Wear 302 (2013) 1171–1179

Contents lists available at SciVerse ScienceDirect

Wear

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

Wear mechanism and notch wear location prediction model in ball nose end milling of Inconel 718

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ARTICLE INFO

Article history:
Received 4 September 2012
Received in revised form
18 December 2012
Accepted 22 December 2012
Available online 7 January 2013

Keywords:
Notch wear
Inconel 718
End milling
High-speed machining
Wear mechanism
Prediction model

ABSTRACT

This study is an investigation of tool wear using a ball-type end mill. The primary purpose of this work is to examine the tool life and wear mechanism when machining Inconel 718 with a physical vapor deposition (PVD)-coated carbide tool and varying the cutting parameters. Notch wear and flaking near the depth of the cut zone were the predominant types of tool failure for the four round cutting tools and were initiated by pitting caused by the repetitive cyclic load. The major factor identified was the large radial depth of the cut. Further examination indicated that the dominant wear was located near the depth of the cut line. On the flank face, smooth and coarse wear types, from abrasion and attrition, occurred at low and high cutting speeds, respectively. A maximum temperature of 521 °C was recorded, which is less than the critical temperature of 650 °C for Inconel 718. A mathematical model was developed to predict the location of the pitting, which was responsible for notching and flaking. This location could then be used to calculate the location associated with the maximum load exerted during the cutting. The error between the predictive model of pitting and the actual notching/flaking was less than 6%.

1. Introduction

Inconel 718 is well known as a material that is difficult to machine, even though it is widely used in high-temperature-environment components that require corrosion resistance, high strength, and ability to withstand creep rupture [1], e.g., in the aerospace industry, nuclear plants, and the biomedical industry [2,3].

Machining is generally difficult because of the toughness of the material and work hardening behavior. Most problems encountered during machining are caused by heat generation [4]. The low thermal conductivity of the material results in high cutting temperature, which is associated with deformation and friction at the tool-chip and tool-workpiece interface [5]. The problem occurs with Inconel 718 when cutting temperatures are below 650 °C, where the hardness of the material increases with increasing temperature [6]. Excessive strain during the ensuing machining passes creates undesirable microstructural alterations of the machined subsurface, causing work-hardening. This hardened surface layer increases the stress on the tool tip, making it sequential cuts extremely difficult [3]. The combination of applied stresses and temperatures causes flank wear and chipping [7]. Inconel 718 is 16, 6, and 4 times more difficult to machine than aluminum, mild steel, and stainless steel, respectively [8]. In machining materials that contain nickel, it is common to find that the notch wear has a significant effect on tool performance during end milling [7,9,10].

Welding and adhesion of the worked material onto the cutting tool, which frequently occur during machining, are the predominant factors causing severe notching and affecting the tool rake face from the consequent pull-out of coating and tool substrate [11]. Therefore, this material has been studied extensively for the analysis of tool life performance and surface integrity.

The life span of the cutting tool was determined from the tool wear, as a worn cutting tool may affect the surface quality. Therefore, predictive models are required to aid in selection of the appropriate process parameters. There are a large number of models related to machining processes, including the prominent Taylor equation for tool life, Archard and Usui's model of tool wear [12], and Altintas's model of cutting force [13]. These basic models have been extended to provide numerous other sophisticated models. Reliable models are necessary to minimize operational costs. However, in practice, some scenarios are difficult to model and require thorough investigation; tool life prediction is one such example. If the wear mechanism involves chipping and fracture rather than abrasion, the tool wear phenomenon is based on probability [14]. Current models have been aggressively developed by different approaches to meet the challenging requirements of today's competitive marketplace [15]; e.g., Quinsat predicted surface roughness by means of feed rate and tool tilt angle, [16]; D'addona, Leone, and Kaya developed tool wear prediction using ANN [17–19]; and Zhao investigated the effects

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http://dx.doi.org/10.1016/j.wear.2012.12.040

Nomenclature

ANN	Artificial neural network
BUE	Built up edge
DOC	Depth of cut
FEM	Finite element method
VB_1	Uniform flank wear
VB_3	Localized flank wear
V_c	Cutting speed
f_z	Feed rate
a_p	Axial depth of cut
a_e	Radial depth of cut
γ	Tangential angle
λ	Tool engagement angle
θ_{fmax}	Locating angle for maximum tangential force
θ_{init}	Locating entry angle
K	Maximum performance chip thickness
R_{eff}	Effective radius
θ_{doc}	Locating angle for depth of cut line
θ_{notch}	Locating angle for pitting area
t_{offset}	Insert offset from tool holder centerline
f_t	Tangential force

of internal cooling of the cutting tool to develop a flank wear model [20]. Fontaine studied the effect of surface inclination on the cutting force [21]. The effect of the stiffness of the cutting tool on tool wear was investigated by Takashi [22], and Shao developed a cutting power model to monitor tool wear in milling [23]. Taking advantage of computer technology, an FEM application was used to study cutting behavior and to estimate tool wear by Xie, Attanasio, and Ozel [24–26], and Nagi and Sivasakthivel predicted tool life by using a statistical method [27,28].

