International Communications in Heat and Mass Transfer 39 (2012) 786–791

Contents lists available at SciVerse ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Analysis of transient average tool temperatures in face milling☆

Xiaobin Cui, Jun Zhao *, Zhiqiang Pei

Key Laboratory of High Efficiency and Clean Mechanical Manufacture of MOE, School of Mechanical Engineering, Shandong University, Jinan 250061, PR China

ARTICLE INFO

Available online 24 May 2012

Keywords:
Transient average tool temperatures
Face milling
Analytical model

ABSTRACT

The increased tool temperature has great effect on tool life, machining efficiency and even the quality of the products in face milling. The objectives of this study are to predict the transient average tool temperatures under different cutting conditions with fixed cutting velocity and metal removal rate, and investigate the evolution of tool temperature with cutting condition. Finite element simulations of orthogonal metal cutting are performed so as to predetermine the evolution process of the heat source on the tool rake face. An analytical model is proposed to calculate and analyze the tool temperatures under nine different cutting conditions. The results reveal that the minimum transient average tool temperature can be acquired by adopting suitable cutting condition. The proposed theoretical method provides insight into the complex evolution of tool temperatures. It also provides information for the search for the optimum cutting condition under which the longest tool life can be obtained.

1. Introduction

In the cutting process, conversion of the mechanical work occurs in the plastic deformation in chip formation and friction between the tool and workpiece, resulting in the generation of heat. As part of the heat conducts into the cutting tool, high tool temperatures appear near the cutting edge. In the interrupted cutting process, the cutting tools are subjected to cyclical heating and cooling as they pass in and out of the workpiece, which is hardly encountered in the continuous cutting process. As a typical interrupted cutting process, face milling is widely used to generate smooth surfaces with high geometric accuracy. In the milling process, the uncut chip thickness and tool–chip contact area on the rake face vary with the tool rotation. The intensity and area of the heat source change cyclically, leading to the complex evolution of the tool temperatures. With the increment of temperature, the cutting tools may become softer and wear more rapidly, resulting in the shorter tool lives, lower machining efficiency, and even lower dimensional accuracy of the products. It is essential to predict and analyze the tool temperatures in face milling process.

Many researches on temperatures in interrupted cutting especially milling have been conducted experimentally and theoretically. In the 1920s, the famous Salomon curve was proposed by Salomon [1] via high-speed milling tests. The curve suggests that the cutting temperature can be reduced as the cutting speed increases. Schmidt [2] investigated the maximum temperature in and near the surface of the workpiece in the milling process using thermocouple embedded in the workpiece. Ueda et al. [3] investigated experimentally the temperature of the flank face of a cutting tool in high speed milling by means of a two-color pyrometer with an optical fiber. Sato et al. [4] developed an infrared radiation pyrometer with two optical fibers connected by a fiber coupler which was applied to the measurement of tool–chip interface temperature in end milling with a binderless CBN tool. McFeron and Chao [5] derived an approximate, iterative procedure for the calculation of the average, transient tool–chip interface temperature in plain peripheral milling. And the average tool–chip interface temperatures were measured by means of a tool-work thermocoupling technique. Palmai [6] reported with no direct experimental support that, in contrast to continuous cutting, as the cutting speed increases the temperatures in interrupted cutting decrease. Stephenson and Ali [7] investigated the tool temperatures in interrupted cutting theoretically and experimentally. Theoretically, the general nature of tool temperature distribution was analyzed by means of the temperature in a semi-infinite rectangular corner heated by a time-varying heat flux with various spatial distributions. The results of this analysis were compared with the cutting temperatures measured using infrared and tool–chip thermocouple technique. Based on the finite difference method, a numerical model was proposed by Lazoglu and Altintas [8] to predict tool and chip temperature fields in continuous machining and time-varying milling process. As reported in the literature, the simulated results are in satisfactory agreement with the measured temperature.

Previous studies on milling temperatures presented much valuable information. But little research was conducted to investigate the tool temperatures in face milling theoretically. As has been discussed, because of the varying intensity and area of the heat source, the evolution process of the tool temperatures is complex in face milling. Moreover, it is difficult to identify quantitatively how the intensity and area of the heat source develop with the tool rotation. Probably for these reasons,

☆ Communicated by P. Cheng and W.Q. Tao.

* Corresponding author.
E-mail address: zhaojun@sdu.edu.cn (J. Zhao).

0735-1933/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.icheatmasstransfer.2012.05.009

Nomenclature

a_p	axial depth of cut, mm
a_e	radial depth of cut, mm
a_c	uncut chip thickness, m
C	the strain rate sensitivity
f	feed rate, mm/r
F_{xi}	data points of the cutting force in X direction, N
F_{yi}	data points of the cutting force in Y direction, N
F_{zi}	data points of the cutting force in Z direction, N
F_r	average value of the resultant cutting force, N
k	thermal conductivity, J/(s m °C)
L_f	tool–chip contact length, m
Lx	the length of the tool–chip contact area along the x-direction, m
Ly	the length of the tool–chip contact area along the y-direction, m
Lymax	the maximum tool–chip contact length, m
m	the thermal softening coefficient
N	rotational speed, r/min
n	the strain hardening exponent
q	heat flux, W/m^2
T	the tool temperature, °C
T_a	the absolute temperature, K
T_r	the reference temperature, K
T_m	the melting temperature, K
v	cutting velocity, m/min

Greek letters

α	thermal diffusivity, m^2/s
$\overline{\sigma}$	the shear stress, MPa
$\overline{\varepsilon}$	the shear strain
$\overline{\varepsilon}\cdot$	the shear strain rate, s^{-1}

Subscripts

AVE	average
p	point

few studies concentrated on the theoretical analysis of tool temperatures in face milling.

