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Spiral point drill temperature and stress in high-throughput drilling of titanium

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Abstract

The spatial and temporal distributions of the temperature and stress of a 9.92 mm diameter spiral point drill are studied in high-throughput drilling of Ti–6Al–4V with 384 mm^3/s material removal rate (MRR). A finite element thermal model using the inverse heat transfer method is applied to find the heat partition on the tool–chip contact area and convection heat transfer coefficient of cutting fluid. The thermal model is validated by comparing experimentally measured and numerically predicted drill temperature with good agreement. Thermo-mechanical finite element analysis is applied to solve the drill stress distribution. Modeling results confirm that the supply of cutting fluid is important to reduce the temperature across the drill cutting and chisel edges. At 183 m/min peripheral cutting speed, 0.05 mm/rev feed and 10.2 mm depth of drilling, the drill peak temperature is reduced from 1210 °C in dry drilling to 651 °C with cutting fluid supplied through the drill body. Under the same MRR, 61 m/min peripheral cutting speed and 0.15 mm/rev feed, the analysis shows that the drill peak temperature is reduced to 472 °C. The temperature induced thermal stress combined with the mechanical stress caused by cutting forces is analyzed to predict the location of drill failure. Applying the modified Mohr failure criterion, the drill cutting and chisel edges are found to be prone to failure in dry and wet drilling conditions, respectively. This study demonstrates the effectiveness of drill thermal and stress modeling for drilling process parameter selection and drill design improvement.

Keywords: Finite element modeling; Temperature; Stress; Drilling; High-throughput; Titanium

1. Introduction

A major technical challenge in machining titanium (Ti) and Ti alloys is the high tool temperature. The inherent material properties, particularly the low thermal conductivity, of Ti and its alloys are the primary cause [1,2]. High tool temperature softens the tool material and is detrimental to the tool life. For drilling, since the tool is constrained in a hole, the high temperature is significant in the drill tip. This results in the limited material removal rate (MRR) and, subsequently, low productivity and high cost in machining Ti.

The research in high-throughput Ti drilling experiments has demonstrated that advanced tool geometry design and proper process parameter selection can achieve high MRR with satisfactory tool life [3]. It is known that the supply of cutting fluid and the selection of feed and cutting speed in drilling greatly affect drill temperature, stress, and life in Ti drilling [3]. The goal of this study is to quantify the spatial and temporal drill temperature and stress distributions in high-throughput drilling of Ti–6Al–4V, a commonly used Ti alloy.

Several methods have been developed to experimentally measure the drill temperature [4]. A common method is to embed insulated wires in the workpiece to form the hot junction of a tool-work thermocouple [5–7]. The thermocouple electromotive force (emf) generated when the tool cuts is recorded through the wire and is used to detect the drill temperature. This method has good repeatability and time response, but can only measure temperatures at discrete points in low-speed drilling due to the short contact period. Using an embedded foil tool-work thermocouple overcomes these problems by replacing the embedded wires with a metallic foil. It can measure the tool temperature across the cutting edge [8]. Disadvantages

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of the tool-work thermocouple method are the requirement of extensive calibration and limited measuring region and period. Commercial thermocouples can also be embedded in the drill to measure the temperature [7,9–11]. It requires careful specimen preparation to avoid damaging the thermocouple during drilling. Thermocouples can only measure temperature at discrete points away from the cutting edge. Since the tool and work-materials are subject to high temperature and undergo hardness change, metallurgical transformation, or even chemical composition change, the micro-hardness measurement [12], scanning electron microscopy [13], and energy dispersive X-ray measurement [14] have been developed to measure the drill temperature. Similarly, drills coated with thermo-sensitive paints can be utilized for temperature measurement [5,15]. A common disadvantage of these methods is that they only measure the peak temperature. Also, these methods require extensive post-test sample preparation and analysis. The infrared thermal camera is not suitable for drill temperature measurement because the drill-cutting region is embedded inside the workpiece.

