THE BASIC RELATIONSHIP BETWEEN RESIDUAL STRESS PROFILE PATTERNS AND FATIGUE LIFE OF PRECISION MACHINED SURFACES IN ROLLING CONTACT

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ABSTRACT

The characteristics of residual stress (RS) profiles and their effects on rolling contact fatigue life for precision turned and ground surfaces with a white layer (WL) are very controversial. The key findings of this study are: (a) The basic RS profiles by a sharp tool can be fundamentally changed by a turned WL but not a ground WL; (b) The hook shaped RS profile of a turned surface may have about 40% more fatigue life than a ground one; (c) The white layer may reduce fatigue life as much as 7-8 times despite the deep compressive RS in the subsurface.

Keywords: Residual stress, fatigue, surface, machining

INTRODUCTION

Hard turning and grinding are competitive finishing processes for the production of bearings, gears, cams, etc. The most significant differences in the characteristics of residual stress profiles [1-6] by “gentle” hard turning and grinding are manifested in two aspects: (i) hard turning with a sharp cutting edge geometry (honed or chamfered) generates a “hook” shaped residual stress profile characterized by compressive residual stress at the surface and maximum compressive residual stress in the subsurface. While gentle grinding only generates maximum compressive residual stress at the surface. However, Tonshoff et al. [3] reported that surface residual stresses generated by the sharp tool can also be tensile, although the magnitude was much lower than that created with a worn tool. (ii) The depth of compressive residual stress in the subsurface by hard turning is much larger than that by grinding [7]. But the magnitude of compressive residual stress at a ground surface is usually higher than that at a turned surface.

Hard turning with a worn tool caused a phase transformed “white layer” at the surface. The white layer generated tensile surface stress [2], but shifted to compression as the depth increased and ultimately attained larger magnitude and affected depth than the residual stress generated by a sharp tool. Similar results [3,8] about the effect of white layer on residual stress were obtained.

The unique pattern of a residual stress profile has been identified as a critical factor of surface integrity for component performance. A compressive residual stress induced by hard turning and grinding was found to improve rolling contact fatigue (RCF) life [5,9,10,11]. Furthermore, deep

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compressive residual stresses in the subsurface may be more beneficial to bearing fatigue life than shallower stresses of greater magnitude [5]. However, a white layer by hard turning may reduce RCF life as much as six times [9]. Nevertheless, others [12] reported that a slight grinding burn does not necessarily lead to an early gear fatigue. Due to the very controversial impact of white layer on fatigue life, a fundamental understanding on the nature of residual stresses associated with different surface types and their effects on fatigue life is essential. However, the literature review reveals several critical unsolved issues. First, the bulk residual stress data is limited to turned and ground surfaces free of a white layer. The nature of residual stress induced by a ground white layer is very ambiguous and lacking. Second, how residual stress resulted from heat treatment affects the final distribution of residual stress is not yet known. Third, how residual stress associated with a turned or ground white layer affects fatigue life has not been clarified yet. Therefore, a linkage between various patterns of residual stress profiles and RCF life has been poorly understood. The objective of this paper is to solve these pressing issues. This has been accomplished by determining the residual stress profiles of turned and ground surfaces with and without a white layer and their effects on fatigue life.

MACHINING TESTS

Four types of unique surfaces were prepared: hard turned fresh (HTF), hard turned white layer (HTWL), ground fresh (GF), and ground white layer (GWL). In addition, an as heat treated surface was prepared as a base line surface.

Dry face turning AISI 52100 steel of 62 HRc (Rockwell Hardness at C load level) discs of 76.2 mm diameter and 19.1 mm thickness was conducted on a rigid, high precision lathe with a BZN 8100 round tool (0.15 mm/15° chamfer & 6.35 mm radius). The cutting velocity, feed, depth of cut are 1.78 m/s, 0.051 mm/rev, and 0.254 mm for the preparation of HTF surfaces using a sharp tool, while a worn tool (VB 0.5 mm) at speed of 2.82 m/s was used for the HTWL surfaces.