In the present study, a theoretical method is proposed to investigate the transient average tool temperatures in face milling of AISI H13 tool steel with uncoated carbide tool. Finite element simulations of metal cutting are performed. The simulated results are analyzed and calculated so as to fit the evolution process of the intensity and area of the heat source. An analytical model for the transient average tool temperatures is established with the variation of heat source considered. As concluded by Longbottom and Lanham [9] in the review of research related to Salomon's hypothesis on cutting speeds and temperatures, the Salomon curve might not be valid for the tool–work interface temperature. In other words, according to most of the existing studies, the increased cutting speed might not lead to reduction in tool temperature. Therefore, for the purpose of reducing tool temperature, investigation on acquiring the minimum transient average tool temperature in face milling with cutting speed and metal removal rate fixed is conducted based on the established model.

2. Evolution of the heat source

The set-up of face milling under consideration is shown in Fig. 1. The diameter of the face milling cutter is 120 mm. Four inserts are

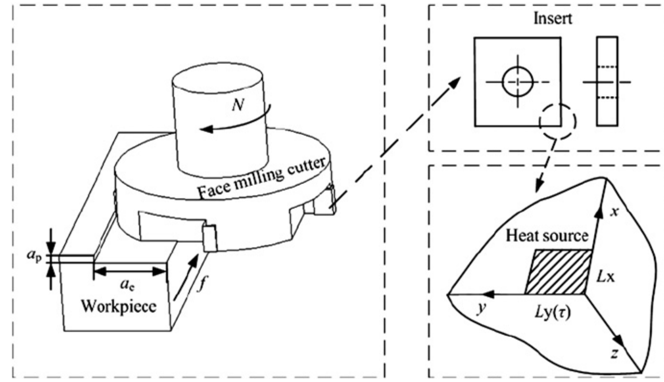

Fig. 1. The set-up of face milling and the simplified heating condition.

clamped peripherally and uniformly. As the axial depth of cut a_p is mainly determined by technological requirements, it remains fixed at 1 mm. The cutting velocity v is kept at an invariable value 600 m/min. The maximum value of radial depth of cut a_e and feed rate f are 60 mm and 0.96 mm/r, respectively. The metal removal rate is fixed.

The evolution of intensity and area of the heat source must be predetermined before the calculation of the tool temperatures. The heat source is assumed to be spatially uniform. The well-known Loewen and Shaw's model [10] is adopted to calculate the intensity of the heat source, namely the transient heat flux entering the tool from the tool–chip contact area. Since the axial depth of cut is unchangeable, the development of heat source area is determined only by the tool–chip contact length which is about to be investigated instead.

In order to apply the Loewen and Shaw's model to calculate the transient heat flux, the transient cutting forces, chip thickness and tool–chip contact length must be known. In the milling process, the uncut chip thickness changes with the tool rotation. Thus, it is difficult to measure directly the chip thickness and tool–chip contact length corresponding to certain transient uncut chip thickness experimentally. In the present study, based on the assumption that the insert in the face milling cutter illustrated in Fig. 1 can be simplified to be a cuboid, the chip thickness and tool–chip contact length are obtained by means of finite element simulations of orthogonal metal cutting under different uncut chip thicknesses. Then, the relationship between the transient heat flux and the uncut chip thickness, and the relationship between the tool–chip contact length and the uncut chip thickness are identified.

2.1. Finite element simulations of metal cutting

Deform-2D™, a Lagrangian implicit code, is used in the simulations of orthogonal cutting AISI H13 tool steel with uncoated carbide. The cutting velocity v is fixed at 600 m/min, and the uncut chip thicknesses are in the range from 0.02 mm to 0.24 mm. Sharp tools are used in all the simulations. The rake angle is −8° and the clearance angle is 8°, corresponding to the milling condition. The thermal conductivity and diffusivity of the carbide are 82 J/(s m °C) and 2.5×10^{-5} m^2/s, respectively. In the simulation process, the tool is modeled as rigid but heat transfer body.

It is essential for successfully simulating the metal cutting to use a suitable material-constitutive model for the workpiece, which should incorporates the effects of stress, strain, strain rate and temperature. The Johnson and Cook model has been used by many researchers to investigate high strain rate, high temperature deformation behavior of steels. In the present study, the Johnson and Cook constitutive equation is used, as shown in Eq. (1):

$$\overline{\sigma} = \left[A + B(\overline{\varepsilon})^n\right]\left[1 + Cln\left(\frac{\dot{\overline{\varepsilon}}}{\dot{\overline{\varepsilon}}_0}\right)\right]\left[1 - \left(\frac{T_a - T_r}{T_m - T_r}\right)^m\right] \quad (1)$$