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Effects of altering surface integrity by electrolytic etching on fatigue performance in rolling contact

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ABSTRACT

A methodology is presented for altering the surface integrity of a machined surface using electrolytic etching. Fatigue parameters are computed to investigate the impact of surface layer removal by electrolytic etching. Generally, surface layer removal reduces crack initiation life. However, it reduces crack propagation life for specimens machined by new tools, while increasing it for specimens machined by worn tools. Consequently, surface layer removal reduces fatigue life when a new tool is used, and increases it when a worn tool is used. Rolling contact fatigue tests substantiate that the fatigue performance of machined surfaces can be significantly enhanced by removing an optimal thickness of the surface layer.

1. Introduction

Because surface integrity ultimately determines the service life of structural components, an extensive understanding of surface integrity is required to implement machining as a finishing process. Surface integrity involves the inherited or altered properties of a surface produced by manufacturing processes and includes residual stress, micro-hardness, and microstructure.

Compressive residual stresses are believed to be favorable for rolling contact fatigue in contrast to tensile residual stresses, which increase the stress corrosion sensitivity and reduce the fatigue limit [1–3]. Gentile and Martin [2] reported that compressive residual stresses induced by nitriding can enhance the rolling contact fatigue performance. They mentioned that compressive residual stresses can prevent the stress-raising effect of hard, non-metallic inclusions.

Zaretsky et al. [4] argued that the maximum compressive residual stress conforms to the maximum fatigue life, whereas Cretu and Popinceanu [5] stated that an optimal value of residual stress is present. Harris et al. [6] showed that the optimal amount of compressive residual stress is subject to the application conditions. According to Dowling [7], fatigue cracking can be delayed by shifting the mean stress to the compressive direction. From this perspective, Liu and Mittal [8] proposed the process parameters that optimize the residual stress distribution for enhancing the fatigue performance of machined surfaces.

The tribological behavior and wear resistance of a machined surface are influenced by its microstructure and hardness alteration [9]. The thermal effect is most important among the three surface damage sources in machining processes: mechanical, thermal, and environmental [10]. Surface damage caused by thermal effects mainly refers to rehardening burn and over-tempered burn.

A rehardening burn is defined as the hard martensitic layer that forms when an austenite is formed by a high surface temperature that exceeds the eutectoid temperature and is then quenched by the cooler substrate. An over-tempered burn is defined as the softened layer created when the surface temperature exceeds the tempering temperature but does not reach the eutectoid temperature. Most research has focused on rehardening burn rather than over-tempered burn.

The rehardening burn layer is more resistant to etching compared to the bulk material and is commonly referred to as a “White Layer” due to its white appearance under an optical microscope. A rehardening burn layer was observed after cutting a steel of hardness 53 HRC with a ceramic chamfered tool, but this layer was not found when machining with a sharp tool [11,12]. Furthermore, white layers were not formed if the tool wear was less than 0.15 mm [13].

Wang and Liu [14] conducted a comprehensive study on the effect of machining conditions on the formation of white layers in machining. Typically, the white layer thickness increases as the cutting speed, tool flank wear, feed rate, or tool nose radius

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increases, but it decreases as the thermal conductivity or the rake angle of the cutting tool increases. Recently, it was reported that white layers form whenever the machined surface exceeds the austenitization temperature of the material [15].

Although general surface integrity factors and fatigue performance of machined surfaces have been investigated [16–20], the specific difference in fatigue parameters due to surface layer removal has not yet been explored. Because the machining-induced residual stress and micro-hardness distribution is of great importance in fatigue performance, this study investigates the impact of surface layer removal by electrolytic etching on the rolling contact fatigue performance. Since tool wear influences surface integrity significantly, specimens are machined using two different cutting tools: new and worn. A new tool is defined as an unused tool, while a worn tool is defined as a tool that was used to machine 150 identical specimens under the same machining parameters. Fatigue parameters are computed based on the residual stress and micro-hardness distribution before and after the removal of a surface layer. Rolling contact fatigue tests are performed to substantiate the predicted fatigue lives.

2. Experimental

2.1. Specimen preparation

Specimens of through hardened AISI 1053 steel were prepared for the experiment because this steel is widely used for bearing applications. Fig. 1 shows the dimensions of the specimen, which were selected to minimize deflection by the chucking forces of a standard jaw and to be uniformly through hardened [21].

