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ScienceDirect

Procedia CIRP 46 (2016) 368 – 371

www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

An analysis of cutting parameters, coated materials and nose radii on residual stresses when turning Inconel 718

Zhiyang Huang, Shaojie He, Zhuang Kejia,Xiaoming Zhang*, Han Ding

State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China

* Corresponding author. Tel.:+86-027-875-59842. *E-mail address:* cheungxm@hust.edu.cn

Abstract

As a critical characteristic parameter of surface integrity, residual stresses on the machined surface and the subsurface have a huge influence on the service quality of a component, such as fatigue life. In this paper, a comprehensive study about the effects of coated materials, nose radii and cutting parameters on finish turning processes is presented. The results show that turning by PVD coated tool with smaller nose radius can produce higher compressive residual stresses or lower tensile residual stresses which can extend the fatigue life of parts. A finite element model is established to explain the difference in residual stresses, it shows that the thermal loads play a dominant role in the generation of residual stresses.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz

Keywords: Residual stresses;Inconel 718; Finish machining; Nose radius; Coated material

1. Introduction

Nickel-based superalloys have been widely used in aerospace engines and nuclear industry, owing to their superior performance such as high resistance to corrosion, mechanical and thermal shock, mechanical and thermal fatigue, creep and erosion at elevated temperature over 650℃ [1]. The superior performance of a machined component strongly depends on its surface condition. It is known that machining Inconel 718 is prone to result in residual stresses on the machined surface and the subsurface which is one of the most important factors affecting the safety of components and fatigue life [2]. In general, residual stresses in machining processes are produced by three sources including thermal loads, mechanical loads and phase transformations [3]. On one hand, thermal loads generate plastic deformations which are responsible for tensile residual stresses. On the other hand, the contact and compression between tool and workpiece produce mechanical loads which generate plastic deformation resulting in compressive residual stresses. Meanwhile, compressive and tensile residual stresses can be induced by phase transformations depending on the relative volume changes and the accompanying plastic deformations [4]. The compressive residual stresses contribute to improve the fatigue life, creep life and crack propagation resistance, but the tensile residual stresses have negative consequences on fatigue life, high tensile stresses can be deleterious to fatigue performance [5, 6]. In order to ensure better reliability and longer fatigue life of components, there is an urgent need to find effective strategy to ensure good surface quality when machining Inconel 718.

The research of residual stresses has attracted a lot of attentions in recent years. Bushlya et al. [7] reported that application of coated PCBN tools, as compared to uncoated ones, residual stresses had shown a tendency of transition from compressive to tensile when machining Inconel 718 with high speed of 300 m/min. Sharman et al. [8, 9] showed that machining Inconel 718 with feed rate of 0.15 mm/rev resulted in tensile surface residual stresses lower than machining with feed rate of 0.25 mm/rev. They also observed that the increasing of tool nose radius from 2 to 6 mm results in the increase of tensile residual stresses. Sasahara et al. [10] proposed a finite element model to predict residual surface stresses. They reported that residual stresses which were perpendicular to the cutting direction became compressive

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doi:10.1016/j.procir.2016.03.123

when a small corner radius tool was used. Madariaga et al. [11] observed that residual stresses profiles on Inconel 718 varied when face turning with different nose radius. In particular, the increase of nose radius induced a higher difference between surface tensile stresses and subsurface compressive peak stresses, which is attributed to an increase of the thermal loads.

Although CBN and PCBN cutting tools can improve the cutting performance when machining nickel-based alloys. But the main high end manufacturers trend to use cemented carbide tools for finishing operations considering the cutting cost [12]. The research about residual stresses on high speed machining of Inconel 718 has been carried out extensively, but a comprehensive study about the effects of coated materials, nose radii and cutting parameters on finish turning process is insufficient. This paper presents a study on relationship between the residual stresses and cutting conditions. It shows that turning by PVD coated tool can produce higher compressive residual stresses or lower tensile residual stresses, and tool with smaller nose radius produces lower residual stresses than tool with larger nose radius. To explain the mechanism of residual stresses, extensive experimental and analytical work has been conducted and a finite element model is proposed which shows that the thermal loads play a dominant role in the generation of residual stresses.

2. Experimental procedure

The dry finish turning Inconel 718 is performed on a rigid CNC lathe. The workpieces used in the experiment are in solution treated and age hardened condition with a hardness of 36 HRC. An uncoated tool and two PVD coated carbide inserts (KENNAMETAL) with ISO designation CNGG120408FF KU10 (NO-08), CNGG120404FS KCU10 (PVD-04) and CNGG120408FS KCU10 (PVD-08) are used for the machining trials. Four levels of process parameters which are listed in Table 1 are chosen to cover a sufficient wide range considering the finish turning process. A $L_{16}(4^5)$ orthogonal array in Taguchi method is considered for performing machining tests. During turning process, the orthogonal cutting forces are measured with a Kistler 9257 B-type multicomponent piezoelectric dynamometer, see Fig. 1.

