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Experimental and Numerical Investigations on Machining Induced Surface Integrity in Inconel-100 Nickel-Base Alloy

T. Özel *, Y.M. Arisoy

Rutgers University, Manufacturing & Automation Research Laboratory, Industrial & Systems Engineering, Piscataway, New Jersey 08854, USA
* Corresponding author. Tel.: +1-848-445-1099 ; fax: +1-732-445-5467 .*E-mail address*: ozel@rutgers.edu .

Abstract

Nickel-base alloys such as Inconel-100 (IN-100) are still the most preferred material for jet engine and gas turbine components. Machining induced surface integrity plays a vital role for component fatigue life and reliability. This study investigates the effects of machining conditions (tool geometry, coating, and cutting parameters) on the resultant residual stress, microhardness and grain size in machining IN-100. Experimental results for measured forces, residual stress, microhardness, and grain size have been presented. In addition, finite element modeling based investigations have been performed to predict not only residual stresses but also microstructure including dynamic recrystallization by implementing the Johnson-Mehl-Avrami-Kolmogorov model. Numerical modeling results were compared with experimental measurements in residual stresses, grain size and microhardness. The effects of cutting conditions on machining induced residual stress, microhardness, and average grain size have been reported.

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1. Introduction

Nickel-base alloys can considerably maintain their strength at high temperatures and long exposures; therefore they are preferred material for components in hot sections of the aircraft and gas turbine engines, nuclear reactors and rocket engines. Nickel-base alloys can be obtained through several different processing routes in the forms of wrought, forged, cast and in sintered i.e. powder metallurgy. Inconel 100 (IN-100) is a Ni-Co-Cr based super alloy which is used in the cast or powder metallurgy (PM) forms and powder processing provides structural uniformity, high strength, and toughness suitable for engine components operating at intermediate temperature regimes such as disks, spacers, and seals [1].

Machining of nickel-base alloys is deemed to be extremely difficult due to their superior yield strength, rapid work hardening behavior, high rigidity, low thermal conductivity, chemical affinity to tool material, and microstructure related hard carbide particles [2]. While excessive tool wear and part distortion issues remain to be solved machining induced surface integrity is also a challenge to be addressed in nickel-base alloy part and component manufacturing. Machining processes can significantly affect finished part surface integrity which can be classified as surface topography related (textures, waviness and surface roughness), property related (residual stresses and hardness), and metallurgical state (microstructure, phase transformation, grain size) characteristics. Extensive reviews of machining induced surface integrity have been provided in literature [3, 4].

1.1. Microstructure of Inconel 100

IN-100 microstructure mainly consists of two phases; γ and γ'. A representative image of the IN-100 microstructure is given in Fig. 1. The γ phase consists of large grains that form the matrix in the material whereas γ' is formed as a result of various processes [5-8]. Three types of γ' have been observed: primary γ', secondary γ', and tertiary γ'. Sizes and distributions of these γ' formations are set by process parameters, for instance, a very fine microstructure may be obtained by a subsolvus

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heat treatment. Milligan et al. [5] states that by varying the cooling rate after the solutionizing step and the solution heat treatment temperature, it is possible to influence the γ grain sizes as well as γ' grain sizes and distributions. It is stated by Wusatowska-Sarnek et al. [6] that primary γ' is affected by the solution treatment temperature, secondary γ' is affected by the stabilization temperature and forms during cooling from the solution temperature and tertiary γ' is controlled by aging. Primary γ'-grains are large enough to be compared with the γ-matrix grains, and can be included in the grain size measurement of the matrix. Wusatowska-Sarnek et al. [7] reports the average IN-100 γ-matrix grain size as 3.82 µm and Milligan et al. [5] reports it as 3.5 µm. Average diameters of secondary and tertiary γ'-grains are given as 120 nm and 8.5 nm respectively. Sizes and distributions of the γ' precipitates play an important role in mechanical properties of IN-100. It is further stated in [7] that a high strength material is obtained in the two phase field (γ + γ') by maintaining the temperature below the γ' solvus, 1460K. A subsolvus solution treatment at 1416K is followed by a two-step aging sequence at 1255K and 1005K to form the strengthening phases. Milligan et al. [5] investigates the PM IN-100 material with tensile tests at 260 and 650°C and states that secondary γ' size and volume fraction has a dominant effect on the strength of the material. It is further claimed that the presence of γ' is important, but its size is not. A decrease in strain hardening is observed with larger secondary γ' particles and with the presence of primary γ' particles.

