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Residual stresses and surface integrity of Ti-alloys during finish turning – guidelines for compressive residual stresses.

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Abstract:

Residual stresses (RS) induced by machining control a component's resistance to progressive failure. It is crucial to identify favorable cutting conditions that promote fatigue-inhibiting compressive RS while preserving other aspects of surface integrity. An extensive investigation was performed in the finish turning regime for two aerospace grade Ti-alloys, Ti-6Al-4V (Ti-64) and Ti-6Al-2Sn-4Zr-6Mo (Ti-6246). A comprehensive evaluation of surface integrity was carried out including RS, surface roughness, the near-surface microstructure, and hardness distribution. The behavior of RS and surface roughness was correlated to the cutting parameters. Within the investigated parameter range, RS were compressive in nature. High MRR conditions and small corner radii were found to promote larger compressive RS for both Ti-alloys. A conflict between RS and surface roughness was observed. While machining at high feed rates enhanced compressive RS, it was detrimental to surface finish. Guidelines were developed for the optimal selection of cutting parameters to achieve desired levels of RS and surface finish.

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Keywords: Residual stresses; titanium; surface integrity; near-surface microstructure.

1. Introduction

Residual stresses (RS) are one of the most important outputs of a machining operation. They have a direct impact on the performance and durability of machined parts. Where stringent restrictions on surface roughness are in effect as in the case of aero-engine components, a finishing operation is often required. Thus, RS generated during finishing are of particular significance [1, 2].

Tensile RS compromise the dynamic strength and chemical resistance of materials [3]. Rough surfaces and machining artefacts also constitute sites where RS are extremely potent. Thus, RS, surface finish, and the near-surface microstructure (NSM) are critical acceptance criteria for aero-engine parts subjected to dynamic loads in harsh operating environments. Consequently, it is of vital importance to identify favorable machining conditions that generate fatigue inhibiting compressive RS without compromising surface integrity.

Together with the physical properties of the tool and workpiece materials, cutting parameters, tool geometry, edge preparation, tool wear, and the method of lubrication have an important influence on the state, magnitude, and distribution of RS in the near-surface layer. Experimental and numerical investigations have identified conditions that can diminish tensile RS and promote compressive RS for a variety of commercial alloys including Ni-alloy Inconel 718 [4-6], bearing steel AISI 52100 [7-9], stainless steel AISI 316L [10, 11], and die steel AISI H13 [12]. While it is clear that tool wear promotes tensile RS, and lubrication serves to diminish them, the effect of cutting parameters and tool geometry is

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largely dependent on the cutting process and the tool/workpiece material combination.

Limited experimental data was found in the open literature on machining-induced RS in Ti-alloys, especially for finish turning. A correlation between RS, surface finish, and the near-surface microstructure for Ti-alloys is practically non-existent. This work aims to fill this gap by determining finish turning conditions that can promote a desirable compressive residual stress state in the machined surface of Ti-alloys while preserving high surface integrity.

2. Cutting experiments

An extensive experimental investigation comprising more than 60 single point longitudinal turning tests was performed on two aerospace grade α/β Ti-alloys, Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo, used in aero-engine compressor parts. These are referred to as Alloy 1 and Alloy 2 and abbreviated as A_1 and A_2, respectively. The investigated range of cutting parameters is listed in Table 1. Machining was performed under flood lubrication with uncoated WC tools with specially manufactured sharp edges (hone radius < 20 μm) on a Boehringer NG 200 turning center equipped with a Kistler 9121 dynamometer. An industrial grade soluble-oil coolant concentrate (TRIM® VHP ® E210) was employed. Each cutting test consisted of 3 cuts performed in sequence with fresh tools: (i) initial cut to eliminate geometrical variations, (ii) semi-finishing cut to induce a similar initial stress state, and (iii) finishing cut with varying parameter combinations. Machining forces and tool wear were assessed as cutting performance indicators. Residual stresses (RS), surface roughness (Ra), hardness distribution, and the near-surface microstructure (NSM) were evaluated as part of a comprehensive analysis of surface integrity.

