CIRP Journal of Manufacturing Science and Technology 7 (2014) 159–167

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

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

Thermally enhanced ultrasonically assisted machining of Ti alloy

Riaz Muhammad [a,*], Agostino Maurotto [b], Murat Demiral [c], Anish Roy [c],
Vadim V. Silberschmidt [c]

[a] Department of Mechanical Engineering, CECOS University of IT and Emerging Sciences, Peshawar, KPK, Pakistan
[b] The University of Sheffield, Nuclear Advanced Manufacturing Research Centre, Sheffield, South Yorkshire S60 5WG, UK
[c] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

ARTICLE INFO

Article history:
Received in revised form 8 January 2014
Accepted 9 January 2014
Available online 4 February 2014

Keywords:
Ultrasonic machining
Hot ultrasonically assisted turning (HUAT)
Hot machining
Ti alloy
Cutting forces
Surface roughness

ABSTRACT

Recently, a non-conventional machining technique known as *ultrasonically assisted turning* (UAT) was introduced to machine modern alloys, in which low-energy, high-frequency vibration is superimposed on the movement of a cutting tool during a conventional cutting process. This novel machining technique results in a multi-fold decrease in the level of cutting forces with a concomitant improvement in surface finish of machined modern alloys. Also, since the late 20th century, machining of wear resistant materials that soften when heated has been carried out with hot machining techniques.

In this paper, a new hybrid machining technique called hot ultrasonically assisted turning (HUAT) is introduced for the processing of a Ti-based alloy. In this technique, UAT is combined with a traditional hot machining technique to gain combined advantages of both schemes for machining of intractable alloys. HUAT of the Ti alloy was analysed experimentally and numerically to demonstrate the benefits in terms of reduction in the cutting forces and improvement in surface roughness over a wide range of industrially relevant speed-feed combinations for titanium alloys.

1. Introduction

In recent decades, titanium alloys have gained widespread application in the aerospace community primarily due to a balanced set of desirable properties, such as light weight, high-strength, good fatigue strength and resistance to corrosion. As a result, Ti alloys are gaining wider application in automotive and biomedical industries. However, these alloys are notoriously difficult to machine owing to several inherent properties of the material. These include low thermal conductivity, which impedes heat transfer out of a cutting zone, generating high process-zone temperatures. Consequently, conventional machining of these alloys leads to poor surface finish and low dimensional accuracy in machined components (Dandekar et al., 2010). Additionally, these alloys are chemically reactive with almost all cutting tool materials, impairing machinability of components (Brecher et al., 2010) features low production rates in their machining.

In the past, most machining operations benefitted from the use of cutting fluids. For manufacturing companies, the costs related to cutting fluids primarily; due to handling of cutting fluids as well as their disposal represent a large amount of the total machining costs. Therefore, dry machining is of great interest due to the current demand for green manufacturing processes (Weinert et al., 2004). Dry machining based on conventional cutting processes poses new challenges as it produces high cutting forces, poor surface finish and poor dimensional accuracy (Machai and Biermann, 2011). As a result, several finishing steps need to be incorporated into a manufacturing process in order to obtain the desired quality of components, increasing the overall machining cost.

New techniques have been proposed to improve machinability of Ti alloys, for instance, cryogenic machining with the use of carbon-dioxide snow (Machai and Biermann, 2011) and liquid nitrogen (Hong et al., 2001). Application of those new techniques affected chip shapes and also improved the surface roughness of the machined components (Yuan et al., 2011).

The shear strength and strain-hardening rate of high-strength materials decrease with an increase in temperature due to thermal softening. Therefore, external heat can be supplied to the workpiece materials to make it softer and easier for a cutting tool to remove a given amount of material, this technique is called *hot machining* (Ezugwu and Wang, 1997). Various types of heat sources have been used for thermal softening of the workpiece materials, for instance, gas torch (Lajis et al., 2009; Maity and Swain, 2008; Ozler et al., 2001; Pal and Basu, 1971), furnace pre-heating (Amin and Talantov, 1986), induction heating (Amin et al., 2008), electric-current heating (Uehara et al., 1983), plasma

---

[*] Corresponding author. Tel.: +92 3452613935.
E-mail addresses: R.Muhammad@outlook.com, R.Muhammad@cecos.edu.pk (R. Muhammad).

1755-5817/$ – see front matter © 2014 CIRP.
http://dx.doi.org/10.1016/j.cirpj.2014.01.002

heating (Kitagawa and Maekawa, 1990) (Germain et al., 2011; Hinds and De Almeida, 1981) and laser heating (Chryssolouries et al., 1997; Sun et al., 2008).

The flame torch is a relatively simple way to heat up a workpiece to a required temperature level. However, this method of heating cannot be used in machining of Ti-based alloys since the torch deposits carbon particles and produces a carbide layer on the specimen. Induction heating is an effective heat source in hot machining. However, it is not efficient in non-ferrous materials. The direct current could be a good alternative for heating; however, the main limitation of direct current is it dependency on cutting speed.

Laser and plasma arcs are the most effective sources of localised heating used in hot machining. However, the capital cost, requirement of high human skills and health concerns are the main obstacle for a use of these methods in hot machining.

