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Surface Integrity in End Milling Titanium Alloy Ti-6Al-4V under Heat Assisted Machining

[1]Turnad L. Ginta and [2]A.K.M. Nurul Amin

[1]Department of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia
[2]Manufacturing and Materials Engineering, Faculty of Engineering, International Islamic University Malaysia, P.O. Box 10, 50728, Kuala Lumpur, Malaysia

Corresponding Author: Turnad Lenggo Ginta, Department of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

ABSTRACT

The advantages of cutting fluids have been strongly debated because of their negative effects on the environment and the health of operators using them. A trend to solve these problems is to use hot machining or heat assisted machining which has been made possible due to technological innovations. However, the effect of heat assisted machining on the surface integrity must be widely investigated. This study presents the effects of heat assisted machining on the surface integrity during end milling of titanium alloy Ti-6Al-4V using uncoated tungsten carbide inserts. The effects of heating temperature on surface integrity are presented. The machined surface was cut and examined below Scanning Electron Microscope (SEM). Vickers micro-hardness distributions below the machined surface were also investigated.

Key words: Thermal-assisted machining, induction coil heating, Ti-6Al-4V, vibration, end milling

INTRODUCTION

Titanium alloys are widely used in aerospace, biomedical and chemical industries primarily due to the exceptional strength to weight ratio, high temperature performance and corrosion resistance. Furthermore, almost all titanium monolithic components in aerospace industry are manufactured by milling. However, titanium alloys are typically difficult-to-cut materials due to the high strength at elevated temperatures, low modulus, low thermal conductivity and high chemical reactivity (Canter, 2009). Because of high temperature generated during cutting titanium alloys, high flooded cutting fluids are required to decrease the temperature and to save the cutting tools.

Due to its negative effect, the reduction of cutting fluid must be considered. The United Auto Workers suggested the Occupational Safety and Health Administration (OSHA) to decrease the permissible exposure limit for metalworking fluids from 5.0 to 0.5 mg m^{-3}. Furthermore, OSHA established the Metalworking Fluid Standards Advisory Committee (MWFSAC) in 1997 to develop standards or guidelines related to metalworking fluids. In its final report in 1999, MWFSAC recommended that the exposure limit be 0.5 mg m^{-3} and that medical surveillance, exposure monitoring, system management, workplace monitoring and employee training are necessary to monitor worker exposure to metalworking fluids (Sun and Guo, 2009).

The quality and performance of a product is directly related to surface integrity achieved by final machining includes the mechanical properties (residual stresses, hardness etc.), metallurgical states (phase transformation, microstructure and related property variations, etc.) of the work material during processing and topological parameters such as finish and other topographical features. If critical structural components in aerospace industry are machined to reach high reliability levels, surface integrity is one of the most important parameters used for evaluating the quality of machined surface (Ulutan and Ozel, 2011).

Some metal cutting researchers focus their interests in surface integrity. The difference between belt and bob polishing methods for surface integrity of titanium alloy Ti-6Al-4V was investigated (Axinte *et al.*, 2009). It was found that both were capable to meet the requirements of minimum workpiece surface coverage if optimised operating parameters were employed. Huang and Ren (1991) investigated the effect of surface integrity on fatigue life of nickel base super alloy GH33A. It was concluded that under the condition of low-cycle fatigue, surface roughness became the main factor and surface hardening had an unfavourable influence on the fatigue life, while the residual stress could be neglected because of its relaxation under the applied loads. Arunachalam *et al.* (2004) studied the surface integrity after machining of Inconel 718 with uncoated tungsten carbides. This investigation, suggested that coated carbide cutting tool inserts of round shape, chamfered cutting edge preparation, negative type and small nose radius (0.8 mm) and coolant would generate primarily compressive residual stresses. Reddy *et al.* (2008) studied the surface integrity of Al/SiC particulate metal matric composite after end milling process. The results showed that the presence of the reinforcement enhanced the machinability in terms of both surface roughness and lower tendency to clog the cutting tool, when compared to a non-reinforced Al alloy. Umbrello and Filice (2009) used modelling white and dark layers formation in for improving the surface integrity in orthogonal machining of hardened AISI 52100 steel. In their study, a hardness-based flow stress and an empirical model for describing the white and dark layers formation were developed and implemented in a FE code. Pusavec *et al.* (2011) investigated the surface integrity in cryogenic machining on nickel alloy Inconel 718. The results showed that cryogenic machining processes could be implemented to improve all major surface integrity characteristics, thus improving the final product quality level.

The current paper is aim to investigate the surface integrity of titanium alloy Ti-6Al-4V after end milling with uncoated tungsten carbide inserts under heat assisted machining using high frequency induction heating. The both topography of the machined surface and the hardness beneath the surface were studied.