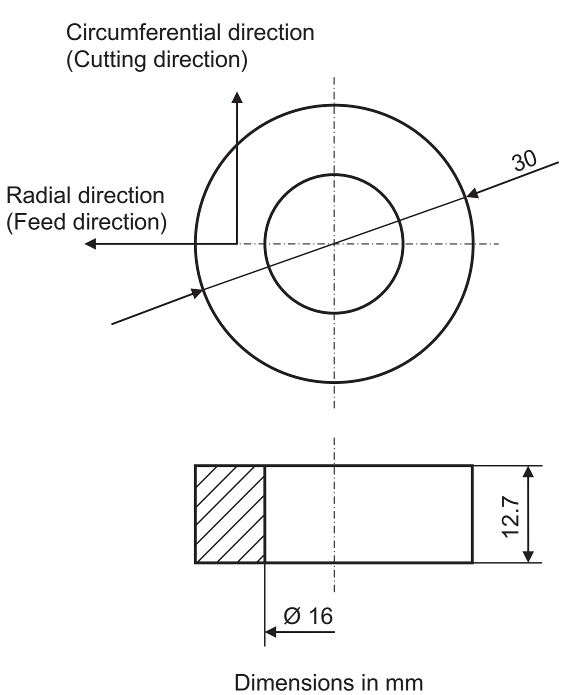

Fig. 1. Specimen dimensions.

2.2. Machining parameters

The flat surfaces of the specimens were machined via face turning using a polycrystalline cubic boron nitride (PCBN) tool (Kennametal KD050) with the machining parameters shown in Table 1. The specimens were machined using two different cutting tools: new and worn. A new tool is defined as an unused tool, while a worn tool is defined as a tool that was used to machine 150 identical specimens under the same machining parameters.

Table 1
Machining parameters.

Parameter	Description
Cutting speed	1.41 m/s
Feed rate	0.08 mm/rev
Depth of cut	0.1 mm
Coolant	Dry
Rake angle	−5°

Subsequently, the surface layer of the machined surface was removed by electrolytic etching using a saturated NaCl solution to investigate the impact of surface layer removal on the fatigue performance. Because pure NaCl leaves a patterned appearance on the surface due to corrosion, a small amount of soap was added to the electrolyte as a preventive measure.

The thickness of the specimen was measured to verify the amount removed after each etching. For each pair of specimens, the thickness of the removed layer was 10, 20, and 30 μm, respectively.

2.3. Residual stress measurement

X-ray diffraction was used to measure the residual stress distribution in the subsurface of the specimen. A Denver-Proto XRD 3000 residual stress analyzer was used with a Cr Kα radiation tube. The $\sin^2\psi$ technique, which is elaborated by Noyan and Cohen [22], was applied to compute the residual stress value. Nine ψ angles were used for the computation: −20°, −15°, −10°, −5°, 0°, 5°, 10°, 15°, and 20° [22].

Residual stress was measured in the circumferential and radial directions (Fig. 1) at the exposed surface and at five different depths: 5.08, 12.7, 25.4, 50.8, and 127 μm. Residual stress was measured in the two directions because stress values in the two directions need to be compared to find the direction for crack initiation and crack propagation. The average of three readings was used as measurement data. The amount of material was removed using electrolytic etching, as described in Section 2.2.

2.4. Micro-hardness measurement

A Leco hardness testing machine (M-400-H) was used for the micro-hardness measurement in the subsurface of the specimen. After the specimen was cut and polished for measurements, the micro-hardness was measured by the Knoop indenter using a 100 g load, which is the largest load that creates a clear reliable indentation close to the surface (Fig. 2).

The measurements were taken at depths of 8.89, 19.05, 38.1, and 88.9 μm, which were chosen as the intermediate depths at which residual stresses were observed. The average of eight readings at the same depth was used as measurement data. A Zeiss metallographic microscope was used to accurately measure the distance of the indentation from the surface.

2.5. Rolling contact fatigue test

Rolling contact fatigue tests were performed using a special test rig (Fig. 3) in a temperature-controlled room at 25 °C. A thrust ball bearing, which had Grade 25 balls of diameter 3.69 mm, was inserted between two specimens. The upper specimen was rotated at 1840 rpm, while the lower specimen was fixed in the test rig. Because typical maximum Hertzian stresses for thrust ball bearing are over 2000 MPa, axial loads that produce maximum Hertzian