Surface RS in the cutting (hoop) direction were measured by x-ray diffraction (XRD). A Cu target was used to generate Kα radiation of wavelength λ = 1.542 Å. Diffraction measurements were collected using the multiple exposure technique in conjunction with the $sin^2\psi$ method. Surface roughness was measured for every specimen along its axis with a Taylor Hobson Form Talysurf Series 2 profilometer. Selected specimens were subjected to three-dimensional topography scans. NSM evaluation was carried out with an Olympus GX-71 inverted optical microscope for 32 cutting conditions in two orientations, parallel to the feed (longitudinal) and to the cutting speed (transverse). The near-surface layer was inspected for machining artefacts and metallurgical alterations. Micro-indentation tests were performed with a Struers Duramin A-300 hardness tester, a Vickers indenter, and an indentation force of 100 g (HV, 0.1) according to ASTM E384.

Table 1: range of finish cutting parameters for single point turning tests.

Parameter	Symbol	Range		Levels
Depth of cut	a_p	0.1 – 0.3	mm	2
Cutting speed	v_c	20 - 90	m/min	2
Feed rate	f	0.05 – 0.25	mm/rev	3
Corner radius	r_ε	0.2 – 1.6	mm	3

An array of 60 indentations was applied perpendicular to the machined surface and parallel to the feed. Indentations were made at 10 sub-surface positions starting at around 0.070 mm and reaching around 1.05 mm in the bulk of the material.

3. Results and discussion

Due to a confidentiality agreement with the project's industrial partner, results are presented in normalized form. Cutting parameter combinations are denoted by (a_{pi}, v_{ci}, f_i, $r_{\varepsilon i}$) where i = 1 to 3 denotes parameter levels in order of increasing magnitude. Results for machining forces, tool wear, RS, and surface roughness were normalized with respect to cutting condition (A_2, (a_{p2}, v_{c2}, f_3, $r_{\varepsilon 1}$)) associated with the Ti-6Al-2Sn-4Zr-6Mo alloy of higher strength. It also corresponds to the highest values of material removal rate, cutting force, flank wear, and compressive RS for the investigated finish turning regime. Vickers micro-indentation hardness (HV, 0.1) was normalized against the bulk hardness of Alloy 2.

3.1 Cutting performance indicators

Depth of cut and feed rate caused a substantial increase in force. Fig. 1 (a, b) shows the upward shift in the cutting force signal for Alloy 1 due to a 40% increase in feed causing an increase of around 30% in the cutting force. In addition, Alloy 2 exhibited an increase in force with increasing cutting speed, especially at high MRR conditions (a_{p2}, v_{c2}, f_3, $r_{\varepsilon i}$). Its higher initial bulk hardness, lower sensitivity to thermal softening, and higher sensitivity to strain hardening contributed to the generation of larger forces. This was determined through the characterization of flow stress behavior for both alloys [13]. This also contributed to a 30% average increase in flank wear beyond Alloy 1 as shown in the SEM images in Fig. 1 (c, d)). In general, cutting tools did not undergo severe flank wear. Cutting edges were free from chipping and plastic deformation.

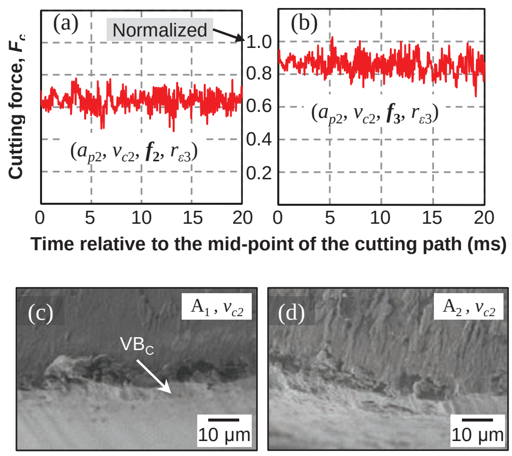

Fig. 1: (a, b) effect of increasing the feed by 40% on cutting force signals for Alloy 1 and (c, d) influence of alloy type on flank wear at the corner radius.