Table 1 Levels of machining parameters for experimental test

Level	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)
1	30	0.05	0.25
2	45	0.1	0.5
3	60	0.15	0.75
4	75	0.2	1

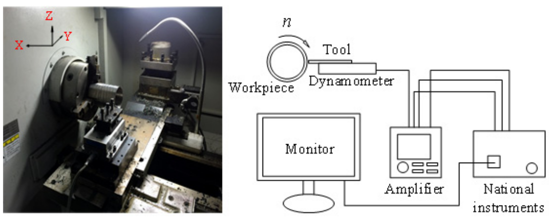

Fig. 1 The test of turning and schematic diagram.

The residual stresses measurement iXRD 300 is used to measure residual surface stresses in the axial (X) σ_x and circumferential (Y) σ_y. The standardized parameters used in the X-ray analysis are given in Table 2. To avoid the accidental error, residual stresses in every direction are measured four times at different measuring points and the ultimate average results are obtained. The tests of residual stresses and measuring points of workpiece are shown in Fig. 2.

Table 2 Standardized parameters used for residual stresses measurement.

Parameter	Standardized value
X-ray tube voltage	20 kV
X-ray tube beam current	4 mA
X-ray target material	Mn_K-Alpha
Collimator type	Round, 2.0 mm
plane	(311)
Bragg	152.8°

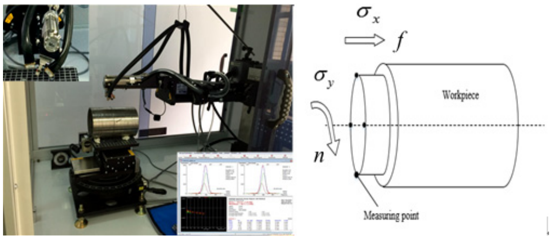

Fig. 2 The residual stresses measurement.

3. Results and discussions

In this study, residual axial surface stress (σ_x) and residual circumferential surface stress (σ_y) are analysed. Experimental results at the same machining parameters with different tools are shown in Table 3.

Table 3 Results at the same machining condition with different tools.

	NO-08			PVD-08			PVD-04		
	σ_x (MPa)	σ_y (MPa)	Force (N)	σ_x (MPa)	σ_y (MPa)	Force (N)	σ_x (MPa)	σ_y (MPa)	Force (N)
1	778.5	123.8	158.0	325.2	-250.4	203.7	412.5	-242.6	190.6
2	434.9	82.8	303.7	367.7	-177.7	563.9	675.8	-155.5	445.2
3	605.4	71	525.2	478.5	-188.7	696.8	669	-162.1	752.6
4	675.9	160.9	805.4	886.4	146.9	949.2	609.2	-271.5	1044.7
5	459.8	72.1	158.2	921.1	143.9	384.2	485.9	-132.8	202.8
6	840.8	220.3	123.9	502.2	89.5	290.5	609.4	-154.8	184.2
7	604.2	156.8	494.6	725.7	166.3	704.6	615.2	-337	681.8
8	548.4	100.5	456.8	890.7	401.2	663.8	647.2	-274.7	687.0
9	810.4	356	222.4	605.7	-112	295.1	512.6	-398.8	185.3
10	845.7	213.7	388.6	581.8	48.5	515.2	466.3	-636.7	445.9
11	850	634	198.3	603.1	12.7	278.8	601.4	-254.1	238.3
12	811.3	564.8	263.4	717.2	233.7	514.9	565.9	-267.5	330.0
13	546.2	314.6	244.0	423.6	86.8	302.9	303.9	-655.3	241.8
14	644.3	398.9	289.5	624.1	113.1	362.8	576.9	-463.8	312.5
15	737.3	320.2	276.9	753.1	308.2	334.6	625.5	-234.1	328.6
16	807.2	461.5	193.1	696.7	243.7	240.5	752.8	-164.3	252.8

3.1. Effects of residual stresses due to coated materials

The average values of σ_x and σ_y generated with NO-08 and PVD-08 according to cutting speed, feed rate and depth of cut are given in Fig. 3 and Fig. 4, respectively. Noted that the residual stresses have the same change trend in two directions and the value of σ_x is lower than σ_y. The residual stresses values are the lowest with the comparison of NO-08 and PVD-08