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Experimental investigations on deformation of soft rock during cutting

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ABSTRACT

An experimental study has been made on the deformation of model soft rocks during orthogonal cutting. Through high resolution imaging of orthogonal cutting experiments under 2-D plane-strain conditions, and consequent image analysis, using particle image velocimetry (PIV), we present the evolution of deformation during the cutting process. In addition to examining the deformation fields, and by analysing force signatures, we examine the effect of tool geometry and the depth of cut on the mechanics of cutting in porous brittle solids. In tracking the deformation continuously, we identify the process of fracture initiation and propagation, as well as the corresponding formation of chips. The cutting force was influenced by depth of cut in far more significant way at negative rake angles. We further demonstrate two types of cutting mechanisms occurring with change in tool geometry and draw correspondence between initiation and propagation of fractures and the cyclic nature of force signatures. In the case of machining at negative rake angle, in addition to cyclic increase and decrease of the cutting force, a clear development of a triangular dead zone at the tool tip is measured and the size of this zone also varies cyclically. The volume change occurring in this dead zone formed at the tool corner during negative rake angle cutting is also tracked. By using image analysis, and isolating the geometry of the crack developed during the experiments, we find that the length of crack propagated during cutting of porous brittle solids is a function of the deformation geometry. The effect of rake angle being far more prominent than the depth of cut. The experiments also show that the extent of surface and subsurface deformation during cutting is limited, and the deformation is localized.

1. Introduction

Drilling, especially in brittle solids such as rock is often encountered in the petroleum and mining sectors in extraction of hydrocarbons, in pile driving in the infrastructure sector and in biomedical sectors in drilling of hard tissue (e.g., teeth, bone). The deformation in a porous brittle solid is complex because of the propensity for localization, fracture and simultaneously occurring volume change during large deformations. Optimal and efficient execution of drilling necessitates a deep understanding of interaction of various dynamic and kinematic variables, which include constitutivity of the solid, geometry of the drill, weight and torque on the drill bit, among others. The advent of polycrystalline diamond compact (PDC) cutters used in drilling of rocks has only underscored the need for a deeper understanding of the interaction between an individual cutter and the solid. An oft-used approach is to decouple the mechanics of drilling into cutting and indentation.[1] Such understanding of the mechanics of cutting and indentation have contributed to optimizing drilling across a range of solids.

The mechanics of severe plastic deformation processes of indentation, cutting and drilling in metals[2–4] have provided the necessary theoretical backing for furthering the understanding of deformation processes in a variety of solids. Porous brittle solids (e.g., soft rocks), due to their complex constitutivity, offer further challenges such as fracture, pore collapse in addition to severe plastic deformation.

The orthogonal cutting configuration, especially in metals, has offered an ideal platform for a comprehensive understanding of the mechanics of severe plastic deformation in a 2-D platform, affording a construct to study the effect of strain, strain rate and the dissipation of temperature.[5] Most of the understanding gained on the mechanics of severe plastic deformation in orthogonal machining of metals has been made by post-mortem analysis of the chip. More recently, utilization of image-based measurement techniques, along with particle image velocimetry (PIV), has opened new doors of understanding[6,7] regarding the mechanics of severe plastic deformation in metals and other solids. Additionally, dynamics of the material-tool interaction, quantification of the deformation, chip characteristics, shear band properties and fracture induced in the material through direct observations have all

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been observed through image-based measurement techniques.

The mechanics of cutting in rocks, representative of a class of natural porous brittle solids, have been analyzed mostly through empirical relationships specifically for certain rock formations. Rigorous analytical and experimental studies have been few and far between. This paper focuses on establishing a physical understanding of the mechanics of cutting in porous brittle solids using image-based experimental measurements. We report a series of orthogonal cutting experiments on a model porous brittle solid. The experiments were conducted by varying generalizable processing parameters in terms of tool geometry and the depth of cut. Images of the region around the tool were captured in time and were analyzed using a particle image analysis algorithm. We further report occurrence of various mechanisms of material removal when the geometry of the cutting configuration is modified.

2. Background

The physics and mechanics of metal cutting since the days of its inception have focused around *ex situ* analyses, including observations of segmented chips, surface folds, wrinkled surfaces, among others. Traditionally, grid-deformation techniques have been used to measure strain in the metal undergoing orthogonal cutting. Parallel marker lines or circles were inscribed on the surface of the metal normal to the cutting direction and the strain was measured by measuring the deflection of the marked lines or the deformation of the circles into ellipses.[8–10] These techniques provided quantifiable measures of the final/overall deformation with very little recourse for elucidating the history of the deformation. More recently, the use of image-based measurement techniques have facilitated accurate, in situ measurement at high temporal and spatial resolution of localization features such as surface folds and regions of intense strain rate.[6,7] These developments in metal cutting have the potential for informing a high fidelity understanding of the mechanics of cutting in more complex materials, such as that occurring in glass fiber reinforced composites, glass, ceramics, porous brittle solids (e.g., rocks).

