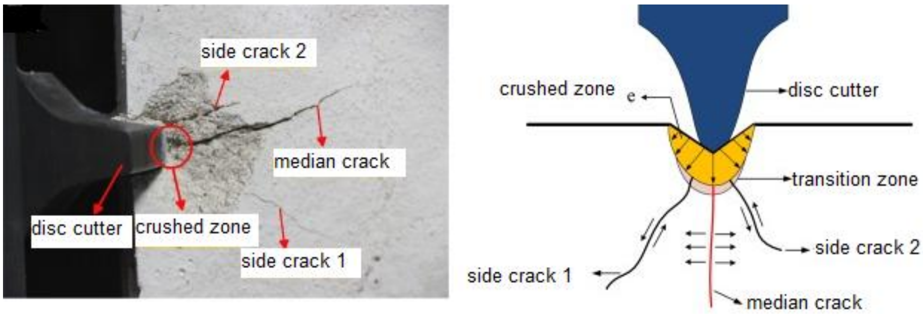

Fig.2. Crack and crushed zones under a disc cutter

The reduction of monotonic rock strength under cyclic loads is named for 'rock fatigue' [11], [12], [15], [16], [17]. 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. It has been shown in many studies that more cracks and small particles occur in the rock fatigue damage mechanism compared to the damage by static loading. If the interface between rock and cutter and the formation of cracks are the main issues in mechanical cutters, it is quite possible to develop highly effective new tunnel cutting technologies by combining rock cutting technologies and rock fatigue mechanism. That's why Dynamic Cutting Disc (DCD) technology has been developed in this way. 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.3) 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.

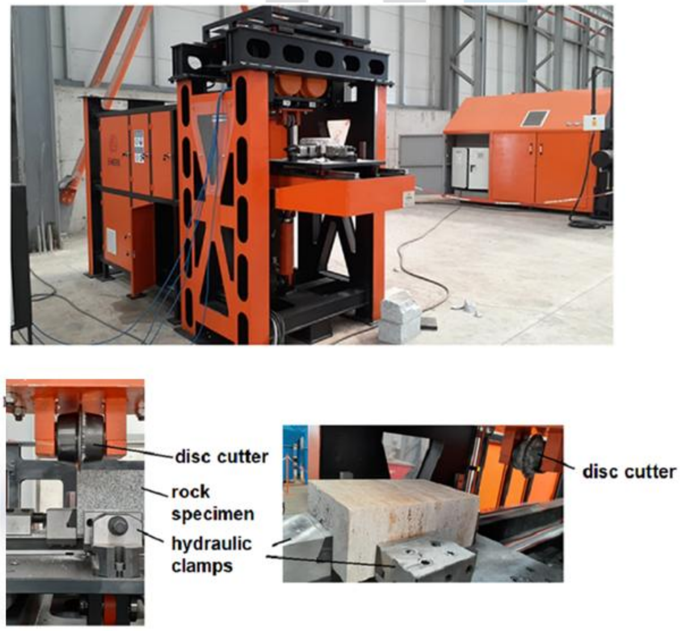

Fig.3. General view of the DCD technology prototype and a single oscillating disc cutter

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.

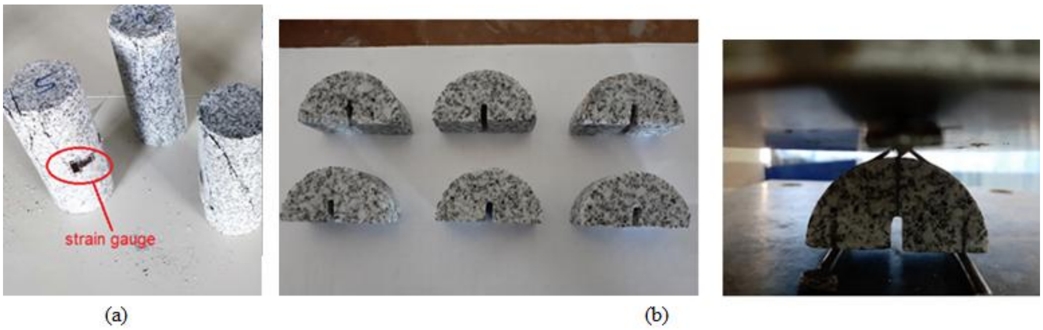

Fig.4. Prepared Bergama granite specimens (a) USC test samples (b) fracture toughness test samples

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.