In milling, the cutting tool is subjected to a rubbing process, and the friction between the cutting tool and the workpiece generates heat [27]. For some operations, milling is an interrupted cutting process, and the wear mechanism is different from that in a continuous cutting process. In continuous cutting at low speed, BUE development is protects the rake face more stably than in the interrupted cutting process, where the tool life is one-tenth of that in continuous cutting [29]. An investigation by Krain et al. [30] reported that abrasion, adhesion and attrition were the main tool wear mechanisms, and a BUE is formed by high pressure and chemical affinity. This finding was supported by Sharman's work on end milling, which showed that BUE formation adheres to the cutting edge, some areas of the cutting tool possess bonds that are stronger than the coating-base material, and the repetitive plucking of the tool coating leads to exposure of the base material and consequent rapid wear of the tool [31]. The wear rate depends on the cutting temperature and the properties of the tool and workpiece material [32]. The wear rate stabilized when the temperature of localized heat was below 600 °C and accelerated when the temperature exceeded 680 °C [33]. Statistical analysis of the machining data revealed that over 80% of the tool performance was caused by the cutting variables of speed, feed rate, and depth of cut (DOC). Similar analysis showed that more than 98% of the tangential component of force is attributable to the influence of these same cutting variables. Cutting speed virtually dominated the wear rate, with DOC and feed rate jointly dominating the tangential component force [34]. In terms of tool geometry, a negative rake angle is preferable to prolong tool life, and a positive rake angle offers a better surface finish [35].

This study focuses on the pitting location. Pitting is the early stage of notch wear. It is based on the maximum force generated during tool rotation, and the mathematical prediction model was derived from the location of the maximum cutting force in conjunction with the maximum chip thickness.

2. Experimental set-up

In the cutting test, a CNC milling machining with a maximum speed of 8000 RPM was used for the experiment. The work material was a 160 mm × 100 mm × 50 mm block of aged, treated Inconel 718. The composition of the material is shown in Table 1. The block underwent a double aging process (Fig. 1.), where the raw Inconel was heated at 980 °C for 1 h, and then rapidly quenched in water, then reheated for 8 h at 720 °C, slowly cooled in the furnace until it reached 620 °C, then held at that temperature for 8 h. Finally, the block was cooled in open air [2,36,37].

The purpose of this aging treatment process is to convert AMS5662 grade (92 ± 2 HRB) to AMS 5663 grade (42 ± 2 HRC).

2.1. Cutting tool material

The cutting tool was a Sumitomo ball nose type milling cutter with a nominal diameter of 16 mm attached to a BIG Hi-Power Milling Chuck DV40-HMC20-85 for powerful and precise clamping. A tool overhang length of 60 mm was maintained throughout the experiment (Fig. 2). The insert was tungsten carbide with multi-layer PVD TiAlN/AlCrN grade ACK 300. The specifications of the cutting tool and tool holder used in this experiment are shown in Table 2.

2.2. Tool wear measurement and analysis

Tool wear was measured using a Mitutoyo toolmaker's microscope with 30× magnification and ±0.003 mm repeatability. To eliminate any influence of the previous cutting effect on the workpiece, each new layer was face-milled and cut into a block, with the last cut-out made using a non-test insert. After the specific pass interval, the cutting tool was removed from the tool

Table 1
Inconel 718 Composition.

Al	B	C	Cb.Ta	Co	Cr	Cu	Fe	Mn	Mo
0.49	0.004	0.051	5.05	0.30	18.30	0.04	18.70	0.23	3.05
Ni	P	S	Si	Ti					
53.0	< 0.005	< 0.002	0.08	1.05					

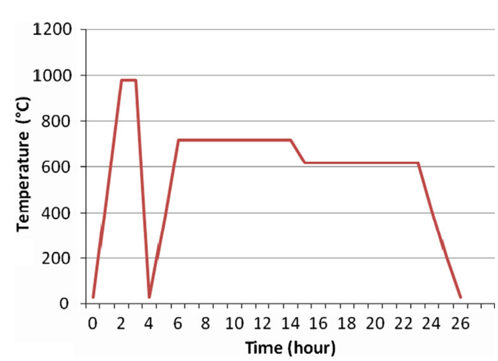

Fig. 1. Double aging schedule of Inconel 718 [2,36].