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Identification of a friction model for minimum quantity lubrication machining

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ABSTRACT

In this paper, we present the development of a friction model as a function of the cutting speed and tool feed rate when machining with minimum quantity lubrication. A finite element model of the minimum quantity lubrication process is developed and simulated by considering the friction coefficient as a state variable. The tool-chip friction coefficients for different machining conditions are obtained through inverse modelling and presented as a mechanistic model. The validated model is utilized to understand the effects of machining conditions, temperature, and contact length of the tool-chip interface.

1. Introduction

The use of cutting fluids during machining operations creates several occupational health risks and many environmental effects as well. The machining fraternity has to cut the environmental burdens without sacrificing the production rate and product quality. This situation has encouraged the development of new machining research areas such as machining using cryogenic liquids, dry machining with high performance cutting inserts and innovative coating techniques, and machining with limited quantity of cutting fluid like using minimum quantity lubrication (MQL) technique (Lawal et al., 2014) and little quantity lubrication (LQL) technique (Zhong et al., 2010). In the MQL technique, a very small quantity of cutting fluid (5 mL/h to 600 mL/h) is injected at the cutting zone in the form of a mist under suitable air pressure (Grzesik, 2008). In case of the LQL technique, the quantity of cutting fluid used is 50 mL/min to 300 mL/min. Although dry machining seems to be the most desired of these techniques, but because of limited cooling and lubrication, it may result in lesser tool life and insufficient surface quality. The successful implementation of dry machining calls for change in the cutting tool design and material, and in the machine tool as well. With an increase in the demand of difficult-to-machine-materials like titanium alloys and nickel based alloys, the scenario becomes much more challenging (Shokrani et al., 2012). Among the foregoing techniques, MQL is a method that can be easily implemented with very limited changes to the existing machine tool (Weinert et al., 2004). Because the amount of cutting fluid used in this process is very small, the hazardous effects can be minimized (Fratila, 2009). Additionally, the machining cost is reduced compared with flood cooling because only a small quantity of cutting fluid is handled in the MQL (Fratila and Caizar, 2011).

Many researchers have shown in past two decades that use of the MQL technique in metal cutting can be beneficial if applied in the proper quantity and at the proper location, i.e., rake face, flank face and in combination of rake and flank face (Hadad and Sadeghi, 2013). Some comparative studies were also made to analyze the positional effect of cutting fluid injection during turning operation (Attanasio et al., 2006). Chemical and physical attributes of cutting fluids used in MQL can also significantly affect cutting performance (Zhang et al., 2012). Although many studies reported the effectiveness of the MQL technique, more studies are required to fully understand the cooling and lubrication mechanism in MQL that is postulated to be significantly different from flood cooling (Sarıkaya and Güllü, 2014). The mist in MQL creates a film on the workpiece that performs convective heat transfer. This is different from flood cooling where a mixed mode, conductive and convective, heat transfer occurs. The mist film also bears some portion of the load experienced by the workpiece during cutting operation. Based on these reasons, the MQL is expected to be more sensitive to changes

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in the process parameters (Kuram et al., 2013). Limited studies have been performed to quantify the friction coefficient between the tool and the chip during the MQL machining. The aim of this study is to propose a predictive friction model for the MQL and thereby obtain a better understanding of machining with MQL under varying process conditions.

The friction coefficient is an important input when modelling machining operations. The effect of friction is incorporated in modelling by relating the frictional stress (τ_f) to the shear strength of material (τ_y), the normal stress (σ_n) and Coulomb's friction coefficient (μ). One of the most commonly used approaches is presented by Zorev (1966). The shear stresses near the tool tip (sticking region) are presumed to be equal to the shear intensity of the material. In the sliding region, the frictional stresses are proportional to the normal stress. Zorev's model is defined by the following:

$$\tau_f = \tau_y \quad if \ \ l \le l_c \tag{1}$$

$$\tau_f = \mu\sigma_n \quad if \ \ l > l_c \tag{2}$$

where l_c is the length of the transitional zone. Later, based on experiments, more realistic models were presented by Eq. (3) (Usui and Shirakashi, 1982) and Eq. (4) (Childs et al., 2000).

$$\tau_f = \tau_y\left(1 - e^{-\frac{\mu\sigma_n}{\tau_y}}\right) \tag{3}$$

$$\tau_f = \tau_y m\left[1 - \left(e^{-\frac{\mu\sigma_n}{\tau_y}}\right)^n\right]^{\frac{1}{n}} \tag{4}$$

where m represents the lubrication effect and n controls the transition zone from the sticking to sliding region.

