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A probabilistic approach for assessing failure risk of cutting tools in underground excavation

Yong Sun*, X.S. Li

CSIRO Energy, PO Box 883, Kenmore QLD 4069, Australia

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ABSTRACT

Accurate assessment of failure risk of cutting tools is essential to the optimization of cutter and drum design as well as the operation of mechanical excavators. In reality, factors involved in the risk assessment often have many uncertainties, e.g., the variations in rock properties and cutting tip material properties. In current practice, these uncertainties have not been considered adequately. The conventional deterministic approach based on mean values or extreme values normally generates a binary assessment (safe or unsafe) and can lead to over- or under-estimation of cutting tool failure risks. To address this issue, a probabilistic risk assessment approach is proposed in this paper, with a case study on the application of the proposed approach to the failure probability assessment of cutting tools for underground roadway development with a continuous miner. In this approach, the property variations of cutting tools and rock are modelled using probability theory, the continuous rock cutting process is discretized, and the failure risk of cutting tools is estimated based on reliability theory. The new approach enables designers and operators to estimate how likely a cutting tool would fail in a given operational condition, and then adjust their design and operation decisions accordingly to achieve an optimal balance between cutting productivity and cutting tool failure risk.

1. Introduction

The efficiency and reliability of cutting tools (picks) play an important role in underground excavation machines, e.g., continuous miners, roadheaders and other mechanical excavators. Accurate assessment of the failure risks of cutting tools is essential for optimal maintenance and operation of the mechanical excavators. The research on the performance and safety of rock cutting tools has attracted great attention of both researchers and engineers from different facets such as cutting pattern (Hurt and Morris, 1982), cutting tool wear (Barzegari et al., 2015; Li and Boland, 2005; Rogers and Roberts, 1991), cutting forces (Evans, 1984; Goktan, 1997; Liu et al., 2009; Yilmaz et al., 2007), DOC (Hurt and Morris, 1982; Liu and Roxborough, 1996; Sun et al., 2012; Sun and Li, 2013), cut interactions (Sun and Li, 2012a), cutterhead vibration (Huang, 2010), numerical simulation (Rojek et al., 2011) and the influence of rock properties on cutting tool performance (Bilgin et al., 2006). In current practice, the failure risk of a cutting tool is generally assessed by a deterministic approach. In this approach, the minimum or mean allowable force obtained from samples of specific types of cutting tools is generally used as the allowable force for each tool population, and the maximum or mean force expected in each application is usually taken as the force acting on the tool. When the exerted force is less than the allowable force, the cutting tool is regarded as safe; otherwise, it is unsafe. However, in underground excavation/mining, factors involved in the failure risk assessment often have many uncertainties. For example, during underground roadway development, rock cutting often encounters large areas where the rock mass properties can vary considerably. In addition, the conditions of cutting tools can also have a large variation. In this case, the conventional deterministic risk assessment approach cannot provide sufficient analytical accuracy.

To address this issue, a probabilistic approach is proposed in this paper by modelling the variations in the acting and allowable forces on cutting tools and to estimate the tool failure risks under a given operational condition using reliability theory. Unlike the binary assessments (safe or unsafe) used in the conventional deterministic approach, the new approach estimates the reliability (or failure probability) of a cutting tool to help engineers and operators understand how likely the tool would fail in a given operational condition. Reliability-based or risk-based assessment has found successful and effective applications for many other engineering assets such as bridges (Stewart, 2001), pipelines (Sun et al., 2009), roofs (Ghasemi et al., 2012), rock slopes (Pine

Abbreviations: DOC, Depth of Cut; TSDC, Thermally Stable Diamond Composite; UCS, Uniaxial Compressive Strength; BTS, Brazilian Tensile Strength; PDF, Probability Density Function

* Corresponding author.
E-mail addresses: yong.sun@csiro.au (Y. Sun), xing.li@csiro.au (X.S. Li).

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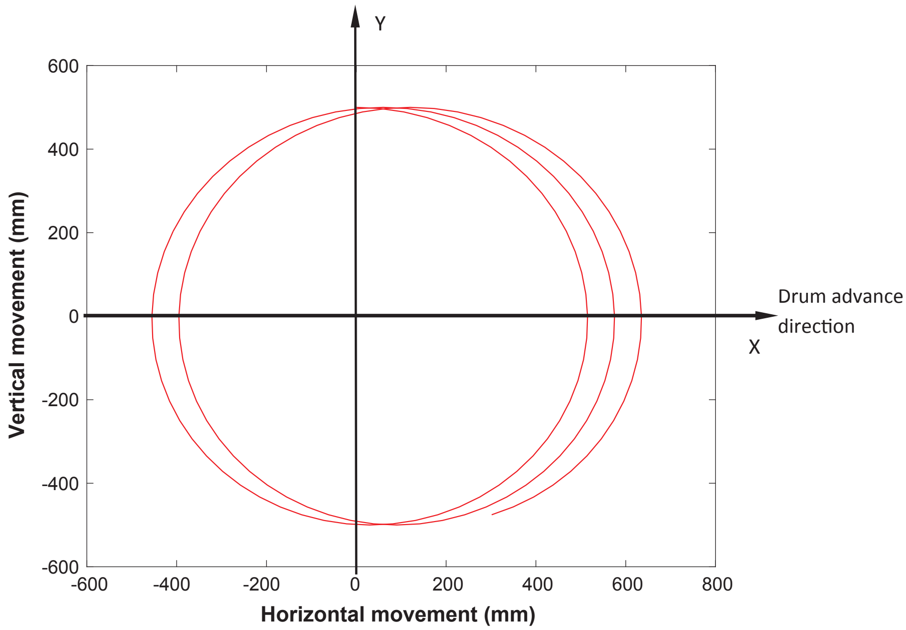

