International Journal of Rock Mechanics and Mining Sciences 107 (2018) 191–200

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Rolling disc model for rock cutting based on fracture mechanics

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ARTICLE INFO

Keywords:
Disc cutter
Thrust force
Fracture toughness
Mixed-mode fracture
Edge crack

ABSTRACT

A rock cutting by a TBM's rolling disc model based on Linear Elastic Fracture Mechanics is considered in this study. From dimensional considerations the factors that primarily influence the normal force exerted by disc cutter mounted on the cutterhead of a rock TBM are: (i) the fracture toughness of the rock itself that controls the propagation of a critical initial crack leading to chipping, (ii) the disc's tip shape that also influences the ratio of normal force to the lateral force and the ratio of the normal force to the rolling force, and (iii) the disc's penetration depth that also depicts together with the disc radius the contact area, and (iv) the spacing between adjacent cuts. The hardness of the rock is then calculated by dividing the normal force with the contact area. These parameters are considered here as the main input parameters for the simulation of the quasi-static propagation of a lateral crack that gives a rock chip starting from the disc towards the adjacent kerf created by the neighboring cutter under the action of a concentrated load. In this first order approach we assume that the size of the starter crack over the penetration depth ratio remains constant. For the accurate computation of the mode-I and mode-II stress intensity factors at each crack growth increment, we have employed the displacement discontinuity numerical method equipped with a special crack tip element based on strain gradient or grade-2 (g2) elasticity theory. Mixed-mode crack growth obeys either the energy balance criterion or maximum tangential tensile stress criterion. The numerical results are then compared with published linear cutting rig test results on four rock types. The accuracy of the maximum tensile tangential stress criterion is better compared to the energy balance criterion. However, even with the simplest self-similar crack growth fracture criterion based on energy balance, we have found acceptable agreement of numerical with experimental results by assuming only one free parameter, namely the mode-I fracture toughness of the rock. It is thus recommended that the rock characterization for disc cutting processes should be done not only by the uniaxial compression and indirect tension tests, but also with a proper fracture mechanics test according to the ISRM Suggested Methods for the determination of the rock fracture toughness.

1. Introduction

Hard rock excavation with a tunnel boring machine (TBM) is performed by the indentation and rolling of certain number of disc cutters which are mounted in a certain arrangement on the front of the cutting wheel. The cutters may have a wedge or V-shaped tip or constant cross-section with flat tip. As the cutting wheel rotates each rolling disc contacts the face along a different circular path. The average spacing between adjacent grooves or kerfs can be found from the circular traces of the disc cutters on the tunnel's face. In simple terms, the mechanized rock excavation is performed by the machine which generates thrust to push the cutting wheel forward until penetration of the cutters at a certain depth and at the same time supplies sufficient torque to turn the wheel against the tangential forces resisting the rolling of discs and indentation. Since the cutting discs are used to transfer the energy from the machine to the rock, it may be realized that a central place in predicting the performance of a boring machine referring to the advance rate, and unit excavation cost, holds the model for the calculation of the cutting forces.

The disc cutting process involves initially indentation of the disc into the rock accompanied with heavily damaged powdered rock material around the contact zone with the disc, formation of radial cracks beneath the tip of the cutter for pre-conditioning the indentation of the cutter in the next pass (the radial tensile crack directly below the tip called "median vent") and later after the passing of the rolling disc above the area, the unloading of the rock around the contact region of the cutting edge that is responsible for the closure of the median vent but on the other hand for imposing sufficiently large tensile stresses leading to the formation of inclined and gently inclined tensile radial cracks called "lateral vents" or "radial vents".[1] At a subsequent stage

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https://doi.org/10.1016/j.ijrmms.2018.04.056
Received 24 November 2017; Received in revised form 26 April 2018; Accepted 28 April 2018
Available online 24 May 2018
1365-1609/

