Procedia Manufacturing
Volume 1, 2015, Pages 644–654
43rd Proceedings of the North American Manufacturing Research Institution of SME http://www.sme.org/namrc

Finite Element Analysis of Machining Damage in Single-Grit Grinding of Ceramic Knee Implants

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Abstract
Alumina is a common biomaterial used for knee implants due to its excellent biomechanical properties. However, the complex geometry and required surface integrity make precision machining of knee implants very difficult. Machining mechanics and damage mechanism is not well understood. In order to better understand the mechanism of alumina grinding, this work presents a numerical simulation of single point grinding of alumina at a shallow depth-of-cut. A 3D finite element model of single-grit ceramic grinding has been developed using the pressure dependent Johnson–Holmquist constitutive model. Failure strain (FS) was adopted as a user-defined element removal criterion to reveal damage mechanism during the grinding process. The predicted machining groove topography correlated well with the experimental observations. Surface and subsurface microcracks were characterized at different FS. The thrust, frictional, and grinding force histories were also investigated. Furthermore, material behaviors at different locations below the machined groove were analyzed to shed light on subsurface microcrack initiation and propagation.

Keywords: Bioceramics, machining damage, surface integrity, grinding, finite element analysis

1 Introduction

Osteoarthritis of the knee joint is a commonly occurring disease that affects more than 27 million U.S. adults (Van Manen et al., 2012). It occurs when protective cartilage wears down and initiates painful bone-on-bone contact. One treatment option is to restore knee function by total knee arthroplasty (TKA) (Bergschmidt et al., 2011). In TKA, the entire joint is replaced by an artificial implant. However, current knee implants made of stainless steel, titanium, and cobalt-chromium alloys have unsatisfactory performance including pitting corrosion, stress corrosion cracking, ion release, and poor wear resistance (BomBač et al., 2007). These problems lead to allergic or other hypersensitivity

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Peer-review under responsibility of the NAMRI Scientific Committee
doi:10.1016/j.promfg.2015.09.058

reactions, bone atrophy, and aseptic loosening that finally result in implant failure. An alternative class of biomaterials that avoids these complications is ceramics. Ceramics are biocompatible and capable of providing long term durability due to their high hardness, high wear resistance, and high strength-to-weight ratio (Carter & Norton, 2013; Marti, 2000). Moreover, ceramics have good wetting and lubrication behavior in vivo which further reduce friction and wear.

Alumina is a promising ceramic biomaterial that has proved successful for orthopedic applications since the 1970's (Maccauro, 2011). Despite its advantages as a ceramic, concerns about reliability still exist today. For instance, alumina has a low fracture toughness which can facilitate crack propagation at flaw sites on or below the surface (Rahaman et al., 2007; Yeung et al., 2010). Eliminating these flaws during manufacturing is the critical technical barrier to improving material strength and performance of knee implants. On the surface, minimizing flaws is more challenging because damage is often introduced during the machining process. This damage can be minimalized by better understanding material removal mechanisms.

Material removal mechanisms can be divided into brittle and ductile modes. In brittle mode, material removal is accomplished through crack nucleation, propagation, and coalescence (Kirchner & Isaacson, 1983). Grinding alumina is traditionally brittle mode and often results in surface and subsurface damage and strength degradation (Malkin & Ritter, 1989; Agarwal & Rao, 2008; Maksoud et al., 1999). On the contrary, material removal in ductile mode is achieved by severe plastic deformation and eventual chip formation. In grinding, sheared chips form when the machining depth is less than a critical cutting depth (Bifano et al., 1991). As a result, surfaces are damage free.

Since grinding includes multiple randomly distributed abrasive grit cutting edges, a single point grinding is widely used instead to investigate material removal mechanisms (Zarudi et al., 1996; Axinte et al., 2013; Zhang & Howes, 1994; Xu et al., 1995; Ma et al., 2014; Zhu et al., 2014; Patten & Jacob, 2008). Even though several numerical models of ceramic machining have been developed, few have incorporated plastic deformation and damage evolution in the material model. Little work has been done to simulate alumina machining that is capable of accurately predicting topography, damage, grinding forces, and transient stress. The objectives of this study are to: (a) simulate the single point grinding of alumina with pressure-dependent plasticity model; (b) investigate material removal mechanisms of machining alumina; and (c) predict the ground surface damage.

2 A Review on Alumina Constitutive Model in Machining

Several research efforts have explored modeling of ceramic machining using elastic or elastic-plastic material models. (Chuang et al., 2003) simulated the stress field when machining silicon nitride with a straight plunge grinding tool using an elastic material model. (Patten et al., 2007) simulated single point diamond tool grinding of SiC. Ductile behavior was incorporated by using a pressure sensitive Drucker-Prager constitutive model. These models could not predict damage induced by machining. In order to capture the ductile/brittle material removal mechanisms in ceramic machining, the constitutive model must include damage evolution.

Other research efforts have used constitutive models that include damage evolution but neglect plastic deformation. (Liu & Zhang, 2002) developed a continuum damage mechanics (CDM) method to simulate ceramic machining. The model considered cumulative damage of ceramic materials and simulated brittle behavior. (Tan et al., 2008) used discrete element method (DEM) to simulate crack initiation and propagation during machining of ceramics. The bulk material was treated as an assemblage of discrete particles bonded together. Cracks were formed by bonds breaking under external forces. This model can effectively simulate crack generation and propagation in brittle mode; however, plastic deformation was not considered in this method. In these models, chip generation and ductile material removal could not be predicted.