Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Machine Tools & Manufacture 46 (2006) 492–499

INTERNATIONAL JOURNAL OF MACHINE TOOLS & MANUFACTURE
DESIGN, RESEARCH AND APPLICATION

www.elsevier.com/locate/ijmactool

The effect of tool geometry on regenerative instability in ultrasonic vibration cutting

M. Xiao[a,*], Q.M. Wang[a], K. Sato[b], S. Karube[b], T. Soutome[b], H. Xu[a]

[a]School of Mechanical and Power Engineering, East China University of Science and Technology, 130 Meilong Road, Shanghai 200237, China
[b]Department of Mechanical Systems Engineering, Utsunomiya University, 7-1-2 Yoto, Utsunomiya, Tochigi 321-8585, Japan

Received 13 December 2004; accepted 4 July 2005
Available online 27 September 2005

Abstract

Ultrasonic vibration cutting as a cutting process has been widely used in the precision machining of difficult-to-cut materials due to an enhanced cutting stability and increased productivity. The authors' previous researches have shown that chatter vibration prediction is made possible by the suggested cutting model. This paper is an attempt to determine cutting parameters based on regenerative chatter prediction in order to facilitate the machining objectives of high accuracy, high efficiency and low cost in ultrasonic vibration cutting. The machinability of SCM440 steel, called typical hardened steel, is investigated theoretically and experimentally. The cutting model is developed by introducing an experimental cutting database of SCM440 steel. The simulation and experimental results show that the workpiece material parameter has a direct influence on the occurrence of regenerative chatter. In order to achieve the chatter-suppressing dynamics in hard ultrasonic vibration cutting, a stability diagram is predicted based on the simulated work displacement for tool geometry changing. The stability diagram indicates that the regions of the chatter-suppressing dynamics expand with increasing tool rake angle and decreasing tool clearance angle. It is also found from the predictive results that regenerative chatter can be suppressed by a change of tool geometry. The determined tool geometry with the aid of the computer simulation is demonstrated through actual data of ultrasonic vibration cutting. By the use of the designed tool geometry, a good experimental result is achieved.

Keywords: Tool geometry; Stability diagram; Cutting model; Regenerative chatter; Computer simulation; Ultrasonic vibration cutting; Hard cutting

1. Introduction

Because of high cutting stability and low cutting force, ultrasonic vibration cutting has been widely applied in machining various hard materials such as hardened steel, ceramics and nickel-base alloy [1–6]. The fundamental feature of this cutting method is that the tool edge is repeatedly separated from the workpiece. The advantage of this kind of intermittent cutting is that it allows for a high accuracy and a low tool wear ratio [5,7]. As it is well known, the regenerative instability of the ultrasonic vibration cutting process still occurs in some materials such as hardened steel [5,8,9]. During the cutting process, the regenerative instabilities are affected by many factors such as workpiece and tool material properties, machine stiffness, tool geometry and cutting edge sharpness, nominal cutting conditions such as feed and depth of cut, etc. [2,5,10]. In some recent research works, the authors have proposed a new cutting model including the ultrasonic vibration cutting process to predict the occurrence of regenerative chatter [2]. With the aid of the chatter cutting model, we investigate some factors such as tool geometry and tool nose radius. For the chatter-suppressing dynamics, the machining accuracy agreed with the predictive theoretical value [2,5].

The fundamental objectives of all the machining methods are high accuracy, high efficiency and low cost. In this paper, the dynamic cutting processes using our cutting model are simulated for ultrasonic vibration cutting of SCM440 hardened steel (AISI4340) in order to facilitate greater harmony of these objectives. Since this metal material has higher hardness and tensile strength than normal carbon steel, we introduce an experimental cutting database of SCM440 hardened steel [2,5,11] in determining the cutting force components of the cutting model.

* Corresponding author. Tel: +86 21 64253264; fax: +86 21 64253264.
E-mail address: mxiao@ecust.edu.cn (M. Xiao).

0890-6955/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2005.07.002

The simulation and experimental results show that the workpiece material parameter has a direct influence on the occurrence of regenerative chatter in ultrasonic vibration cutting. In order to achieve the chatter-suppressing dynamics in hard ultrasonic vibration cutting, a stability diagram is predicted based on the simulated work displacement for tool geometry changing. The stability diagram indicates that the regions of the chatter-suppressing dynamics expand with increasing tool rake angle and decreasing tool clearance angle. It also is found from the predictive results that regenerative chatter under a general range ultrasonic vibration cutting condition can be suppressed by a change of tool geometry. Comparisons of the simulation and experimental results are given to verify the designed tool geometry.