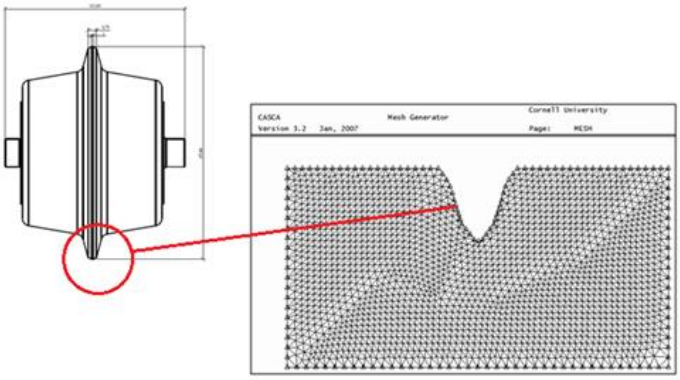

Fig.5. Cutting test geometry and disc tip profile made with the CASCA mesh generator

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

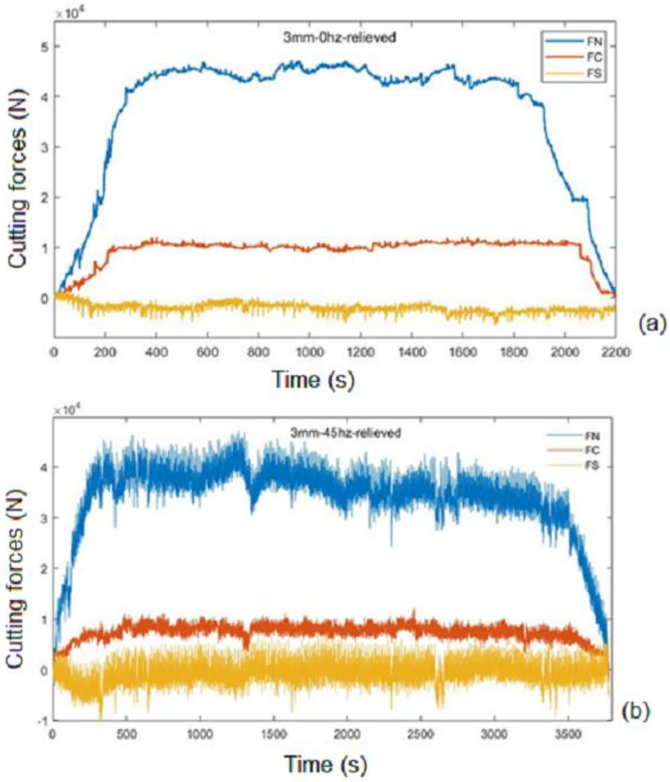

Fig.6. Comparison between (a) cutting forces of disc cutting without oscillation and (b) oscillating cutting with 45 Hz frequency

After mesh and geometry modeling, stress analyzes were performed with the FRANC program. The first modeling series was started with static loading and the Quassi-static loading modeling series was made later. In the first modeling series, unrelieved cutting modeling was performed with a single disc (Fig.7). Fig.7 shows the distribution of the maximum principal stress ($\sigma 1$) in a loaded rock under a single disc. A high tensile stress concentration has occurred in front of the disc tip and a compressive stress concentration has occurred along the side parts of the tip. However, just above this compressive stress zone, another tensile stress zone has formed. These tensile stress zones show the possible initiation of lateral crack formation that cause fragmentation in rock cutting. This result is quite compatible with the results given in the literature because the main crack expected in this type of insert close to the V type is the median crack and it is expected to occur due to tensile stress at the cutter tip [10], [14].

