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Comparison of residual stresses in cryogenic and dry machining of Inconel 718

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Abstract

This paper focuses on the analysis of residual stress differences between cryogenic and dry machining of Inconel 718. A novel method for calculating the residual stress differences is proposed based on the assumption that the elastic-plastic deformations for cryogenic and dry machining of Inconel 718 are the same. The residual stress differences depend only on the temperature differences at the start of material elastic unloading which can be obtained by finite element analysis. For validation, a series of cryogenic and dry turning experiments have been conducted and the residual stresses are measured.

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Keywords: Cryogenic machining; residual stresses; finite element analysis

1. Introduction

Residual stress is one of the most widely used surface integrity parameters in many industrial and research communities. It has a great impact on performance and service life of the components.

To produce the desired residual stresses state, liquid nitrogen (LN), is used as cryogenic coolant in manufacturing processes. It has received great attention for it is environmental friendly, energy saving and easy to dispose.

By analyzing the surface integrity characteristics of machined surface for different combinations of cooling/lubrication machining conditions, cryogenic machining processes can be implemented to improve all kinds of surface integrity, such as: residual stresses on the machined surface and sub-surface, surface hardness, and surface roughness, thus improving the product quality [1]. Another research conducted by J. Kenda et al. [2] shows that cryogenic machining process results in larger compressive residual stresses, especially at deeper levels below the machined surface, thus improving product quality and performance characteristics in terms of fatigue life and wear resistance by using different cooling/lubrication conditions turning of Inconel 718. Besides, cryogenic machining helps improve the machining performance in terms of reduced tool wear, temperature, and surface quality [3]. During the cryogenic machining, the temperature in cutting zone, the temperature-dependent tool wear and the surface roughness are reduced, while the hot-strength and hot-hardness of the hard-to-cut material remain high [4]. Another research gives a similar conclusion that cryogenic machining enables substantial reduction in the cutting temperature, decrease in cutting forces, and favorable in the chip formation and chip-tool interaction, therefore the machinability characteristics are improved [5].

It is well known, residual stresses are a result from both mechanical influences with inhomogeneous plastic deformation and thermal effects with thermal loadings. In this paper, comparison of residual stresses in cryogenic and dry machining of Inconel 718 is presented. A novel method for calculating the residual stress differences between cryogenic and dry machining of Inconel 718 is proposed. The residual stress differences depend only on the temperature differences at the start of material elastic unloading based on the assumption that the elastic-plastic deformations for cryogenic and dry machining of Inconel 718 are the same. 3D finite element analyses are conducted to obtain the temperature differences.

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Turning experiments of Inconel 718 with cryogenic machining and dry machining are briefly introduced including the cooling conditions, cutting parameters, workpiece and the acquisition devices such as cutting forces, temperature and residual stresses.

2. Experimental Procedure

Machining experiments consists of two cooling conditions: liquid nitrogen cryogenic machining and dry machining. LN is delivered to the rake face of the cutting tool. WNMG080404SF 1105 inserts from Sandvik and high pressure coolant turning holder, PWLNR 2525M-08-JHP from Iscar are used providing an approach angle of -5°. To make sure the LN reaches steady, the turning process is initiated about 3 minutes later after LN is delivered. Fig. 1 shows the experimental setup. The infrared image during the cutting process is placed on the top-left corner of the figure. The coordinate system shown in this figure is used throughout the paper.

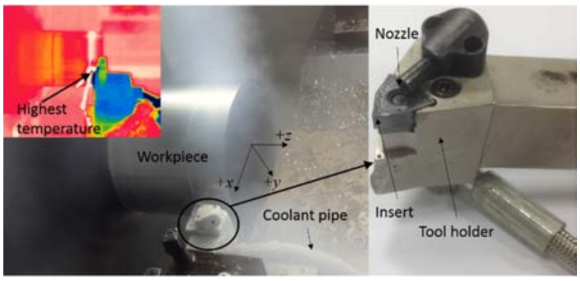

Fig. 1. Experimental setup of cryogenic machining and infrared image during the cutting process.

The workpiece used in this paper is made of nickel-based high temperature alloy - Inconel 718 in a ring form of out diameter of 120 mm, thickness of 10 mm and length of 170 mm. The workpiece was annealed at 900 °C for 3 hours and cooled inside the furnace to room temperature to relieve the internal stresses.

For easy comparison, the same cutting parameters are selected for cryogenic and dry conditions machining. The cutting parameters including the depth of cut, tool feed rate and cutting speed are shown in Table 1.

Table 1. Cutting parameters of cryogenic and dry machining.

Number of the experiment	Depth of cut, a_p (mm)	Feed rate, f (mm/rev)	Cutting speed, V_c (m/min)
1	0.7	0.3	60
2		0.2	40
3		0.1	80
4	0.5	0.3	40
5		0.2	80
6		0.1	60
7	0.3	0.3	80
8		0.2	60
9		0.1	40

The cutting forces are measured using a multicomponent dynamometer, Kistler 9257B, and the temperature is measured by an infrared camera, Flir A325sc focused on the chip formation area as shown in Fig. 1. An X-ray diffraction equipment, Proto iXRD combo is used to evaluate the residual stresses. To acquire the distribution along the depth direction, the electro-polishing method is used to remove the workpiece surface layer by layer.

3. Analysis of effects of cryogenic machining on residual stress

During the cutting processes, excessive plastic deformation and high temperature occur. The cooling effect of cryogenic machining helps reduce the temperature. As we can see in Fig. 2, the yield stress of Inconel 718 is almost constant with the temperature ranging from 20 °C to 700 °C. So we can postulate that *the mechanical deformation including the elastic strain and stress for cryogenic and dry machining are almost the same*. This is confirmed by Wang and Rajurkar [4].

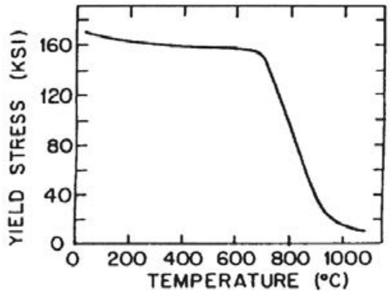

Fig. 2. Yield stress of Inconel 718 vs. temperature reproduced from Leshock [6].

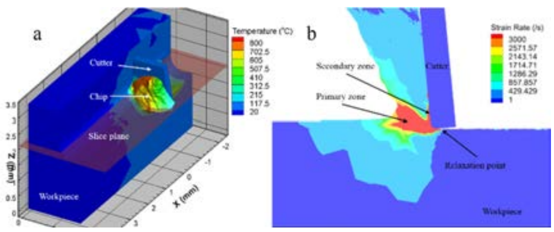

Fig. 3. (a) temperature field in 3D FEM simulation of turning with a slice plane; (b) strain rate field of the cutting process extracted from the slice plane.

The residual stress model proposed by Liang is adopted here. Interesting readers can refer to Ref. [7] for details. Assuming no plastic deformation occurs during the elastic and thermal unloading process, residual stresses can be given in a simple form:

$$\sigma_{yy}^R = \sigma_{yy}^S - \frac{E\varepsilon_{yy}^S + (1+\nu)\left(\sigma_{xx}^S\nu - E\alpha T^S\right)}{1-\nu^2}$$
$$\sigma_{zz}^R = \sigma_{zz}^S - \frac{\nu E\varepsilon_{yy}^S + (1+\nu)\left(\sigma_{xx}^S\nu - E\alpha T^S\right)}{1-\nu^2} \qquad (1)$$