2. Modeling

2.1. Mechanism of ultrasonic vibration cutting

Fig. 1 illustrates a schematic diagram of ultrasonic vibration cutting. The system comprises a rotary cylindrical workpiece with a cutting velocity v and an oscillating tool along its cutting direction at a frequency f with an amplitude a. Fig. 2 shows the ultrasonic vibration cutting mechanism. The displacement x of the oscillating tool can be given by $x = a \sin \omega t$, where ω and t are the angular velocity of the tool and the cutting time, respectively. The displacement of the cutting tool starts to cut at t_a and separates the workpiece from t_b. At $t = t_b$, the tool vibration velocity $\dot{x} = a\omega \cos \omega t_b$ and the cutting velocity v is given by $v + a\omega \cos\omega t_b = 0$. Thus, if $2\pi af > v$, the expression has solutions and a cutting force of pulse type is generated. Since the distance between the oscillating tool and the moved workpiece in the interval from b to a' is equal, the relation can be obtained from:

$$a \sin \omega\left(\frac{2\pi}{\omega} + t_{\mathrm{a}}\right) - a \sin \omega t_{\mathrm{b}} = v\left(\frac{2\pi}{\omega} + t_{\mathrm{a}} - t_{\mathrm{b}}\right) \quad (1)$$

The edge contact rate r is defined as the net cutting ratio at each tool vibration period T:

$$r = \frac{t_c}{T} = \frac{t_b - t_a}{T} \quad (2)$$

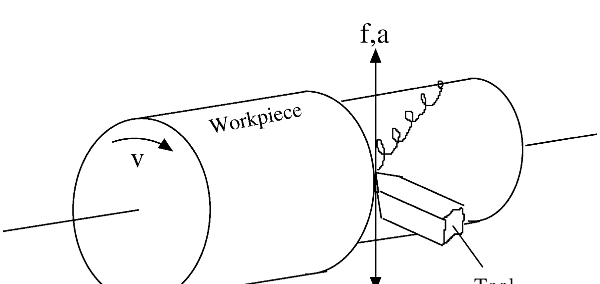

Fig. 1. Schematic diagram of ultrasonic vibration cutting.

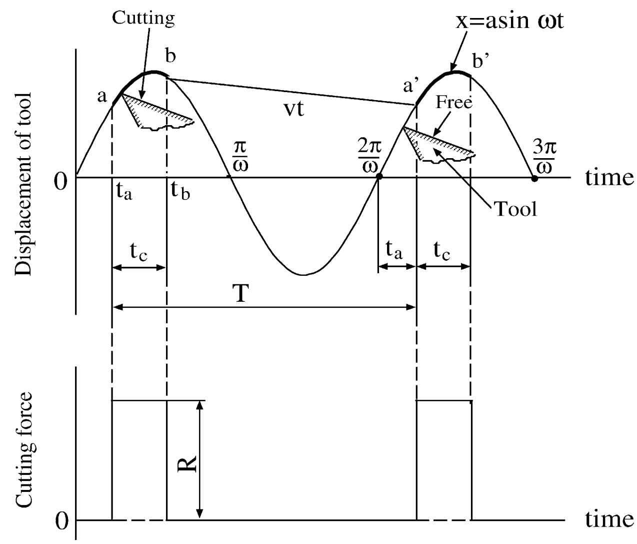

Fig. 2. Mechanism of the pulse cutting force in ultrasonic vibration cutting.

These relation can be written as:

$$\frac{af}{v} = \frac{1 - r}{2 \sin \pi r \cos\left[\cos^{-1}\left(-\frac{v}{2\pi af}\right) - \pi r\right]} \quad (\text{for } 2\pi af > v) \quad (3)$$

Additionally, the pulse cutting force R_{uvc} is given by $R_{uvc} = R\tau(t,r)$, where R is a cutting force of the ordinary cutting and $\tau(t,r)$ is an edge contact unit step given by the

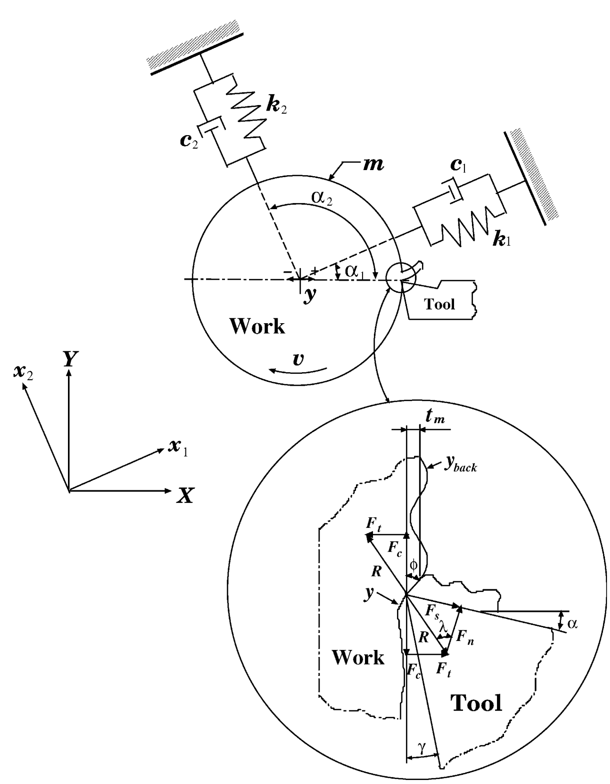

Fig. 3. Vibration model of chip formation with two degree of freedom.