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Studies on the formation of discontinuous rock fragments during cutting operation

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ABSTRACT

A rock fragmentation process is simulated during mechanical cutting of rock using an explicit finite element code, LS-DYNA. In the simulation, a cutting tool is orthogonally moved against stationary rock materials made of sandstone and limestone. Rock material properties have been incorporated using an advanced damage constitute material model. Simulations were performed for various rake angles at different cutting velocities and cutting depths. The variation of cutting forces, stresses, rock fragment morphology and the character of fragment formation have been investigated. Overall, the results indicate that the explicit FEM is a powerful tool for simulating rock cutting and the fragmentation process. More specifically, the separation of rock fragments from the base rock slab was accurately predicted using the numerical model. The cutting forces and rock fragment characteristics were strongly influenced by rake angle when compared to cutting tool velocities for a given depth of cut. This information is shown to be highly pertinent to better understanding cutting rates and tool wear.

1. Introduction

As the oil and gas industries attempt to drill for reserves at greater depths, it is extremely important to better understand the tribological interactions between the cutting tool and the embedded rock. This is because reaching deep oil and gas reserves requires the continual cutting of rock at extremely high pressure and high temperature (HPHT) conditions. Decreased penetration rates in deep HPHT drilling has been identified by many drilling experts as one of the most important factors threatening the future of the deep gas drilling market. There is a significant demand for improvement in rock drilling technology to accomplish higher penetration rates and longer tool life, which depends to a large degree on the understanding of the tool-rock cutting process.

Many experimental investigations have contributed to a better understanding for the rock-tool interaction, tool wear, and thermal behavior during cutting using a PDC (Polycrystalline Diamond Compact) cutting tool [1–5]. Since experiments are usually costly to run and it is difficult to directly observe the rock fragmentation removal process, numerical simulations have been performed to elucidate rock-tool interaction during rock cutting. Various numerical models such as the Finite Difference Method (FDM) [6–11], the Finite Element Method (FEM) [12–32], the Discrete Element Method (DEM) [33–36], and the Boundary Element Method (BEM) [37,38] have been employed in the past for modeling of rock-tool interaction problems. McKinnon and Barra [7] performed numerical investigations using FDM. The authors [7] incorporated Fast Lagrangian Analysis of Continuum (FLAC) code in the FDM to study the relationships between fracture initiation, growth, stress field and boundary conditions. It was found that the fracture development in a region undergoing deformation may vary significantly depending on whether the boundaries were confined or unconfined. No chip formation was detected using this numerical code. Kou et al. [20] simulated the failure process of rock cutting by using two-dimensional plane strain Rock Failure Process Analysis (RFPA) which is a simple FEM code. This model qualitatively predicted the considerable damage occurring locally, under and ahead of the cutter, the dipping tensile fractures that were the characteristic damage signature. The model also predicted the development of variously shaped chips ahead of the cutter. However, it can be believed that there will be a major problem for adopting RFPA in rock cutting simulation as the failed elements were not really separated from the intact elements and after a larger strain the method will fail to work. Although, RFPA model appears to be an attractive and simple means but is limited to only in the investigation of initial failure mechanism. Cho et al. [31,32] studied the rock fragmentation process using explicit finite element code, AUTODYN-3D. In these simulations, cut rock volumes were determined by use of an erosion option that was available in

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the simulation code whereby rock elements that reached tensile failure level during simulation were immediately eliminated. Cut rock volumes were simply calculated from the removed (eroded) mass during modeling. Huang and Detournay [35] studied the rock-tool interaction using DEM (2D) with Particle Flow Code (PFC) to analyze failure mechanisms in indentation and cutting of rocks. The authors concluded that the rock fragments can be simulated using the DEM. Tan et al. [37] used a Displacement Discontinuity Method (DDM) which is an indirect BEM to simulate cracks and chips formation process by indentation tools. The results showed that chips were formed by multiple mechanisms of either tension or shear, or their combinations. However, chip separation was not detected in this study.

In this study, rock-cutting simulations were performed using an explicit FEM approach as it is more advanced and versatile than the other methods. The most important feature of the FEM is that the chip formation mechanism can be studied at the micro level. The FEM can also provide detailed information on the distribution of temperature, stresses, strains and strain-rates in the chip formation zone. In earlier efforts [17–20], chip formation has been investigated using the FEM technique. The chipped rock fragments, however, were not separated from the work-piece because of the limitation of the numerical method. In addition, most of these simulations are either "in-house" codes or with subroutines, which significantly limit their availability to the engineering community. Thus, in the present investigation, chip fragmentation process was studied using commercially available FEM code, LS-DYNA. The simulations were carried out for a wide range of rake angles, depths of cut, and cutting velocities. The cutting forces, distribution of stresses and morphology of discontinuous rock fragments separated from the base rock have been studied.

