International Journal of Machine Tools & Manufacture 84 (2014) 45–57

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

Experimental determination of the tool–chip thermal contact conductance in machining process

Vahid Norouzifard*, Mohsen Hamedi

School of Mechanical Engineering, College of Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran

ARTICLE INFO

Article history:
Received 21 September 2013
Received in revised form
23 March 2014
Accepted 7 April 2014
Available online 23 April 2014

Keywords:
Thermal contact conductance
Tool–chip interface
Machining
Inverse method
IR thermography

ABSTRACT

Tool–chip contact is still a challenging issue that affects the accuracy in numerical analysis of machining processes. The tool–chip contact phenomenon can be considered from two points of view: mechanical and thermal contacts. Although, there is extensive published literature which addresses the friction modeling of the tool–chip interface, the thermal aspects of the tool–chip contact have not been investigated adequately. In this paper, an experimental procedure is adopted to determine the average thermal contact conductance (TCC) in the tool–chip contact area in the machining operation. The tool temperature and the heat flux in tool–chip contact area were determined by inverse thermal solution. Infra-red thermography was also used to measure the average chip temperature near the tool–chip interface. To investigate the effects of the work piece material properties on the tool–chip TCC, AISI 1045, AISI 304 and Titanium materials were considered in the machining experiments. Effects of the cutting parameters such as cutting velocity and feed rate on TCC were also investigated. Evaluating the tool–chip thermal contact conductance for the tested materials shows that TCC is directly proportional to the thermal conductivity and inversely proportional to the mechanical strength of the work piece. The thermal contact conductance presented in this paper can be used in the future numerical and analytical modeling of the machining process to achieve more accurate simulations of the temperature distribution in the cutting zone and better understanding of the tool–chip contact phenomena.

1. Introduction

In metal cutting processes, large plastic deformation of the work piece material increases the cutting zone temperature. High temperature of the cutting zone strongly affects tool wear, tool life, work piece surface integrity, and chip formation mechanisms, and contributes to the thermal deformation of the cutting tool. The majority of the heat is generated in the chip. Fig. 1 shows the interface of the tool, chip and the work piece along with the heat generation zones and schematics of heat propagation near the tool–chip contact. There are three heat generation zones related to the plastic deformation zones around the tool–chip contact area: primary deformation zone (PDZ); secondary deformation zone (SDZ) and tertiary deformation zone (TDZ). Depending on the cutting velocity, specified fraction of the generated heat in PDZ diffuses to the work piece material and the rest is removed from the cutting area by the chip material. Heat is generated in the secondary deformation zone (SDZ) due to shear deformation in the chip and sliding friction at the tool–chip interface. Since the contact area between the tool and SDZ is much larger than the part of tool in contact with TDZ, effects of the generated heat in TDZ on the tool temperature are neglected in this paper. Part of the generated heat in the chip is transferred to the tool through the tool–chip contact area. In addition to the transferred heat, the heat generated from sliding friction in the interface affects the tool temperature distribution. The tool–chip thermal contact characteristics and friction are two important phenomena that affect tool temperature directly. Thus, to investigate the thermal phenomena in machining process successfully, thermal interaction between the tool and chip should be well understood [1]. Thermal contact conductance (TCC) in the tool–chip interface as the important tool–chip thermal contact characteristic is a useful parameter to investigate and to simulate temperature fields in the tool and the chip.

The recent studies on the tool–chip contact phenomena have mostly focused on experimental and numerical investigations of friction on the tool rake face as well as investigation of temperature distribution and heat partition factor in the tool–chip interface. For example, Shi et al. [2] and Filice et al. [3] utilized finite element (FE) model to investigate friction in metal cutting. Childs [4] and Ozel [5] assessed performance of commonly used friction models through numerical simulation of machining process. Rech [6] investigated the effects of various tool coatings on the

* Corresponding author.
E-mail addresses: v.norouzi.fard@ut.ac.ir (V. Norouzifard), mhamedi@ut.ac.ir (M. Hamedi).

http://dx.doi.org/10.1016/j.ijmachtools.2014.04.003
0890-6955/

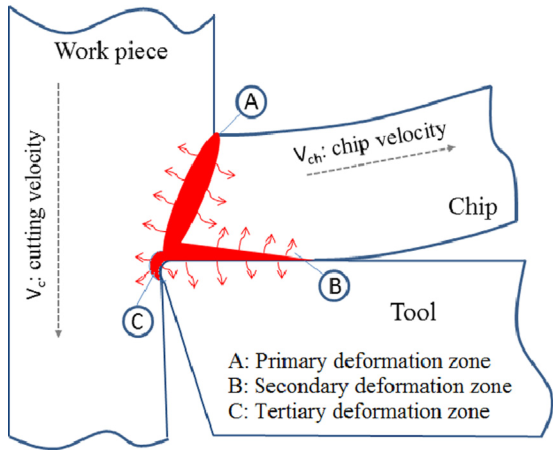

Fig. 1. Heat generation zones and heat propagation in machining.

