Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

International Journal of Machine Tools & Manufacture 46 (2006) 623–630

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

www.elsevier.com/locate/ijmactool

Investigation of the torque characteristics in vibration tapping of hardened steel

Baolin Yin*, Rongdi Han

Department of Mechanical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, People's Republic of China

Received 1 February 2005; accepted 7 July 2005
Available online 6 September 2005

Abstract

Vibration tapping is presented in this paper to solve this problem, as high-speed steel tap is incapable of tapping small-hole (M3) in hardened steel (50HRC). Theoretical analysis with fracture mechanics indicates that the impact effect of the tap on the workpiece results in increased II-type stress intensity factor and extended micro cracks, leading to lower plastic deformation, reduced cutting forces and a much lower tapping torque, and the torsional rigidity of the tap is enhanced in vibration tapping as proved by dynamic analysis. The experimental results show that with well chosen amplitudes, tapping torque decreases as vibration frequency increases, and tapping torque increases as net cutting time ratio increases, where net cutting time ratio influences the tapping torque more significantly. Vibration tapping is then proved to be a practical solution to the problem of small-hole tapping in hardened steel.

Keywords: Vibration tapping; Hardened steel; Micro crack; Tapping torque; Torsional rigidity

1. Introduction

Small-hole tapping (M3) in hardened steel (>45HRC) is a very difficult task. Hardened 0.45%C steel possesses high strength ($\sigma_b \approx 1700$ MPa) and the tapping torque (M3) in these materials is approximately 1.3 N m. Therefore, tap breakage appears to be one of the major problems in the process, possibly due to excessive torque. Hardened steel possesses high hardness, which is close to the hardness of high-speed steel (HSS) tap. It always causes machining troubles such as tool wear and tipping. High tapping torque results in other problems associated with the tapping vibration chatter including thread dimensional accuracy and thread shape error. It is clear that conventional process could not fulfill the requirement of small-hole tapping for hardened steel in view of tap strength, hardness and torsional rigidity. However, with the rapid development of modern manufacturing technologies, such as aircraft and space shuttle, some components need to be tapped after being quenched, taking geometrical accuracy and surface strength into account. Traditionally, the machining of hardened steel components is the domain of grinding operations.

The technology of vibration cutting presented 50 years ago by Kumabe [1] has various effects, e.g. reducing cutting force, improving surface quality, restraining tool wear, and so on. Vibration tapping has been applied to titanium alloys and other materials to increase the tapping efficiency and reduce the overall tapping torque. There have been many contributions to vibration tapping on different materials under different process conditions [2–5].

Zhang [2] built a vibration-assisted tapping device, in which a piezoelectric actuator was used to generate vibration along the axis of the tap at a frequency of 50–1600 Hz and an amplitude of 0.1–5 μm. It turned out that a torque reduction was always obtainable in vibration tapping of brass. Zhang [3] and Gou [5] carried out the experiments on vibration tapping in titanium alloys. It was reported that the frictional torque was reduced and the tap life was prolonged. Patil [4] carried out the research on the influence of different process conditions on tapping torque and thrust during machining, and optimum conditions were found to lengthen the tap life.

However, little information can be available on vibration tapping of hardened steel. A systematic investigation is therefore of great importance. This paper presents theoretical analyses on two major mechanisms for vibration tapping of hardened steel, i.e. reduction of tapping torque

---

* Corresponding author.
E-mail address: baolin_yin@hit.edu.cn (B. Yin).

0890-6955/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmachtools.2005.07.014

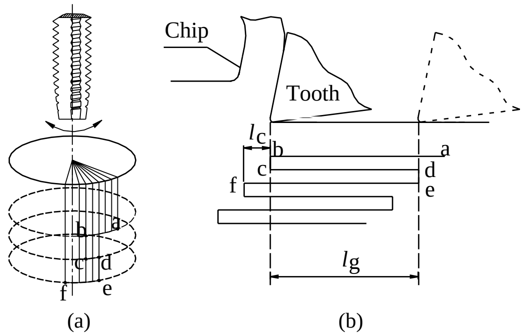
Nomenclature

a_p	depth of cut
a	reciprocal of dilatational wave velocity
A	vibration amplitude in vibration tapping
b	reciprocal of shear wave velocity
c'	viscous damping coefficient
c	reciprocal of Raleigh wave velocity
C	the constant sensitive to tool orthogonal rake
f	forced vibration frequency in vibration tapping
f_s	feed
F_c	cutting force
F_{ci}	torsional force on the tap resulting from the elementary cutting edge
J	rotational inertia
K_{II}	II-type stress intensity factor
l_c	net cutting distance in each vibration cycle
l_g	the largest separation distance in each vibration cycle
M	tapping torque
M_c	the maximum impulse torque in vibration tapping
M_f	frictional torque
n_c	net cutting time ratio in vibration tapping
p	intensity of pulsating force
R_i	the radial distance from the axis of rotation to a point on the ith cutting edge
S	torsional rigidity of the tap
S_n	nominal torsional rigidity of the tap in vibration tapping
t	time
t_c	net cutting time in each vibration cycle
T	vibration cycle
u_i	the displacement vector, the subscript denoting the direction of displacement
ν	Poisson ratio
Λ_h	chip thickness compressing ratio
γ_o	tool orthogonal rake
θ	torsional angle of the tap in vibration tapping
θ'	torsional angle of the tap in conventional tapping
σ_{ij}	the stress component. The first subscript indicates the direction of the normal to the plane on which the stress acts and the second subscript indicates the direction of the stress itself
τ_s	shear yield strength
ϕ	shear plane angle
ϕ_n	nominal shear plane angle in vibration tapping
μ	shear modulus
ξ	the damping ratio
ω	forced vibration circular frequency in vibration
ω_n	natural frequency

and enhancement of torsional rigidity of the tap. The tapping experiments were also carried out to verify the theoretical analyses.

2. Theoretical analysis of vibration tapping process

Fig. 1(a) shows the torsional vibration tapping process. In order to simplify analysis, the process is simplified to an orthogonal cutting model for a single cutting tooth as shown in Fig. 1(b). The motional locus of the tool edge in the operation of separative vibration cutting is shown in Fig. 1. In each vibration cycle, a layer of metal is cut ahead of the tooth in a distance l_c. From point c to d, separation between the rake face and the chip occurs. The distance between c and d is specified by l_g. Subsequently the tooth comes back to the workpiece, which moves from point e to f, with the contact between the tooth and the chip being re-established, so that the new vibration cycle is formed. The pulsating cutting force and the alternate motion due to vibration application are the two major mechanisms, which are different from conventional processes.



(a) (b)

Fig. 1. Cutting model for vibration tapping.

2.1. Reduction of tapping torque in vibration tapping

Fig. 2 shows the mechanism of pulsating cutting force generation in vibration tapping. A transversely isotropic,

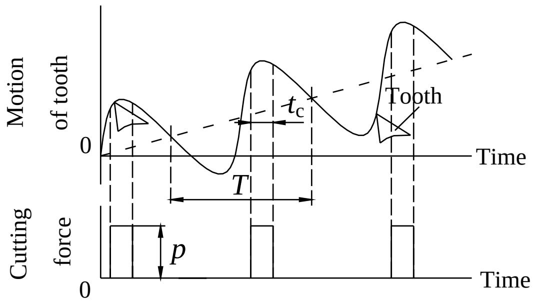


Fig. 2. Mechanism of the pulsating cutting force in vibration tapping.