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Orthogonal cutting of cortical bone: Temperature elevation and fracture toughness

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ABSTRACT

During surgical procedures, the heat development of bone cutting can lead to thermal cell necrosis and secondary implant instability. Therefore, fundamental knowledge on heat development and temperature control is crucial. This paper investigates the basic principles of the machining of cortical bone in an orthogonal cutting process. Cutting forces, temperature elevation and chip formation were measured in real time for two different rake angles and six different cutting depths. A non-linear relationship between cutting depth and cutting forces as well as temperature elevation was found. The cutting behavior changed from a ductile to two distinguishable fracture cutting modes with increasing cutting depth. A linear correlation between cutting forces and temperature elevation of both bone chip and workpiece was determined ($R^2 = 0.8697$). An increasing rake angle lowered cutting forces and temperature elevations significantly and was explained using a fracture mechanics approach. Additionally, a new method to calculate the fracture toughness of (quasi-)brittle materials from orthogonal cutting tests was introduced.

1. Introduction

Surgical tools like drill bits, burs and bone saws are frequently used in orthopaedic interventions. Those tools are often not optimized to reduce the heat of the surgical procedures or even not adapted for cutting bone. However, the heat development of bone cutting can induce thermal cell necrosis (death of cells) which might lead to secondary implant instability [1] or to the damage of surrounding structures (e.g. nerves [2]). To reduce this risk and improve the tool design of future surgical tools, it is necessary to achieve a deeper understanding of how cutting tool design and process parameters relate to cutting forces and temperature elevation.

In order to investigate the basic principles for the machining of bone material, the cutting process has been reduced to an orthogonal cutting operation. The orthogonal cut enables a detailed experimental investigation of the cutting zone where the edge of a cutting tool is used to cut through a material in a linear movement. Measurement of the cutting forces and temperature elevations, as well as observation of the chip formation provide a knowledge base for the optimization of tool design and process parameters. Overall process optimization results in decreased cutting forces and temperatures, improved surface qualities and tool life.

In order to analyze cutting forces and temperature elevations, high speed optical and infrared cameras are needed. Thermal camera measurements have been previously used to investigate and reduce the heat development of a drilling process in bone. [3] Additionally, the necessary emissivity constant of cortical bone has been formerly determined [4].

Wiggins and Malkin [5] as well as Jacobs [6] were the first to investigate the cutting forces of orthogonal cutting of cortical bone with respect to the osteonal cutting direction, tool rake angle and cutting depth. They found a non-linear relationship between cutting depth and cutting forces as well as a strong dependency of cutting direction on cutting forces, in relation to the bone micro-structure. Regardless of cutting depth or direction, it was found that an increase in tool rake angle decreases the cutting forces. This information has already been used to improve the geometry of surgical drill bits [3]. More recent investigations by Yeager [7], Plaskos [8] and especially by Sugita et al. [9,10] found that the cutting mode changes from continuous to fracture chip type at a certain cutting depth. There is no known study on the temperature measurement of the orthogonal cutting of bone.

In the latest research on orthogonal cutting of cortical bone, Liao and Axinte [11] made a great contribution to classify and explain the different cutting modes which depend on the cutting depth. They

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distinguish three cutting modes: The shear cutting mode (SC) which is only found at small cutting depths (≤20 μm) without fracture due to the small cutting forces. In the shear-crack cutting mode (SCC) (20 ~ 80 μm), the shear stress concentration along the presumed shear plane initiates a Mode II crack that runs from the top surface of the chip to the tip of the cutting tool along the shear plane. At an even greater cutting depth, the cutting mode changes to a so called fracture cutting mode (FC) in which the chip is fractured into larger pieces which appears to be close to a Mode I fracturing process.

The analytical modeling of the orthogonal cutting process of metals was first established by Ernst and Merchant in 1941 [12]. They developed the shear plane model to describe and predict cutting forces for orthogonal metal cutting. Even though there has been numerous modifications (shear zone, slip-line, etc.) and it was found to be inadequate for many applications as described by Astakhov [13], it remains a widely used model for orthogonal cutting of ductile materials. The latest advancements in modeling orthogonal cutting have been summarized by Arrazola et al. [14] which include analytical, mechanistic, empirical or hybrid methods often calculated with FEM but limited to certain applications. Recent advances in numerical modeling of bone cutting have been summarized by Marco et al. [15] but there are only limited models for the cutting of brittle or quasi-brittle materials [16].

However, compared to metals, cortical bone is a very different material with a quasi-brittle and not ductile behavior. It is anisotropic with osteons (∅200 μm) acting as "fibers" in a rather brittle matrix. Cortical bone has different intrinsic mechanisms to prevent crack growth which leads to a high fracture toughness that depends on the direction of the cutting process with respect to the osteonal structure.