tribological phenomena at tool–chip contact area such as friction, tool interface temperature, and chip formation using experimental measurements. On the other hand, a number of researchers focused on the tool–chip thermal phenomena. Abukhshim et al. [7] reviewed the previous research on heat generation and heat dissipation in the machining process as well as the temperature measurement techniques applied in metal cutting and estimation of heat generation, heat partition and temperature distribution in metal cutting. They concluded that consideration of interactions between the tool and chip in the interface is based on certain assumptions and not on understanding the physics of the contact. Akbar et al. [8] simulated chip formation in orthogonal metal cutting using a thermo-mechanical coupled finite element (FE) analysis and validated the model with the results from cutting tests. They also used the FE model to assess the sensitivity of the model outputs to the specified value of heat partition. Akbar et al. [9] also investigated the heat partition factor in the secondary deformation zone using analytical models available in the literature. Grzesik [10] experimentally studied effects of tool coating on the tool–chip interface temperature using a tool–chip thermocouple. Grzesik and Nieslony [11] estimated the interface temperature and heat partition to the chip in continuous dry machining using analytical models. Luchesi and Coelho [12] developed an inverse model to estimate the moving heat source and heat convection coefficient in the machining process. Umbrello et al. [13] determined the global heat transfer coefficient at the tool–chip interface by a hybrid experimental–numerical method. Analyzing all these investigations reveals that the thermal interaction in the tool–chip contact has not been studied sufficiently and merits more research.

TCC emanates from the fact that contact is made only at discrete locations in engineering surfaces, rather than over the entire area [14]. Therefore, during heat transfer in two contacting solid materials, the heat flow path is constricted in bodies' interface. Constriction in heat flow path causes temperature drop at the interface. Effective simulation of the temperature fields in the tool and the cutting zone using the FE method requires accurate definition of the tool–chip TCC.

There are tracks in the literature about experimental measurement of TCC in other manufacturing processes [15–17]. Rosochowska et al. [15,16] measured TCC between a cylindrical specimen pressed between two cylindrical tools under pressure and temperature conditions near the forging process. Dour et al. [17] applied a non-intrusive heat transfer gauge to measure transient TCC between mold and melt during the die casting process. In the metal cutting process, literature review shows that in simulation of orthogonal cutting through the FE method different values of TCC in the range of 10^4–10^7 W/m^2 °C for the tool–chip interface are considered [18,19]. Coelho et al. [19] mentioned TCC as a useful parameter for FE simulation since there is a lack of knowledge about TCC in the machining process. They assumed a value for TCC in the tool–chip interface based on the experimental results of Rosochowska et al. [16]. Filice et al. [20] assessed the simulation of orthogonal cutting process capabilities to analyze the thermal phenomena. They conclude that new consistent extensions of the numerical simulation (i.e., three dimensional analysis) need accurate description of the heat exchange phenomena at the tool–chip interface. Recently, Courbon et al. [21] experimentally investigated the existence of the thermal contact conductance/resistance in the tool–chip contact area and studied the role of this parameter on simulation of machining process using the FE method. They concluded that although the tool–chip contact conductance/resistance has no significant effect on the macroscopic outputs of the numerical solution such as the average cutting force and chip thickness, it highly affects heat transfer outputs such as heat partition, temperature amplitude, and temperature distribution. They also concluded that wherever accurate prediction of the temperature fields in the tool is desired more attention should be paid to this parameter. Therefore, experimental measurement of TCC is of interest for numerical and analytical simulations of the metal cutting process. Experimental determination of TCC in machining is a complex procedure due to the tool–chip contact characteristics such as high normal pressure, high temperature and sliding of the chip on the tool rake face. Umbrello et al. [13] developed an inverse procedure to determine global heat transfer coefficient in metal cutting and determined this coefficient by comparing experimental data with finite element results. They inserted a thermocouple in the cutting tool near the tool–chip interface and simultaneously developed a two-dimensional orthogonal cutting finite element model.

There are two limitations in the method used by Umbrello et al. [13]. Primarily, only a small part of the tool and work piece geometry has been simulated by 2D finite element models due to limitations in the processing capacity of available computers. Therefore, boundary conditions applied in 2D FEM models are not the same as real boundary conditions in the experiments. The other issue is the position and orientation of the embedded thermocouples where it is parallel to the heat flux flowing into the tool and close to the high temperature gradients near the tool–chip contact area. Dour et al. [17,22] and Davies et al. [23] recommended to accommodate thermocouples not only perpendicular to the heat flux but also far enough from the high temperature gradients. The hole manufactured to insert thermocouple near the tool–chip interface changes the distribution of thermal fields in this area. The perturbation is amplified by increasing the ratio of the hole radius to the thickness of the wall between the hole and the interface. This uncertainty can be reduced by welding the head of the thermocouple to the end of the hole and insulating the hole lateral surface from the thermocouple [22]. For detailed study of the effect of the thermal gradient on the measurement error, also see Attia and Kops [24–26]. A thermocouple inserted near the high temperature gradients measures the average temperature of the temperature distribution formed at its hot junction. Whereas, in the finite element simulation, the average temperature of the end surface of the modeled thermocouple is known as the thermocouple temperature. Thus, measuring the TCC in the tool–chip interface in metal cutting conditions using a new method which does not have the aforementioned problems still remains a challenging research issue.

The objective of this paper is to develop an experimental procedure to determine the average TCC in tool–chip contact area in machining operation. To estimate TCC, the bodies' temperature at the contact area and the heat flux flowing through the interface