To solve the spatial and temporal distributions of the drill temperature, an inverse heat transfer method has been developed [16]. Thermocouples embedded in the drill provide the temperature input data for the drill finite element thermal model. This model estimates the cutting edge heat generation rate by minimizing the discrepancy between the measured and predicted temperature at the thermocouple locations. This method has been demonstrated in dry drilling of commercially pure Ti at low cutting speed (up to 73.2 m/min) using the setup with a stationary drill and thermocouple wires routed through holes in the drill body [16]. This setup is adequate for dry drilling but not suitable for the high-throughput drilling of Ti because of the need to use cutting fluid and the interference of cutting fluid with thermocouple wires in through-the-drill holes. In this study, shallow grooves were ground on the side (margin surface) of the drill body to guide the thermocouple wires from the drill tip to outside of a stationary drill.

Most of the drill thermal analyses by previous researchers were conducted under the dry condition. In drilling with a supply of cutting fluid, so called wet drilling, the research on drill temperature is limited. Arai and Ogawa [17] measured drill temperature using the embedded wire tool-work thermocouple method in drilling Ti–6Al–4V with an external cutting fluid supply. Kalidas [18] modeled the workpiece temperature in drilling cast aluminum (Al) 356 with an external cutting fluid supply. Due to the high temperature in Ti drilling, supplying the cutting fluid via through-the-drill holes is necessary to enhance the drill life [3]. To the best of our knowledge, no research publication is available on the analysis of spatial and temporal drill temperature distributions with an internal cutting fluid supply. This research is aimed to fill this gap. In this paper, the spatial and temporal drill temperature distribution in high-throughput (384 mm^3/s MRR) drilling of Ti–6Al–4V with an internal cutting fluid supply is studied using the inverse heat transfer method.

The drill temperature and cutting forces can be used as inputs to analyze the spatial and temporal distributions of the drill stress. For high-throughput Ti drilling, the drill temperatures and forces are both very high. Severe deformation and highly localized stresses are expected in the drill and will eventually lead to the drill failure. The drill deformation has been studied by Bono and Ni [10] using a finite element model for drilling Al 319. The stress distribution in the drill has also been investigated both experimentally [19] and numerically [20]. This study conducts more in-depth drill stress analysis using the thermo-mechanical finite element model and predicts the initial failure location in a spiral point drill. The von Mises stress of the drill used in high-throughput drilling of Ti–6Al–4V has been presented in Ref. [21]. For the WC–Co tool material, the brittle fracture is different from the failure of ductile metals predicted using the von Mises failure criterion [22–24]. More advanced analysis of WC–Co at microstructure level has been conducted [25,26]. In this paper, three most frequently used brittle failure criteria, Rankine, Mohr–Coulomb [27], and modified Mohr criteria [28], are compared to select the most suitable failure criterion for drilling. The location in the drill likely to initiate the failure is identified in the analysis.

In this paper, the experimental setup of Ti drilling tests and drill temperature measurements are first introduced. The inverse heat transfer and finite element modeling of the drill are then discussed. The drill temperature measurement and validation are presented. Finally, the drill stress, deformation, and failure analyses are performed.

2. Experimental setup and design

The drilling experiment was conducted in a Mori Seiki TV 30 computer numerical control (CNC) vertical machining center. Fig. 1(a) shows the experimental setup with a rotating 25 mm diameter Ti–6Al–4V bar and a stationary 9.92 mm diameter spiral point drill (Kennametal K285A03906). Two fluid jets, under 0.2 MPa pressure, can be identified shooting from the drill body. Under the drill holder was a Kistler 9272 dynamometer to measure the thrust force and torque. As shown in Fig. 1(b), the tips of 0.127 mm diameter thermocouples (OMEGA 5TC-TT-E-36-72), denoted as TC1 and TC2, are embedded in grooves hand ground on the drill flank face and located close to the cutting edge. An X–Y coordinate is defined at the center of the S-shaped chisel edge in the spiral point drill. The Y-axis is parallel to the tangent at the apex of the curved cutting edge. Coordinates of the tips of two thermocouples are identified in Fig. 1(b). Thermocouples are covered with cement (Omega OB-400) to secure the position and prevent the contact with the rotating workpiece. Unlike the setup in dry drilling with thermocouple wires going through holes inside the drill body [16], thermocouple wires in this study were routed up the drill