Overall, the aim of this research is, for the first time, the investigation of the thermal increase in the orthogonal cutting process of cortical bovine bone and its relationship to cutting forces depending on the tool design and cutting depth in order to improve future surgical tool development and to reduce thermal cell necrosis. Additionally, we introduce a new method to calculate the fracture toughness of brittle or quasi-brittle materials using orthogonal cutting tests.

2. Materials and methods

2.1. Experimental setup

A custom test bench was used to conduct the experiments (at Fraunhofer Institute for Production Technology). It consists of a hydraulic linear slide carrying a specifically prepared workpiece (specimen). The linear slide allows the acceleration of the workpiece up to a velocity of v_c=140 m/min. The orthogonal cutting operation is then performed by moving the workpiece against a cutting insert. The cutting insert is mounted to the height adjustable platform, which allows precise adjustment of cutting depths, and the granite bed of the test bench via a force measuring platform (Kistler Type 9129AA; Sampling Rate 10 kHz). Stiffness and accuracy of the setup is achieved by granite foundation and hydraulic linear slide.

The setup allows for the systematic investigation of different tool types (micro geometry, substrate, coating, etc.), different workpiece materials (metals, ceramics, fiber-reinforced materials, etc.) and process parameters (cutting velocity, cutting depths, etc.). Furthermore, the setup provides an excellent accessibility of the chipping zone, which allows for a detailed investigation of the chip forming behavior, the temperature elevations and the cutting forces. High-speed-imaging is performed by a high-speed-camera (DRS Lightning RDT PlusTM; Frame rate 6000 fps; Frame size 512×424 pixel) while temperature measurements are done using thermal imaging (FLIR X6580sc; Frame rate 574 fps; Frame size 640×300 pixel; Integration time 0.506 ms; Emissivity 0.96 [4]) (Fig. 1).

2.2. Sample preparation

Bovine cortical bone samples were extracted from fresh femur and tibia of dairy cows older than four years acquired from a local slaughterhouse. They were pre-cut using a hand saw and further prepared to their final dimension of 3 mm×20 mm ×25 mm using a diamond band saw (Exakt, Germany). The long edge of the sample (25 mm) is thereby orientated parallel to the osteonal axis of the bones as shown in Fig. 2. Additionally, a thin slice of bone was cut from each sample perpendicular to the axial orientation (30 mm×20 mm ×0.5 mm). These slices were than checked for primary osteonal structures and sorted out if lamellar bone was found. In most cases, the osteonal structure was only found in the middle part of the diaphysis because of the highest stresses [17]. In fast growing bovine bones, the lamellar structure is only slowly remodeled within the life span of around 20 years, however, dairy cow bones are the oldest commercially available bones. In total, 25 osteonal bone samples were produced. It will be discussed that there is a clear difference between primary and secondary osteons which has been so far neglected in the literature. The bone samples were kept at −20 °C and thawed in saline solution prior to experiments.

2.3. Experimental procedure

The experimental procedure was designed to investigate how tool rake angle and cutting depths affect the cutting force and temperature during bone cutting. Therefore, tungsten carbide tools (WC-10%Co; uncoated) with two different rake angles (γ=10° and 40°) but the same clearance angle (α=15°) and a small cutting edge radius (r_{beta}=5 μm) were selected (see Fig. 3 for nomenclature). The width of the tools (5 mm) transverse to the cutting direction was larger than the sample's width. Five tools were used for each rake angle and changed within the experiments to avoid excessive tool wear (Fig. 4).

The average cutting depths of surgical tools like drill bits is up to ca. 50 μm while a non-linear cutting behavior has been reported for larger cutting depths reported in the literature. Therefore, six cutting depths were chosen (h=12.5, 25, 50, 75, 100 and 150 μm) to investigate the changes in cutting mode. The cutting velocity was set to v_c=8 m/min to represent the average speed of surgical cutting tools (e.g. standard surgical drill bit, ∅3 mm, 1000 RPM).

Experiments were conducted for both cutting tools at all cutting depths and repeated three times for temperature measurements and one time for high speed camera videos. To ensure a smooth and planar surface, the bone samples were pre-cut and the surface topography was measured with a built-in measuring device. Afterwards, the sample was cut and the surface height was measured again so that set and actual cutting depths were available. Multiple operations have been performed using one sample, but the samples were randomized so that repetitions were not done on the same sample.

The cutting force was measured parallel (F_c) and normal to the workpiece surface (F_{cn}) as shown in Fig. 3. The sample width (w) is measured for each sample (circa 3 mm). Mean, minimal and maximal average cutting forces were extracted from the time interval of the cut which showed a continuous cutting behavior. Additionally, the averaged maximal temperature elevations of the bone chip and work piece were extracted from the same time interval as used for the cutting forces using the Flir ResearchIR software (Flir, USA). The region of temperature extraction was defined close to the rake face of the cutting tool and on the work piece surface directly behind the tip of the cutting tool.

3. Results

An overview of the high speed optical and thermal camera images for different cutting depths and the two different rake angles is given in