MATERIALS AND METHODS

End milling tests were conducted on Vertical Machining Centre (VMC ZPS, Model: MLR 542). Titanium alloy Ti-6Al-4V bar was used as the work-piece. Machining was performed with a 20 mm diameter end mill tool holder fitted with one insert. Uncoated tungsten carbide inserts were used in the experiments. All of the experiments were run under on line heating. High frequency induction heating was utilized to run the heat assisted machining. The experimental set up for the machining is shown in Fig. 1. Surface integrity of machined surface was done by employing Scanning Electron Microscope (SEM). The objective of the investigation is to identify the presence of defects, such as cracks, droplets of built up edge or chip fragments on machined surface. For this investigation the distribution of the microhardness below the surface layer were recorded under different heating temperature. Apart from that the microstructure of the layer below the surface

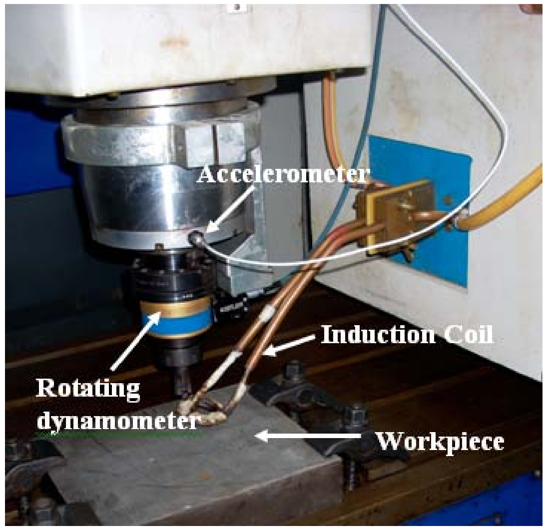

Fig. 1: The experimental setup

was also investigated. Distributions of micro-hardness measured up to certain depth beneath the surface after end milling under room temperature and on line heating machining were also investigated. The measurements were taken at a length interval of 0.01 mm starting from the top surface up to a depth of 0.5 mm beneath the surface.

RESULTS AND DISCUSSION

To the naked eye, all the machined workpiece surfaces looked excellent, however, worsening was evident in the same samples observed under SEM. Figure 2 is clearly observed the presence of some chip fragments and Built-Up Edge (BUE) on the surface for both room temperature and heat assisted machining. High temperature generated during cutting of Ti-6Al-4V is substantially responsible in the build-up of chip fragments on the machined surface which finally depreciates the surface finish.

Distributions of microhardness are presented in Fig. 3. The measurements were taken at a length interval of 0.01 mm starting from the top surface up to a depth of 0.5 mm beneath the surface. According to the hardness, the surface layer is divided into three zones, namely heat affected zone (Zone I), strain hardened zone (Zone II) and the base material (Zone III). Microhardness in Zone I is relatively lower than that of the strain hardening zone (Zone II) and the base materials (Zone III) as shown in Fig. 3. It may be related to the fact that the heat which is generated during cutting considerably acts in softening the thin layer below the surface.

This heat is reasonably adequate as a driving force to promote annealing arrangements within the microstructures. As the preheating temperature increases, the driving force for annealing obviously increases which results in lower microhardness. For instance, the distribution of micro hardness after end milling at online heating temperature of 650°C is slightly lower compared to those of under room temperature and preheated machining at 315°C, as shown in Fig. 3. It is related to the fact that the density of the dislocation is suddenly lower, which reduces the effects of strain hardening and therefore decreases the hardness. From the Fig. 3 it is also shown that

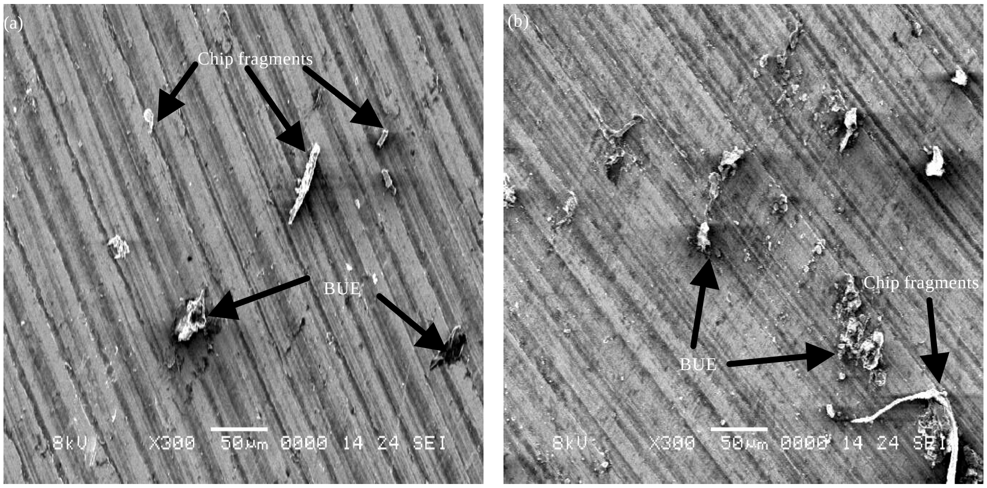

Fig. 2(a-b): SEM Image of machined surface in end milling at, (a) Room temperature and (b) 650°C, Cutting speed = 70 m min^{-1}, axial DOC = 1 mm, Feed = 0.088 mm tooth^{-1}

