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Influence of rake angle on surface integrity and fatigue performance of machined surfaces

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ABSTRACT

This study investigates the influence of the rake angle on the surface integrity and fatigue performance of hard machined surfaces. The results demonstrate that a higher rake angle induces more compressive residual stresses and a more softened layer. Changing the rake angle was found to increase the crack initiation life up to 104% and crack propagation life up to 256%. Consequently, changing the rake angle increased the fatigue life up to 224%. The fatigue tests demonstrated that the rake angle has a significant influence on the fatigue life and that the effect is further increased if the loading is reduced.

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1. Introduction

Hard machining is a finishing process for materials with a hardness above 45HRC and has been proposed as a replacement for the abrasion-based superfinishing process. Hard machining has many advantages over conventional methods in terms of the surface integrity, cost, productivity, and geometric flexibility. However, an extensive understanding of the surface integrity is needed for its application as a finishing process. Especially, the residual stress significantly influences the service performance of the machined surfaces. Thus, a considerable amount of research has gone into investigating the process parameters that significantly influence the residual stress.

Brinksmeier [1] investigated residual stresses of hard turned surfaces. He reported that increasing the depth of cut yields larger compressive residual stresses on the surface, while a higher feed rate increases the depth of stressed region. König et al. [2] reported that a higher in-feed increases the level of compressive residual stresses and depth of the affected zone below hard turned surfaces. Abrão and Aspinwall [3] compared surface integrity of hard turned surface with that of ground surface. The experimental results indicated that hard turning induces more compressive residual stresses than grinding.

Matsumoto et al. [4] investigated the surface integrity of precision hard turned surfaces. They reported that hard turning produces compressive residual stresses into a deep subsurface, which is beneficial for enhancing the fatigue performance. Furthermore, they found that the tool edge geometry is the dominant factor for determining the residual stress profile below hard turned surfaces. Dahlman et al. [5] investigated the effect of rake angle, feed, and cutting depth on the residual stresses in hard turning. They found that the rake angle and feed have a strong influence on residual stresses, while the cutting depth does not affect residual stresses significantly.

Hua et al. [6] studied the effects of tool geometry, workpiece hardness, and cutting conditions on the residual stress profile of hard turned surfaces. Their results showed that an optimal combination can increase compressive residual stresses in both axial and circumferential directions. Li et al. [7] investigated the effects of tool coating, insert type, tool wear, and tool breakage on residual stresses below the turned surface of RR1000 nickel-based superalloy. They reported that the tool type, tool coating, tool wear, and tool breakage influence the residual stresses of face finish turned surfaces significantly.

Ventura et al. [8] compared the performance of an asymmetric rounded edge with that of a single chamfered tool in hard turning. They reported that the asymmetric rounded micro geometry increases tool life and induces more compressive residual stresses, although cutting forces increase. Jouini et al. [9] investigated the surface integrity and fatigue performance of hard machined components. They reported that a higher cutting speed induces more compressive residual stresses, and extends the compressive zone in depth. Furthermore, the rolling contact fatigue life of hard machined components increased as the surface roughness Ra decreased.

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It was found that the chamfer-hone induces compressive residual stresses, while generating a higher surface roughness [10]. Revel et al. [11] reported that a higher cutting speed induces more compressive residual stresses in both circumferential and tangential directions, while a higher depth of cut increases compressive residual stresses only at the machined surface, but not in depth.

Zhang et al. [12] predicted the residual stress profile of hard machined surfaces by using the experimental data. Their predictions based on a back-propagation neural network model achieved less than 10% errors, while the conventional linear regression model indicated more than 1000% errors in circumferential residual stresses. Li et al. [13] developed a two-dimension fully thermo-mechanical coupled finite element model based on the Johnson-Cook plasticity model. The predicted residual stress profile below a high-speed end-milled surface showed a reasonable match with experimental data.

Mittal and Liu [14] developed a model to predict residual stresses below hard turned surface. Their model incorporated machining parameters so that an optimal residual stress distribution can be proposed to enhance the fatigue performance of hard machined surfaces. Liu and Guo [15] investigated the effect of sequential cuts on residual stresses in a hard machined layer. They found that the state of residual stresses of hard machined surfaces can be improved by controlling second cut.