Ultrasonically assisted turning (UAT) is a non-conventional machining technique that employs superposition of high-frequency ($f \sim 20$ kHz) and low-amplitude ($a \sim 15$ μm) vibro-impacts on the cutting tool, preferably, in the cutting direction (Babitsky et al., 2004; Maurotto et al., 2013; Muhammad et al., 2013). The first vibration-assisted machining technique was used in the 1960s by Skelton (1968). This novel technique offered a significant improvement in processing of modern alloys by reducing the level of cutting forces considerably, and provide a better surface finish of machined components (Moriwaki et al., 1992). Furthermore, 2D ultrasonically assisted machining was also carried out to investigate cutting forces and surface roughness in a machined component (Shamoto et al., 1999). Recently, analytical models were developed for ultrasonically assisted oblique turning (Nategh et al., 2012) that elucidated underlying complexity of the process.

Over the last few decades, a significant amount of work has been carried out in improving the experimental setup of UAT as well as in development of numerical models of the process (Maurotto et al., 2012; Muhammad et al., 2012a,c). A significant reduction in cutting forces was reported in machining of Ti-15V3Cr3Al3Sn designated as Ti-15333.

However, there is still a need for improvement of the machining process to further reduce cutting forces in turning of Ti-15333. So, conventional hot machining technique was combined with UAT to form a new hybrid turning process called *hot ultrasonically assisted turning* (HUAT). In this paper, cutting forces, temperature of the process zone and surface roughness of a workpiece machined with HUAT are analysed at various cutting conditions. To study the underlying deformation mechanism in the material, a finite element orthogonal turning model was developed to investigate stresses and temperature of the process zone in the vicinity of the cutting tool-workpiece interaction zone that is not possible in experimentations due to the opaque nature of the workpiece material.

2. Experimental work

2.1. Experimental setup

A universal lathe machine was appropriately modified in house to mount a band resistance heater around the cylindrical workpiece during the machining process in addition to a customised ultrasonic cutting head (Fig. 1). A Kistler piezo-electric dynamometer with a sensitivity of ±0.1 N (KIAG-SWISS Type-9257A) bolted on the cross slide of the Harrison lathe was used to record cutting forces in real time. The dynamometer has a recording frequency of 3 kHz and is capable of force measurements up to 5 kN. The frequency of the data-acquisition system is lower than the excitation frequency of an ultrasonic transducer; as a result, average cutting forces were recorded, especially in the ultrasonic machining process. To monitor vibrational characteristics of the tool during all experimental runs, a non-contact measuring technique based on a laser vibrometer was used.

For hot machining tests, a band-resistance heater, encapsulating the workpiece, was used as a heat source to increase the temperature of the workpiece to $300\,^{\circ}\mathrm{C} \pm 10\,^{\circ}\mathrm{C}$. For thermal measurements, a teflon coated, K-type thermocouple, with a maximum measurement range of $1200\,^{\circ}\mathrm{C}$ and a thermal camera (FLIR ThermaCAM$^{\mathrm{TM}}$ SC3000) for real time acquisition were used. A 4-channel K-type thermometer HHM290/N was used to record the measured temperatures. The new stirling-cooled quantum well infrared photon (QWIP), enable the FLIR ThermaCAM system to capture images at low-noise detection and high image stability and uniformity. Further details of the system are listed in Table 1. In experimentation, a continuous mode of recording was employed to capture a thermal distribution in the process zone in conventional and assisted turning processes. The ThermaCAM® QuickView$^{\mathrm{TM}}$ software was used to analyse the data of the *FLIR ThermaCAM*$^{\mathrm{TM}}$ *SC3000* system. A typical temperature distribution on the surface of workpiece in hot machining at $300\,^{\circ}\mathrm{C}$ is shown in Fig. 2.

In the thermal analysis of the process zone, the heater movement was controlled manually. The camera mounted on the cross slide was moved away from the heater to avoid any thermal damage to the infra-red system during the heating time, as suggested by the manufacturer. The heater was used to heat up the workpiece to a required temperature and then removed from the workpiece material during the turning test.

Subsurface deformation and micro structural changes in the machined surface depend on the maximum temperature rise in the process zone in turning operation. Thus development of new tool materials as well as the advancement of machining technology will depend, to a large extent, on the knowledge and limitations of cutting temperatures that influenced the life and performance of the tool. To date, many experimental (Lajis et al., 2009), analytical (Krabacher et al., 1951), and numerical methods (Childs, 2011; Muhammad et al., 2010, 2011, 2012d) were developed to determine the temperature levels during the cutting process.

2.2. Surface roughness and sub-surface analysis

The surface quality in machining operations directly affects machining economics (Childs, 2010). The surface topography of machined workpiece depends on machining parameters, parameters of interface at the cutting tool tip and instability of the cutting process (chatter).

The irregularities on the surface, in different patterns, tend to form a texture that ultimately determines machining quality and is directly related to the structural integrity of machined parts. In this study, Zygo® interferometry was used to analyse conventional turning (CT), hot conventional turning (HCT) and HUAT. This technique characterises and quantifies surface roughness, step heights, critical dimensions, and other topographical features with excellent precision and accuracy. All measurements are non-destructive, fast and require no sample preparation. Additionally, it provides high-resolution graphical images and numerical tools to characterise accurately the surface structure of the test parts. The Zygo® interferometry instrument NewView$^{\mathrm{TM}}$ 5000 series was used for surface topology analysis of the machined workpiece.

It is well known that Ti alloys are sensitive to oxidation at elevated temperatures due to their high reactivity with oxygen. In the current study, the entire tests were carried in the open air without protective atmosphere. In order to investigate microstructure of a material machined with CT, HCT and HUAT, light microscopy was carried out using Nikon Optiphot, with a GXCAM-5 acquiring system.