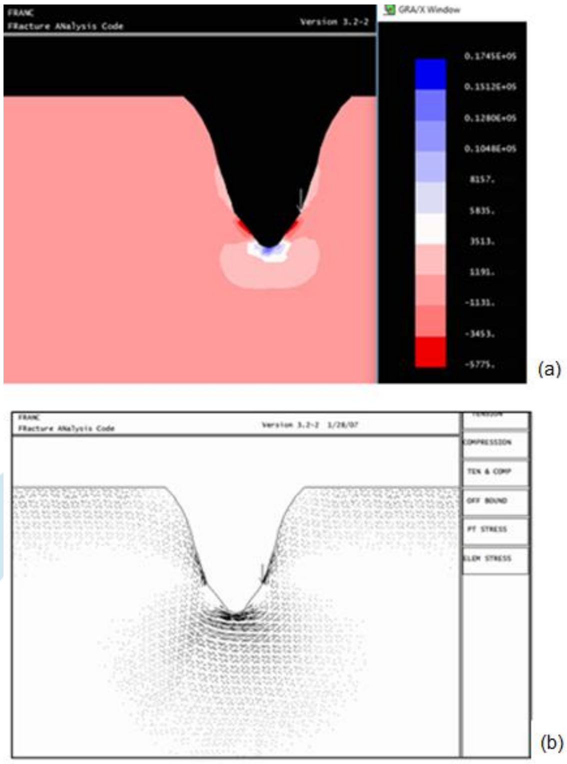

Fig.7. Stress distribution under a disc cutter (a) maximum principal stress (+) values are tensile and (-) values are compressive stresses (b) stress bar display of the tensile stress and concentration zones

Fig.8 shows the numerical analysis result obtained by the FRANC2D program using the Paris criteria. A relieved cutting, that is in the use of adjacent cutters, between two discs is modeled in Fig. 8 and the relationship between crack length and number of cycles is shown. When the crack length is between 6-8 mm, in the low-cycle fatigue graphic, II. It is seen that the stable fatigue crack growth, which is the stage of unstable crack propagation, is passed. This stage happens in about the twentieth cycle. In other words, it can be said that in the cutting experiments performed with the DCD set, rock chips may occur at a frequency of 20Hz. Therefore, it is seen that the numerical analysis done with FRANC give quite consistent results with the experimental data.

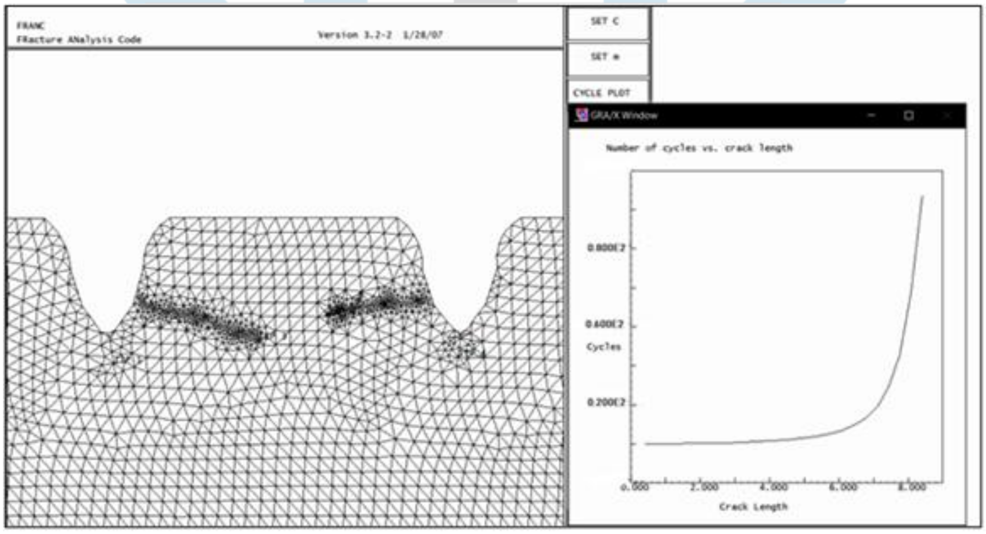

Fig.8. Quasi-static disc cutting modeling using the Paris criterion with FRANC2D

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.9. 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.9. (a) Comparison between the cutting grooves obtained with the DCD and conventional disc cutter (b) cut and