Glass is often used as a model system for studying brittle solids. In the cutting or machining of glass, the depth of cut employed governs whether the fundamental material removal mechanism occurs in a ductile or brittle mode. In a series of orthogonal cutting experiments on glass,[11] the depth of cut was continually increased by tilting workpiece specimens by a small angle. It was observed that at lower depths of cut, the material removal occurred predominantly through plastic deformation of the workpiece (ductile mode) and at higher depths of cut, the material spalled out of the glass through brittle fracture (brittle mode). Complimentarily, Chiu et al.[12] have also used an analytical model for a crack propagating along an interface parallel to the free surface during cutting. These finite element analyses have also shown that the crack initially moves parallel to the surface of the material and as the bending moment on the crack tip increases, the crack trajectory moves towards the free surface resulting in removal of the chip.

Mishnaevsky[13] developed a mathematical model using the concept of the energy required for spalling of a chip element, for cutting of brittle materials and derived the expressions for cutting force, depth of damage zone and energy required for the spalling of the chip. This model was backed by experimental observations made during cutting of brittle materials. More recently, analytical and experimental work on brittle solids, such as glass fiber reinforced composites and bulk metallic glasses, have also been studied through cutting experiments. Soldani et al.[14] and Arola and Ramulu[15] reported a series of 2-D finite element (FE) simulations for orthogonal cutting of Long Fiber Reinforced Polymer (LFRP) to determine the effect of numerical parameters, with validation by experimental results on orthogonal cutting of unidirectional graphite epoxy composite. The effect of numerical parameters (e.g., mesh orientation, energy required for breakage of a mesh element) and tool geometry (e.g., rake angle, cutting edge radius) were analyzed in these studies. From these results, thrust and cutting forces increased with decrease in rake angle and increase in cutting radius. Further, these FE simulations showed that the chip morphology was influenced by rake angle and energy needed for the breakage of an element.

Rocks, which are another important class of porous brittle solids, also show a transition from ductile to brittle response when subjected to large deformations, such as that occurring in cutting. FE analysis of rock cutting has revealed some very interesting physics of the response, including transition from ductile to brittle response and the role of individual process parameters. The rake angle and depth of cut used in rock cutting have been shown to have a significant influence on cutting force and chip formation.[16,17] In that, cutting forces increased with increase in depth of cut and decrease in rake angle, while the velocity of cut did not have a primary influence on the cutting force. Similar FE modelling was performed to study the cutting by a single PDC cutter[18] and has also been extended to 3D using both FE and DEM simulations.[19–21] The change in behaviour from ductile to brittle response in rocks depends on the depth of cut of the material and is related to the characteristic length $l = K_{IC}/\sigma$ where K_{IC} is fracture toughness and σ is the uniaxial compressive strength of the material.[22–24]

Grima et al.[25] studied the effect of hyperbaric pressure on the material removal mechanism of rocks. It was observed that at higher ambient pressure, the chip formation was dominated by shear failure and at low ambient pressure the chip formation was dominated by tension cracks. Rock fragmentation in orthogonal cutting is affected by the rake angle and depth of cut, and is independent of cutting speed.[17] The cutting force increases with increase in depth of cut and decrease in the rake angle. Various experimental studies have focused on understanding the effect of cutting tool geometry,[26–28] friction between

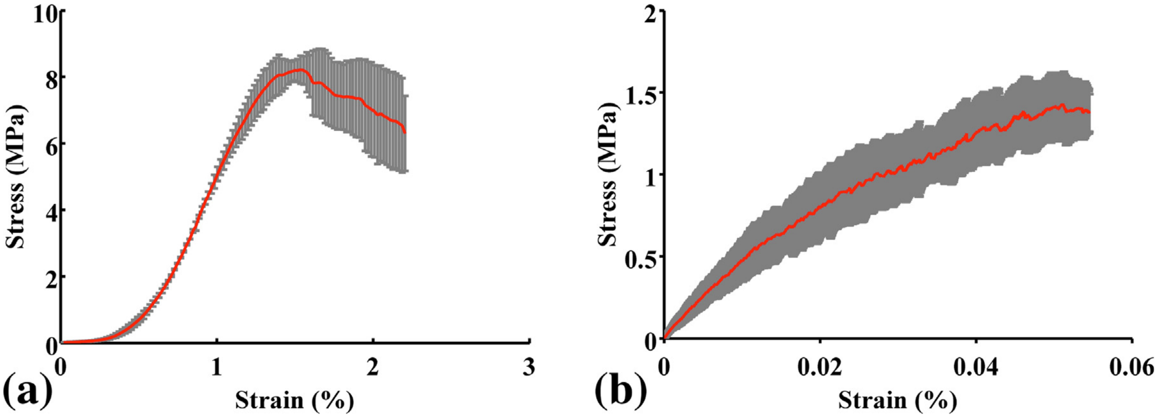

Fig. 1. Stress-strain curve for 52% porosity samples showing (a) compressive, (b) tensile stress.