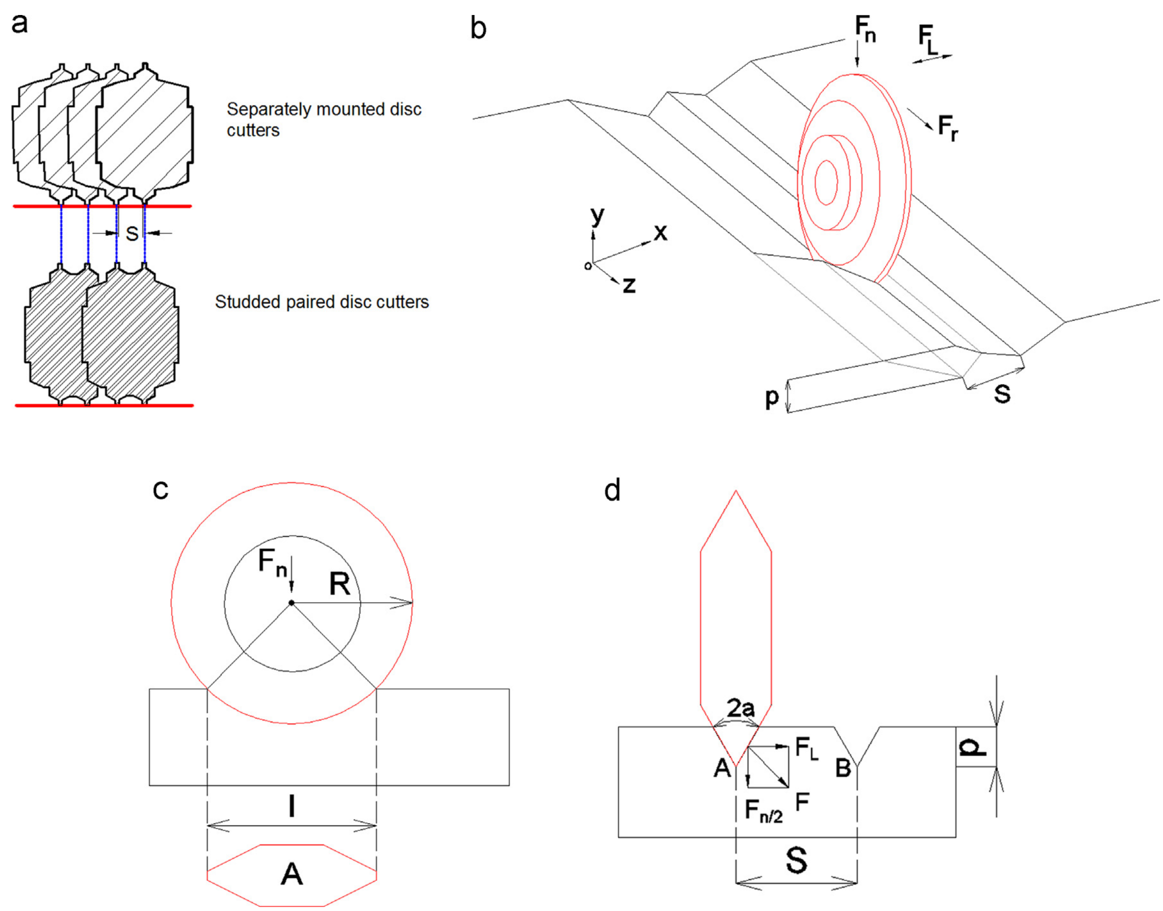

Fig. 1. (a) Two alternative roller disc cutter mounting commonly in use today, (b) Forces exerted on a rolling disc in an isometric view of the cutting process. (c) side view of the disc cutter and projected contact area, and (d) front view of the wedge shaped disc with normal and lateral forces and geometry.

one or more mixed mode I-II cracks (i.e. mode I and mode II) propagate more or less parallel with the free surface towards the neighboring newly formed groove or free surface that finally lead to chip formation. In this manner one expects that the chips have a width of the order of kerf spacing S, thickness of the order of disc penetration p, and length one to three times the chip width.[2] In some cases of large penetration depths p, the path of the mixed-mode crack is concave upwards leading to "undercutting".[3] As is displayed in Fig. 1a that shows two alternative disc cutter configurations on the cutterhead the disc cutting neighboring kerfs are not loaded at the same time, i.e. there is already a kerf at distance S from the neighboring rolling disc in order to facilitate crack propagation towards this kerf and subsequent chip formation. The sketches of Fig. 1b-d illustrate the basic force and length parameters involved in the disc cutting process.

A large number of empirical, analytical or computational models have been developed in the past for the prediction of disc cutter forces in Linear Cutting Rigs (LCR) and TBM's. Below we outline the most applicable models which are also relevant with this study.

One of the first disc cutting models has been proposed by Roxborough and Phillips[4] for a wedge disc cutter. These investigators proposed that the normal force F_n that should be exerted on the disc having a 'V-profile' (or wedge-shaped section) with a wedge angle φ (e.g. Fig. 1c) in order to penetrate into the rock at a depth p (i.e. Fig. 1a) is the product of the UCS (Uniaxial Compressive Strength) of the rock with the projected contact area A of the disc (Fig. 1b). Also based on the assumption of straight mode-II crack path extending at a distance S between neighboring cuts the model predicts that the ratio of UCS to the shear strength of the rock is equal to the S/p ratio. Other early but worth mentioning prediction models for single V-shape disc cutters were also proposed by Sanio[5] and Sato et al.[6]

The Colorado School of Mines (CSM) model[7,8] considers both the wedge and constant-section disc profiles and admits any pressure profile acting along the disc-rock contact area. The CSM model gives the analytical expression for the contact pressure accounting for the effect of spacing S of neighboring cuts, the penetration depth, the width of the cutting tip, the UCS and TS (tensile strength) of the rock. It also contains an empirical dimensional constant to match experimental data. Based on an appropriate assumption of the contact pressure distribution i.e. uniform, linear or parabolic, the normal and rolling forces are subsequently estimated from the known contact pressure. This model have been used for the estimation of the TBM cutterhead performance in many tunneling projects with a high degree of success.[9–11]

Another way to predict the cutting forces exerted to the rock when a disc cutter acts alone (unrelieved cutting) or with a neighboring cut (relieved cutting) is by using the theorems of limit analysis[12] and first principles of Damage Mechanics[13] to account for the pre-existing cracks in rock masses in the continuum model for the rock. A model that rests on a modified Mohr-Coulomb failure model with arbitrarily small tensile strength, the upper-bound limit analysis theorem for such a geomaterial and damage mechanics to consider the effect of pre-existing cracks on the intact rock strength parameters, has been recently proposed and validated against some real-life TBM registered data.[14] Apart from the disc features, arrangement on the cutterhead, and the penetration depth per revolution, the rest input rock parameters for the prediction of cutting forces by this model are: (1) the Bieniawski's RMR (Rock Mass Rating) or Barton's Q rating or Hoek's GSI index, (2) the uniaxial tension strength (UTS), (3) the UCS, and (4) the internal friction angle of the rock that is not considered by all previously referenced models.

Regarding computational modeling of the disc cutting process one