Fig. 1. Locus of a pick during continuous cutting (modified from Sun et al., 2012).

and Roberts, 2005), settlements caused by tunneling (Camos et al., 2016) and cutting tools for manufacture (Salonitis and Kolios, 2013), but it has never been applied to cutting tools used on underground mining machines. Rock cutting tool reliability analyses have not been systematically conducted.

The development of probabilistic approach in this paper is demonstrated and validated through a case study on the picks with cutting tips made from TSDC. TSDC was chosen because it is a relatively new material with high wear resistance, high hardness, high compressive strength and high thermal stability (Li et al., 2008). It hence has been proposed to replace tungsten carbide (WC) as cutting tips in picks for hard rock cutting (Li et al., 2011). However, as a relatively new material, the manufacturing technology of TSDC cutting tips is still being developed. As a result, the material properties of TSDC cutting tips often fluctuate within a considerable range, and a probabilistic method should be applied to analyze the failure characteristics of the TSDC-tipped tools.

The probabilistic risk assessment approach has been discussed in authors' previous paper (Sun and Li, 2012b) under the condition that forces acting on pick tips are deterministic and time-independent. Furthermore, in (Sun and Li, 2012b), only failure probabilities at individual cutting moments have been considered. In this paper, a new approach is proposed to include the condition that exerted forces on picks also vary randomly because of the uncertain properties of rock during a rock cutting process. Besides, instead of considering individual cutting moments, the failure probability of cutting tools during the cutting process is investigated.

The remainder of the paper is organized as follows. Section 2 presents the fundamental procedure of the proposed probabilistic risk assessment approach and Section 3 demonstrates the application of the approach through a case study which is followed by conclusions in Section 4.

2. Probabilistic risk assessment approach

In underground excavation such as underground roadway development for coal mining, cutting tools (normally picks) often have different failure modes, including cutting tip damages such as tip wear, tip crack and tip snap off, and tool body damage such as body wear and body bending. Cutting tool failure can be caused by one or a combination of these failure modes (Sun and Li, 2014). These failure modes result from various causes. One of the major causes is that the force acting on a cutting tool during mining operation exceeds its allowable force (or strength). Cutting tool failure risk due to this type of cause is the focus of this study. In addition, the following analysis is mainly based on underground roadway development for coal mining with continuous miners. However, the developed method can be extended to other scenarios.

Note that risk is generally described as a combination of occurrence likelihood of an event (here it is a failure) and its consequence (Standards Australia/Standards New Zealand, 2009). Failure risk is often calculated using the product of failure probability and the failure consequence (Ghasemi et al., 2012). When the consequences of failures are the same, the risks of the failures are directly proportional to their probabilities. Hence, risk assessment herein focuses on the estimation of the failure probability of cutting tools during rock cutting operation.

2.1. Rock cutting process in mining operation

Underground roadway development with a continuous miner is normally composed of a number of cutting cycles. In underground coal mining, a cutting cycle often refers to the drum movement for cutting the whole face including sumping into to cut roof, shearing down to cut seam and floor, and moving backwards to clear the floor. To avoid confusion, the cutting cycle herein only indicates this cyclic movement. To implement a cutting cycle, a drum normally needs to rotate a number of revolutions.

Fig. 1 shows a track profile or locus of a cutting tip during a rock cutting process, with advance of 60 mm per revolution of the drum and without considering the change of the drum advance direction (Sun et al., 2012). The area cut by the tool in one revolution of the drum typically has a shape similar to a crescent moon (Fig. 2). As a result, the DOC of a tool during a revolution of the drum changes from zero to the maximum and back to zero. The change of the DOC is affected by drum's tip-to-tip diameter, rotational speed and advance speed (i.e., the advance speed of the drum center along the cutting direction), and will generally result in changes to the forces acting on the tool.

2.2. Forces acting on a cutting tool

During rock cutting, there are three orthogonal forces acting on the tip of a cutting tool as shown in Fig. 3. In this figure, the cutting