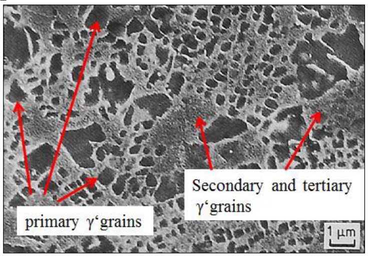

Fig. 1. Typical microstructure of IN-100 alloy [8].

Table 1. Typical grain size of IN-100 nickel-base alloy [5]

Phase	Grain size [µm]	Volume Fraction
γ grains	4.2	balance
Primary γ' grains	1.28	0.25
Secondary γ' grains	0.109	0.32
Tertiary γ' grains	0.021	0.024

1.2. Machining Induced Microstructure

During the machining process, the microstructure is altered due to large plastic deformations and temperatures. The machining effects will be investigated through microhardness and grain size measurements.

2. Machining experiments

In order to investigate the effects on machining on IN-100, a set of experiments have been conducted. Effects of different machining and tool parameters on the microstructure of Inconel IN-100 are investigated using a cylindrical workpiece (see Fig. 2) where a_p is the depth of cut, F_c, F_f, and F_p are the cutting, feed, and thrust forces, and r_β is the cutting edge radius of the tool. IN-100 alloy disks used in the experiments are manufactured via powder metallurgy route with a chemical composition of 18.3% Co, 12.3% Cr, 4.9% Al, 4.3% Ti, 3.3% Mo, 0.7% V, 0.1% Fe, 0.06% C, 0.02% B, 0.02% Zr and Ni balance. After face turning, approximately 3-5 mm thick disks from the machined section were cut off at least 5 mm away from the surface of the disk and the new surface was cleaned with very gentle machining. A constant depth of cut (a_p=1 mm), two cutting speed levels (v_c=12 and 24 m/min) and a constant feed (f=0.05 mm) were used under dry cutting conditions. In these experiments, uncoated cutting inserts made of tungsten carbide in cobalt binder (WC/Co) with up-sharp (edge radius of r_β=5±0.5µm as measured) and edge prepared with abrasive brushing for r_β=25±1.0µm µm (WC25) and r_β=10±0.7µm (WC10), and TiAlN coated inserts (r_β=10±0.7µm as measured) have been used. Cutting forces have been measured and the results are given in Fig. 3 together with uncertainties. There is no replication for the experiments, and the uncertainties for cutting, feed and thrust forces are between 5%-10%, 5%-17% and 9%-39%, respectively.

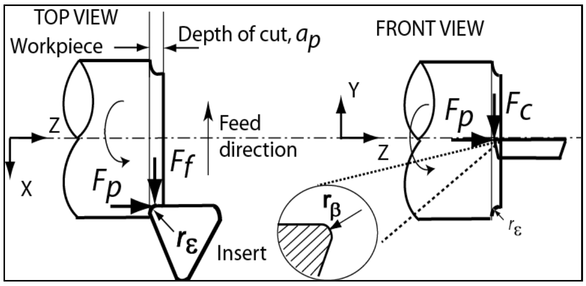

Fig. 2. Experimental configuration used in face turning.

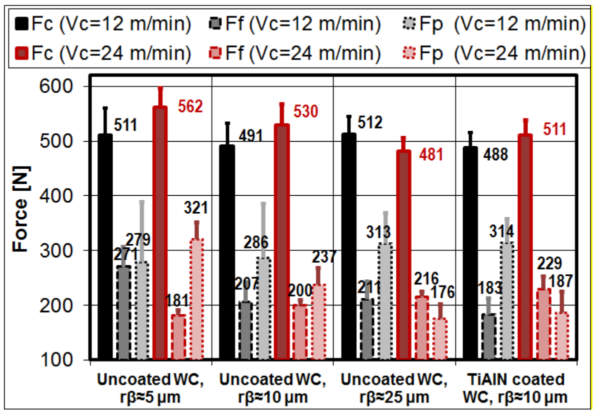

Fig. 3. Forces measured in face turning of IN-100.

2.1. Residual stress measurements

Residual stresses on IN-100 disks were measured