The formation of chips broken out of rock in mechanical rock cutting is the main subject of all rock cutting theories. According to the principles of fracture mechanics, a crack can propagate in any direction that provides the least surface energy and continues to propagate as long as the stress intensity value at the crack tip is above the critical density factor (fracture toughness KIC). This propagation stops when the stress intensity drops below the critical value or when the crack encounters a free surface (which may be another surface). Since the rock cutting process with DCD is a dynamic cutting process, the part breaking mechanism is different from the part formation theory and findings of the vibrationless traditional cutters. Since a technology such as DCD is being developed for the first time in the world, effective mechanisms will be the first to be investigated. In order to explain the damage mechanism that is effective in such a dynamic cutting, dynamic/cyclic indentation and rock fatigue mechanisms, which are the closest studies to this mechanism, were used. In the cyclic sinking mechanism, it is accepted that another cracking series occurs during the first contact of the cutter with the rock surface and during the cracking with the increase of the load and the separation of the cutter from the rock.
A new damage mechanism needs to be explained, with the addition of fatigue cracks and sub-critical cracks in addition to the cracks and crushed zones formed under a non-vibration classical disc cutter. Very high forces are applied to the rock with mechanical cutting machines using disc cutters, and under such high loads, of course, both crushed and crack zones are formed in the rock. If the effect of dynamic loadings such as DCD is added in addition to this situation, it would not be wrong to expect extra damage mechanisms outside of these zones. As a result, the damage mechanism in the rock under an oscillating disc in the DCD system can be explained by these proposed three basic mechanisms: 1) Formation of crushed and cracked zones under the non-oscillating disc cutter 2) A large crushed zone (Fracture Process Zone FPZ) caused by the rock fatigue mechanism formation and extra cracking starting in and around this zone, and 3) extra cracking that occurs when the load is applied and unloaded due to the cyclic indentation mechanism (Fig.10).

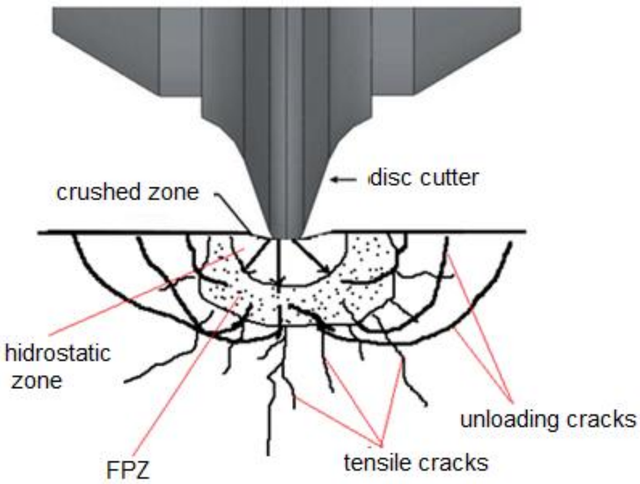

Fig.10. The crushed and cracked zones formed in the rock under the DCD

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], [21], [22]. 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.

IV. CONCLUSIONS

The DCD rock cutting tests performed with the DCD set at 3mm and 5mm vertical distance of cut, 20 Hz and 45 Hz frequencies were completed, and all three cutting forces were recorded successfully. In general, the reduction in cutting forces obtained with 45 Hz vibration is 25%, while the decrease is 20% with 20 Hz. It was attained that the magnitude of the average FN decreased more than FR when the disc oscillated at 45 Hz The reasons for the reduction in the cutting forces and the more material being cut with the dynamic cutter compared to the non-oscillating cutter are explained by the damage mechanisms in the rock-disk interaction zone and the principles of fracture mechanics. According to the experimental and numerical analysis results, there are two effective damage mechanisms in this interaction zone: rock fatigue damage mechanism and cyclic indentation damage mechanism. The FPZ, which is a larger cracked crushed zone, was obtained by the rock fatigue damage mechanism under dynamic disc cutter. It has been determined that the amount of removed rock material obtained by cutting with DCD is almost three times higher than the amount of cut material obtained with a conventional non-oscillating cutter. More cracks occurred with the rock fatigue mechanism and the FPZ resulting in more rock chips than with the non-oscillating conventional 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 DCD cutting compared to conventional vibration-free cutting.

V. ACKNOWLEDGMENT

This study was supported by The Scientific and Technological Research Council of Turkey -Project No:117M738. The Author would like to thank to the EBERK Tunnelling and Foundation Technologies in Turkey.