Recently, some experimental studies reported the friction coefficient during the MQL. Faverjon et al. (2013) investigated the influence of MQL on the friction coefficient and work-material adhesion during machining of cast aluminum with various cutting tool substrates made of polycrystalline diamond and high-speed steel. Mondelin et al. (2011) analyzed the effect of the sliding velocity on the friction coefficient under different conditions, such as dry sliding, emulsion application, straight oil application and MQL. The experiments were performed on a lathe tribometer without engaging the actual metal cutting performance. The friction coefficient was found to decrease with straight oil and mist lubrication under all sliding velocities. Some recent experimental works likewise concentrated on understanding the cooling capacity of the MQL technique under different air pressures as well as for different oil concentrations (Kurgin et al., 2012). A few modelling-based investigations on cooling and lubrication during the MQL process were reported. Mechanistic modelling (Marksberry and Jawahir, 2008) and analytical modelling (Li and Liang, 2007) approaches were used for tool wear and cutting force predictions. These models developed for the cutting force prediction show that the MQL fluid has an important effect on the cutting force but not on cooling effect. This observation was supported by Sukaylo et al. (2005), who used finite element method (FEM)-based inverse modelling approach to calculate the heat transfer coefficient. This study did not consider the effect of friction; however, it revealed that the heat generation varies with the cutting speed, whereas the heat transfer coefficient remains almost constant. The change in the heat transfer coefficient due to a change in speed is counterbalanced by the associated change in temperature with speed. In another investigation, Wang et al. (2009) performed a comparative study of the dry, flood cooling and MQL techniques while machining a Ti6Al4V alloy. The mean friction coefficient value was calculated from the experimental data. Then, the coefficient values were used when simulating the cutting process. The cutting force and thrust forces were estimated using the simulation, and the results were compared with experimental values.

These investigations deal primarily with the effect of different cooling and lubricating strategies used in the MQL machining process. It is not clear how tribological parameters such as the friction coefficient should be chosen in an FEM simulation of different machining processes with varying process conditions. New friction models need to be developed that incorporate the dependence of the friction coefficient on the sliding velocity, which corresponds to the cutting speed and feed velocity in actual machining operations. As mentioned by Özel (2006), predictions are more exact if the friction is implemented as a variable friction model at the tool chip contact in the finite element simulations. Variable friction models replace the friction coefficient in Eqs (1)–(4). The existing models have limitations, and further experimental—numerical efforts are required to describe the interaction between the tool and workpiece (Vaz et al., 2007). Modelling-based investigations are worth considering for process variants, such as MQL, where the tool-chip interaction is quite different compared with the other machining techniques.

In the present study, we exhibit an inverse modelling based approach for identifying the friction model when machining with the MQL process. Unlike previous investigations, the present study aims to account for the effects of the shop-floor applicable machining parameters, cutting speed and tool feed-rate, when predicting the friction coefficient. The friction model is based on actual machining data and does not depend on machining conditions that could be partially simulated on a tribometer. The following section presents an FEM model of the MQL process followed by the inverse modelling approach for developing the friction model. The model is validated and the outcomes of the investigations are discussed, followed by a conclusion derived from this investigation.

2. FEM model of the MQL process

A plain turning operation was used for modelling and simulation of MQL. The aerosol was assumed to be injected on both the rake face and flank face. Fig. 1 shows a 2D representation of the turning operation. The cooling effect was applied in such a way that both the rake face and the flank face were assigned with the heat transfer coefficient. The same setup is depicted in Fig. 2.

Unlike the previous studies, the actual heat transfer coefficient of the oil and air mixture, which was experimentally measured (Kurgin et al., 2012), was used in the present investigation. The commercial FEM software AdvantEdge was used to model and simulate the operation. It uses updated-Lagrangian finite element codes to simulate high unconstrained plastic flows, which generally occur during the machining operation, under the constraint that the solid is remeshed continuously. The number of nodes used for meshing was 24,000. The following relations (Eq. (5) and Eq. (6)) represent the constitutive model (Marusich and Ortiz, 1995).

$$1 + \left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}^p_0}\right) = \left[\frac{\sigma_m}{g(\varepsilon^p)}\right]^{m_1}, \quad if \ \ \dot{\varepsilon}^p \le \dot{\varepsilon}_t \tag{5}$$

$$1 + \left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}^p_0}\right)\left[1 + \frac{\dot{\varepsilon}_t}{\dot{\varepsilon}^p_0}\right]^{\frac{m_2}{m_1}-1} = \left[\frac{\overline{\sigma}}{g(\varepsilon^p)}\right]^{m_2}, \quad if \ \ \dot{\varepsilon}^p > \dot{\varepsilon}_t \tag{6}$$

where σ_m, is the effective von Mises stress, g is the flow stress, ε^p is the accumulated plastic strain, $\dot{\varepsilon}^p_0$ is the reference plastic strain rate,

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