International Journal of Machine Tools & Manufacture 61 (2012) 20–26

Contents lists available at SciVerse ScienceDirect

International Journal of Machine Tools & Manufacture

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

Air jet assisted machining of nickel-base superalloy

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ARTICLE INFO

Article history:
Received 24 September 2011
Received in revised form
6 May 2012
Accepted 9 May 2012
Available online 23 May 2012

Keywords:
Air jet assisted machining
Nickel-base superalloy
Tool life
Tool wear
Tool cooling
Computational fluid dynamic analysis

ABSTRACT

Nickel-base superalloy has various excellent properties. However, in machining of this alloy, acceleration of tool wear results in short tool life and deterioration of the surface integrity. Therefore, it is difficult to conduct high-speed machining of this alloy. In this study, nickel-base superalloy was finish-turned with a coated cemented carbide tool at higher cutting speeds. A new lubrication method called air jet assisted (AJA) machining was applied for improving cooling and lubrication environment. The results of cutting experiments showed that the air jet assistance to the conventional wet machining extended the tool life to a certain extent effectively. Flow of cutting fluid was visualized through computational fluid dynamics analysis and improvement of cooling environment and tool life by means of air jet assistance in AJA machining were discussed from the heat transfer at the tool flank face.

1. Introduction

Nickel-base superalloy is widely used for various parts and structures for aerospace, marine, chemical processes, etc. because of its superior creep, corrosion and oxidation resistances, and very high toughness and strength at elevated temperatures. However, it is a typical difficult-to-machine material and has disadvantageous properties for machining: poor thermal conductivity, high strength at elevated temperatures, high work hardening coefficient and strong chemical affinity with tool material [1]. These properties are likely to increase temperature and stresses on the tool face, degrade the integrity of finished surface [2] and cause tool damages such as flank wear, notching wear, edge chipping etc. [3], resulting in short tool life.

For the above reason, every effort for increasing the cutting speed and cutting efficiency of this alloy has been made for many years. This includes development of cryogenic machining [4], hot machining with laser heating [5], hybrid machining [6], machining using high pressure coolant [4,7] and rotary machining [8]. Rotary machining with a spinning tool on a CNC multifunctional lathe [9] has become of major interest and is applied to rough machining lately. However, these special machining methods have not yet been applied in industries widely and commonly.

Development of cutting tools also has contributed to increase in cutting speed and cutting efficiency of this alloy. Fiber reinforced ceramics [7,10] and composite ceramics [5,11] have been applied to cutting tools for high speed machining. Lately, new CVD coated cemented carbide tools have been developed for machining at higher cutting speeds [12]. However, apart from rough machining, there is still no good solution for finish machining, to which a button insert is not usually applied.

A new lubrication method called air jet assisted (AJA) machining was reported as a solution of high-speed finish-machining of nickel-base superalloy [13]. In this machining method the jet of compressed air was applied to the tool tip in addition to cutting fluid in conventional wet machining. Preliminary experiments showed that AJA machining had a favorable effect on the tool life extension [13]. Application of this method to titanium alloy Ti-6Al-4V extended the tool life of an S10 type uncoated cemented carbide by 20% or more [14].

In this study, AJA finish-turning of nickel base superalloy Inconel 718 was conducted using a CVD coated carbide tool. Then, the influences of the cutting and lubrication conditions on the tool life were investigated. Nitrogen jet assisted wet machining was also performed and tool lives for different gases were compared. Computational fluid dynamics (CFD) analysis was conducted for visualizing the flow of cutting fluid around the tool tip engaged in machining. From the results mechanisms for improving cooling and lubrication environments in AJA machining were discussed in a quantitative manner.

2. Experimental method

In AJA machining, not only cutting fluid but a jet of compressed air as well is applied to the tool tip as shown in Fig. 1

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http://dx.doi.org/10.1016/j.ijmachtools.2012.05.005

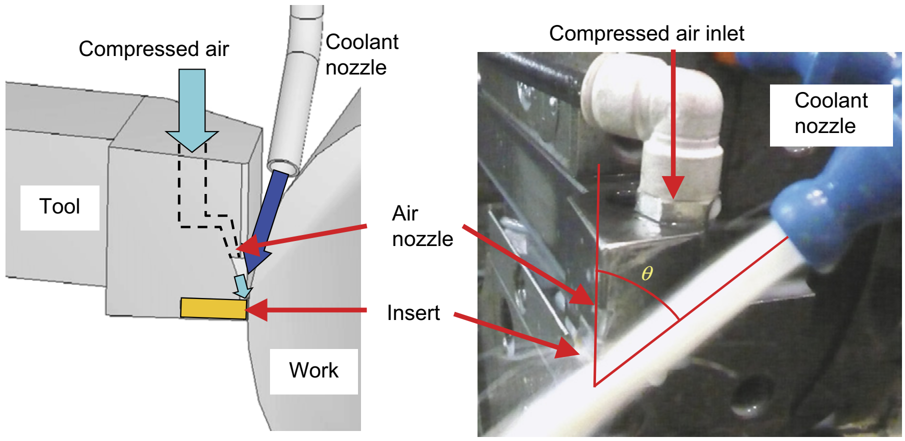

Fig. 1. A schematic of AJA machining method and application angle θ.

schematically. The air jet was applied to the tool tip from an air nozzle at the flank face of a tool holder as in the case of minimum quantity lubrication machining [15], but without oil mist. The cross section and inner diameter of the air nozzle were 0.95 mm^2 and 1.1 mm, respectively. The distance from the air nozzle to the tool tip was 12.0 mm. The pressure of compressed air for generating the air jet was fixed at 0.54 MPa in gauge pressure. Its flow rate was measured to be 61.7 l/min (NTP) using an area flowmeter. Its mean velocity was calculated to be 175 m/s on the assumption that its pressure was kept at 0.54 MPa at the exit of the nozzle.