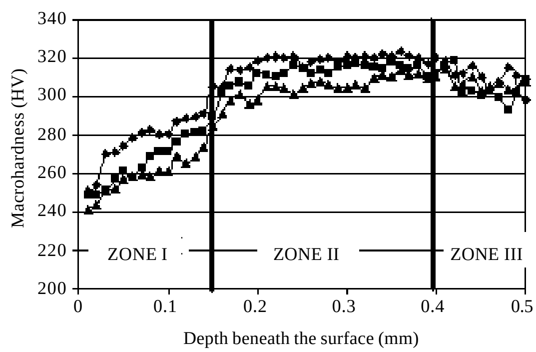

Fig. 3: Microhardness value beneath the machined Cutting speed = 70 m min^{-1}, axial DOC = 1 mm, Feed = 0.088 mm tooth^{-1}

Zone I reaches the range of up to ~0.15 mm below the surface. In the zone more than 0.15 mm from the surface, the effect of heating substantially decreases, which is inadequate as driving force for annealing arrangement. Due to the plastic deformation, the micro hardness in this zone (Zone II) is also relatively high and then considered as strain hardening zone. Moreover, as the distance from the surface increases, the strain hardening effect caused by shearing and plastic deformation gradually decreases and as a result, the distribution hardness returns to the initial value (base metal). In this case, the distance of strain hardening zone is found up to 0.4 mm beneath the surface.

Under room temperature machining, the heat generated during cutting has less effects on the microstructure alteration. No grain growth is occurred in this condition, as presented in Fig. 4a. As the preheating temperature increases, there is an adequate driving force for atomic arrangement, initiating and establishing grain growth, as shown in Fig. 4b. The sizes of the grains are

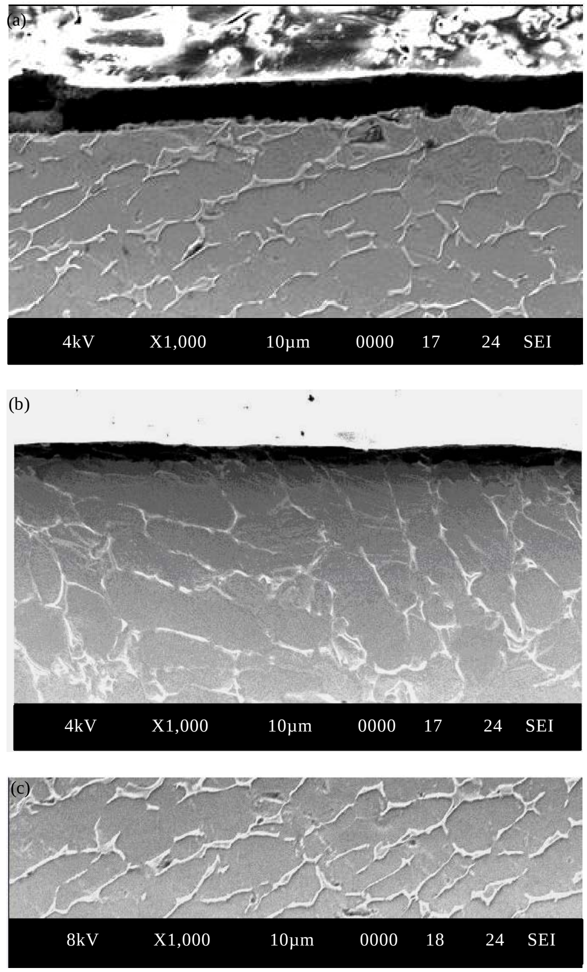

Fig. 4(a-c): Microstructure alterations in end milling with uncoated WC-Co inserts at (a) Room temperature and (b) Preheating at 650°C and (c) The base metal

substantially bigger compared to the grain size of the base metal (Fig. 4c). In metallurgy terms, an increase in the size of grains decreases the hardness of the materials.

CONCLUSIONS

The presence of some chip fragments and built up edge on the surface for both room temperature and heat assisted machining are observed. High temperature generated during cutting of Ti-6Al-4V is substantially responsible in the build-up of chip fragments on the machined surface which finally depreciates the surface finish.

Subsurface alternation has been investigated in the present study and it proves that machining substantially furnish effects from the top surface into the beneath of the workpiece. Strain hardening phenomena was found during heat assisted machining. Meanwhile, grain growth phenomenon also occurs. The higher the preheating temperature, the bigger the grain growth occurs, which is confirmed by the micro-hardness distribution beneath the surface.

Under room temperature machining, the heat generated during cutting has less effects on the microstructure alteration. No grain growth is occurred. An increase in preheating temperature substantially increases the driving force for atomic arrangement, initiating and establishing grain growth.

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