2. Material and methods

All simulations were performed using an explicit non-linear finite element code, LS-DYNA. In the simulations, a tool and a base rock slab were considered for modeling. The base rock slab was modeled as a rectangular block of 50 mm in length and 20 mm in height. Two-dimensional quadrilateral elements were implemented for both the cutting tool and base rock. A mesh of 9550 nodes and 9201 elements were used. The displacement boundary conditions applied to the finite element model were as follows: (a) the bottom nodes of the base rock slab were fully constrained in *X*-, *Y*-, and *Z*-directions, (b) the base rock slab was constrained in the *Z*-direction and (c) the cutting tool was constrained in the *YZ* plane. The cutting tool had a rake angle, α, of $+15^\circ$, 0° and -15°. The relief angle of the cutting tool was 15°. The cutting tool was moved against the stationary base rock slab at sliding velocities, v, of 0.1, 1, 4, 10, 50 and 100 mm/s in the horizontal direction. These velocities were specifically chosen as similar range of cutter velocities has been utilized for rock cutting process [39,40]. For a given sliding velocity, the simulation was performed for depths of cut (d) of 1, 2, 3 and 4 mm. The deformation of the cutting tool was assumed to be negligible compared to the base rock slab. Material type RIGID_20 [41] was assigned to the cutting tool and the Damage constitutive law material type MAT_105 [41] was used for the base rock slab. The damage constitutive law adopted in the models allows the defining of advanced parameters for the tool's penetration into the base rock slab and for the fragmentation of the rock. The material properties assigned for the cutting tool and the base rock slab are presented in Table 1. Two types of rock materials, sandstone and limestone, were considered in the present investigation. The cutting tool and the base rock slab contact interface was simulated using automatic two-dimensional node to surface contact. The friction factors (static and dynamic) are assumed to be 0 (friction less sliding) in the contact model.

Table 1
Properties of tool and rock materials [42].

	Materials	Density (ρ) kg/m^3)	Young's modulus (E) (GPa)	Poisson's ratio (ν)
Cutting tool	Steel	7830	210	0.30
Base rock slab	Sandstone	2000	7.453	0.33
	Limestone	2700	15	0.20

Table 2
Input damage parameters for Mat_105.

Damage parameters	**Values**
Damage threshold (r_D)	0.003
Damage strength (S)	1.0
Critical damage value (D_c)	1.0×10^{-3}

It is well known that at the initial stage of rock cutting, intense crushing of the rock occurs and only then as cutting progresses cracks generated at a certain depth in the rock, leading to the formation of rock fragment. The formation of rock fragments is one of greatest interests, since precisely at this stage the maximum effectiveness of fracturing is achieved [43]. To predict both the initiation of a fracture (location, size) and further propagation of the crack (growth path), it is necessary to know in detail the stress field, which is highly dependent on the material model performance. Thus, one of the biggest challenges associated with modeling the behavior of rock cutting is the difficulty of incorporating a realistic material model that can accurately represent the physical system. The material damage model incorporated in the material database library of LS-DYNA has the ability to separate rock fragments from the base rock. Hence, in the present investigation, the damage material model is considered.

In LS-DYNA, the MAT_105 damage model [41], incorporated in the material library, is basically an elastic visco-plastic material model combined with the continuum damage mechanics (CDM). The CDM model was proposed by Lemaitre [44]. The effective stress, $\bar{\sigma}$, which is the stress calculated over the section that effectively resists the forces can be related to the damage variable (D) and stress tensor (σ) and is defined by

$$\bar{\sigma}=\frac{\sigma}{1-D} \tag{1}$$

The evolution equation for the damage variable is defined as

$$\dot{D}=\begin{cases}\frac{Y}{S(1-D)}\dot{r} & for\ r>r_D\ and\quad \sigma_1>0\\ 0 & for\ r\le r_D\end{cases} \tag{2}$$

where r_D is the damage threshold, $\dot{r}$ is damage governed by plasticity, S is a damage strength, Y is the damage strain energy release rate, and σ_1 is the maximum principal stress. The damage strain energy release rate (Y) is given by

$$Y=\frac{\sigma_{vm}^2R_v}{2E(1-D)^2} \tag{3}$$