REFERENCES

[1] Evans, I., 1962. A Theory of the Basic Mechanics of Coal Ploughing, International Symposium on Mining Research, Missouri, 761-798.
[2] Bilgin, N., Çopur, H., ve Balcı, C., 2014. Mechanical Excavation in Mining and Civil Industries, CRC Press, 366 s.
[3] Nishimatsu, Y., 1972. The Mechanics of Rock Cutting, International Journal of Rock Mechanics and Mining Sciences, 9, 261-270.
[4] M. Hood, H. Alehossein, 'A development in rock cutting technology'. International Journal of Rock Mechanics and Mining, vol. 37, pp:297–305, 2000
[5] M. Hood, Z. Guan, N. Tiryaki, X. Li, S. Karekal. 'The benefits of oscillating disc cutting'. Australian Mining Technology Conference: 'New Technologies to Produce More with Less'; 27 - 28 September 2005, Fremantle, Australia, 2005
[6] Y. Nishimatsu, 'The mechanics of rock cutting', International Journal of Rock Mechanics and Mining Science, vol. 9, no:2, pp:261-270, 1972
[7] L.H. Chen, J.F. Labuz. 'Indentation of rock by wedge-shaped tools', International Journal of Rock Mechanics and Mining Science, vol. 43, pp: 1023–1033, 2006
[8] S. Karekal, 'The effect of variable amplitude cyclic loading on hard rock under triaxial stress condition'. PhD thesis, The University of Queensland, Australia, 2000.
[9] H.Y. Liu, 'Numerical modelling of the rock fracture process under mechanical loading'. Licentiate PhD Thesis, Luleå University of Technology, Sweden, 2003.
[10] B. Chiaia, 'Fracture Mechanisms Induced in A Brittle Material by A Hard Cutting Indenter', International Journal of Solids and Structures, vol. 38; pp: 7747-7768, 2001
[11] Haimson, B.C. 1978. 'Effect of cyclic loading on rock'. Dyn. Geotech. Testing ASTM STP, 654, 228–245.
[12] Erarslan, N. 2016. 'Microstructural investigation of subcritical crack propagation and fracture process zone (FPZ) by the reduction of rock fracture toughness under cyclic loading'. Eng. Geol. 208, 181 – 190.
[13] Q.S. Kou, Y. Huang, X. Tang, P.A. Lindqvist, 'Identification of the governing parameters related to the rock indentation depth by using similarity analysis', Engineering Geology, vol. 49, pp:261 – 278, 1998
[14] B.N. Whittaker, R.N. Singh, G. Sun, Rock fracture mechanics: principles, design and applications, Amsterdam, Elsevier, 1992
[15] P.B. Attawel, I.W. Farmer, 'Fatigue behavior of rock' International Journal of Rock Mechanics and Mining Geomechanics Abstracts, vol. 10, pp:1–9, 1973
[16] M.N. Bagde, V. Pedros, 'Fatigue and dynamic energy behavior of rock subjected to cyclical loading'. International Journal of Rock Mechanics and Mining Science, 46, pp:200–209, 2009
[17] N. Gatelier, F. Pellet, B. Loret, 'Mechanical damage of an anisotropic porous rock in cyclic triaxial tests'. International Journal of Rock Mechanics and Mining Science, vol. 39, pp:335–354, 2002

[18] N. Erarslan, 'Static and Cyclic Laboratory Testing of Brisbane Rocks'. PhD Thesis. The University of Queensland, Australia, 2011
[19] R.O. Ritchie, Y. Murakami, Comprehensive Structural Integrity, Elsevier, Boston, MA, 2003
[20] P. Kumar, M. Makhatha, E. Srijan, A.K. Sengupta Dutt, 'Prediction of the Propagation of Fatigue Cracks in Part-Through Cracked Pipes with CASCA and FRANC2D'. Transactions of the Indian Institute of Metals, vol. 73, pp: 1417–1420, 2020
[21] E.Z. Lajtai, E.J. Scott, B. Duncan, J. Carter, 'The effect of strain rate on rock strength'. Rock Mechanics Rock Engineering, vol. 24, pp:99–109, 1991.
[22] X. Li, D. Gu, Rock impact dynamics, Central South University of Technology Press, Changsha, China, 1994
[23] A. Ingraffea, 'Case studies of simulation of fracture in concrete dams' Engineering Fracture Mechanics, vol.35, 1-3, pp: 553-564
[24] ISRM 2015. The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014, Ed. R. Ulusay, Springer 2015, Switzerland