By contrast, an emulsion type of cutting fluid was applied to the tool tip in both AJA and conventional wet machining. The concentration and flow rate of the cutting fluid were 6.7% and 5.25 l/min, respectively. The distance from the exit of the coolant nozzle to the tool tip was 50 mm. The inner diameter of the nozzle was 9.0 mm at the exit; hence, the mean velocity of the cutting fluid at the nozzle exit v_L was calculated to be 1.375 m/s (82.5 m/min). The application direction of cutting fluid was set at

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} \tan\lambda/A \\ 1/A \\ \tan\theta/A \end{pmatrix} \tag{1}$$

with

$$A = \sqrt{\tan^2\lambda + 1 + \tan^2\theta} \tag{2}$$

where X, Y and Z are the depth-of-cut direction, cutting direction and feed direction, respectively. Because angle λ is fixed at -5°, angle θ shown in Fig. 1 is a single variable called the application angle of cutting fluid.

The work material was Inconel 718 precipitation-hardened to Vickers hardness 460 HV. An S01 grade insert of CVD-coated cemented carbide with two main coating layers of TiCN and Al_2O_3 was used for finish turning Inconel 718 on a CNC lathe. The types of the insert and its holder were CNMG120404-MJ and PCLNR2525, respectively. Cutting conditions were depth-of-cut a_p=0.2 mm, feed rate f=0.1 mm/rev and cutting speed v_c=1.3 and 1.5 m/s (V=78 and 90 m/min). The tool life criterion adopted according to the tool manufacturer's recommendation was the maximum width of flank wear VB_{max}=0.16 mm. Beyond this criterion, large cutting edge recession was often caused by the expansion of the crater wear to the cutting edge.

Tool wear tests were first conducted in AJA and conventional wet machining at cutting speed 1.3 and 1.5 m/s and $\theta=20^\circ$ and then, at cutting speed 1.5 m/s and different application angles of

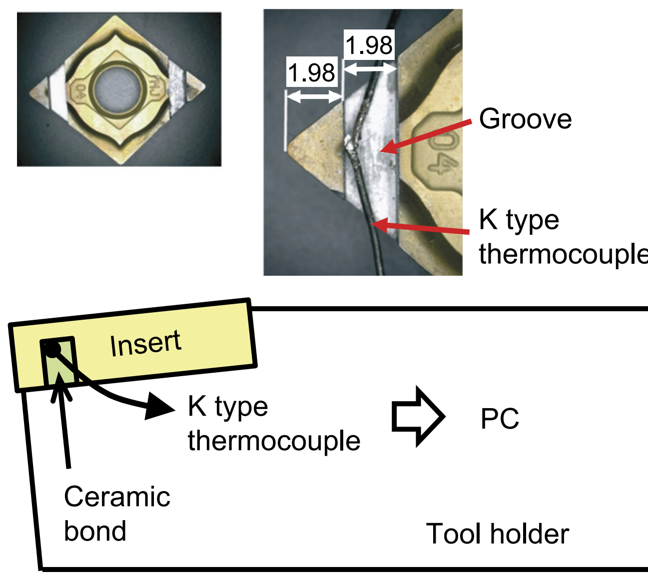

Fig. 2. Insert with a thermocouple for measuring temperature inside the tool.

cutting fluid θ. The maximum width of flank wear was measured with an optical microscope. From the results, the effect of the air jet on the tool wear was investigated. Next, compressed nitrogen was applied from the air nozzle to the tool tip instead of compressed air at the same pressure of 0.54 MPa as in AJA machining. This machining method is called nitrogen jet assisted (NJA) machining. Tool lives in NJA and AJA machining were compared at the same application angle $\theta=20^\circ$.

Cutting forces in dry, conventional wet and AJA machining were measured with a piezoelectric dynamometer at different cutting speeds and $\theta=20^\circ$. Temperature inside the insert was measured with a K type thermocouple in dry, conventional wet and AJA machining at cutting speed 1.5 m/s and $\theta=20^\circ$. Fig. 2 shows an insert with an insulated thermocouple 0.32 mm in diameter, whose hot junction was put in a corner of a groove made by wire electric discharge machining. The groove was filled with ceramic bond and then, this insert was clamped on a tool holder upside down as shown in Fig. 2. Finally, the surface finish of machined surfaces at early stage of dry, conventional wet, AJA and NJA machining at cutting speed 1.5 m/s and $\theta=20^\circ$ was measured with a profilometer. Results obtained for AJA, NJA, conventional wet and dry machining will be indicated by "AJA", "NJA", "wet" and "dry", respectively in the following sections.