Because of the stochastic nature of the fatigue performance of mechanical components, probabilistic terms have been used to represent the fatigue life. The fatigue crack initiation is influenced by the size and shape of defects [16]. To predict the fatigue crack growth and fatigue life, the presence of residual stresses should be considered [17]. The fatigue performance is influenced by the material properties, dent sharpness, and topology of the microstructure [18]. The most effective ways to reduce the probability of fatigue failure have been reported to be reducing the maximum crack size and increasing the fatigue threshold [19].

Because hard machining produces a more consistent surface integrity below machined surfaces than conventional superfinishing processes, the deterministic nature of hard machining yields more consistent repeatability of the fatigue performance, which enables more reliable prediction of the fatigue life [20,21]. When compared to the maximum Hertzian stress, the maximum modified equivalent stress is a better predictor for the fatigue life of hard machined surfaces [22]. The slope of the compressive residual stress profile has been demonstrated to be an important factor for rolling contact fatigue damage [23]. The relative fatigue damage can be characterized by multi-axial fatigue damage parameters under the influence of machining-induced residual stress profiles [24].

General surface integrity factors of hard machined surfaces have been investigated extensively. However, there has been no experimental and analytical studies on the influence of the rake angle on the surface integrity and fatigue performance of hard machined surfaces. Because the machining-induced residual stress and micro-hardness distribution are dominant factors that determine the fatigue performance, this study investigated the influence of the rake angle on the residual stress and micro-hardness distribution below the hard machined surface. The rolling contact fatigue lives were predicted based on the residual stress and micro-hardness distribution to examine the influence of the rake angle on the fatigue performance. Subsequently, rolling contact fatigue tests were performed to verify the predictions.

2. Experimental

2.1. Specimen preparation

Specimens of through-hardened AISI 1053 steel were prepared for the experiment. This steel is widely used for hard machining and bearing applications. Table 1 lists the material properties and composition of AISI 1053 steel. Fig. 1 shows the dimensions of the specimen, which were selected for uniform through-hardening and minimal deflection owing to the chucking forces of a standard jaw [25].

To ensure concentricity, the specimens were turned and ground in several steps. Subsequently, the flat surfaces were face-turned under the machining conditions given in Table 2. The cutting tool used in the experiment was a cubic boron nitride (CBN) tool with a tool nose radius of 0.79 mm. To investigate the influence of the rake angle, the specimens were machined at three different rake angles: 5°, 15°, and 20°. The tool geometry is shown in Fig. 2.

2.2. Residual stress measurement

X-ray diffraction was used to measure the residual stress distribution. A Denver-Proto XRD 3000 residual stress analyzer was used with a $CrK\alpha$ radiation tube. To compute the residual stress, the $\sin^2\psi$ technique was used [26] with nine ψ angles.

Table 1
Material properties and composition of AISI 1053 steel.

Elastic modulus	Poisson's ratio	Hardness	Composition (wt%)
200 GPa	0.285	950 HK_{100}	C 0.48–0.55, Mn 0.70–1.00, P 0.04, S 0.05

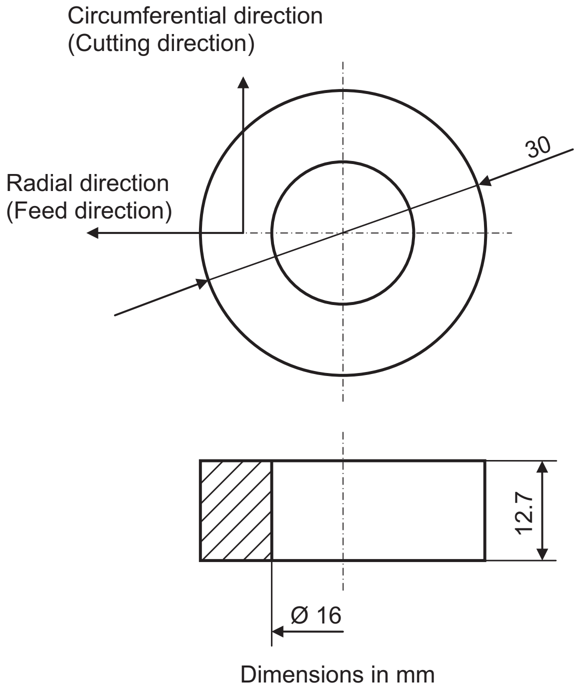

Fig. 1. Specimen dimensions.

Table 2
Machining conditions.

Parameter	Description
Cutting speed	2.0 m/s
Feed rate	0.15 mm/rev
Depth of cut	0.1, 0.2, 0.3 mm
Coolant	Dry
Rake angle	5°, 15°, 20°

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