Grinding was conducted at a surface grinder with an Al₂O₃ 20A60H fresh grinding wheel. The GF surfaces were prepared at wheel speed 23.9 m/s, table speed 15.2 m/min, cross feed 5.14 mm/pass, and down feed 12.7 μm/pass with water soluble coolant. The GWL surfaces were prepared at same machining condition except the down feed 26.0 μm/pass and without coolant. The measured surface roughness across feed marks of the turned and ground surfaces is 0.16 μm Rₐ. The 3-D surface topography of the machined surfaces also has equivalent root mean square of 0.2 μm. The white layer thickness for the HTWL and GWL surfaces is about 7 μm.

RESIDUAL STRESS CHARACTERIZATION

Residual stress profiles in Figure 1 were measured by the x-ray diffraction method coupled with layer removal by etching. Residual stress measurements were carried out using a 4-axis Bruker-AXS x-ray machine with an area detector. Using a cobalt source (λ = 1.7889 Å), the three-dimensional scans involved 29 scans between 90° ≤ 2θ ≤ 107° for 9 tilt angles (θ = 0°, ±10°, ±20°, ±30°, and ±40°) at each of three rotation angles (ψ = 0°, 45°, and 90°). The x-ray was generated using 35 kV and 20 mA and passed through a 0.8 mm collimator. For repeatability,
three x-ray scans were made at each depth and the results were averaged to give the residual stress profiles. The average and variance of residual stresses in Figure 2 show a good measurement repeatability (<10%) although the variation is expected due to several sources of measurement uncertainty.

![Figure 1 Residual stress profiles in feed direction](image1)

**HTF vs. GF surfaces**

Several differences between gentle hard turning and grinding are observed for the residual stress profiles. In the feed direction, the maximum compressive residual stress occurs at the surface for the case of grinding while maximum compressive residual stress occurs at a shallow depth (5 µm) for hard turning. Also, the magnitude and affected depth of residual stress is greater for hard turning. Due to the gentle machining conditions used for both surface types, the affected depth of residual stress is rather shallow (< 20 µm). In the cutting (or grinding) direction, the maximum compressive residual stress occurs at the surface for both hard turning and grinding. Considering the residual stress at the turned surface has a certain variation in Figure 2. The maximum compressive residual stress has a great chance to be in the subsurface. It implies that a “hook” shaped residual stress profile may be still produced in the cutting direction. However, the magnitude of residual stress generated by hard turning is more than 3 times larger than that for grinding and the affected depth is nearly twice as deep. It should be mentioned that the magnitude of residual stress may change significantly for different machining conditions, but the patterns of residual stress profiles are very stable as far as a sharp tool or grinding wheel is used.

![Figure 2 Measurement repeatability of residual stress](image2)
HTWL vs. GWL surfaces

The residual stress profiles of the HTWL and GWL surfaces show significant differences. In the feed direction, both surfaces generated a tensile surface residual stress. Maximum tensile residual stress was located at the surface for the hard turning case, while maximum tensile residual stress occurred in the subsurface (5 µm) for grinding. While the GWL surface shows tensile stress throughout the entire measured depth (90 µm), the HTWL surface becomes compressive beyond 12 µm. At the depth of 40 µm the compressive residual stress becomes a maximum (-826 MPa). The residual stress remains compressive for the HTWL surface to a depth of at least 110 µm. The affected depth of residual stress measured for HTWL surface is much greater than the GWL surface. In the cutting direction, similar trends are observed. The GWL surface shows a slightly compressive (-46 MPa) residual stress, while the HTWL surface has a tensile (102 MPa) residual stress. At the depth of 5 µm, both HTWL and GWL surfaces have the largest magnitude of tensile residual stress with the HTWL surface having the largest magnitude. Beyond this depth, residual stress of the GWL surface decreases slowly, becoming stable at about 20 µm. However, residual stress of the GWL surface decreases slowly, becoming stable at about 20 µm. However, residual stress of the GWL surface becomes compressive around 15 µm and attains a maximum compressive residual stress of -834 MPa at 30 µm. Beyond this depth the residual stress slowly decreases less than 200 MPa at 110 µm.

HTF vs. HTWL surfaces

The HTWL surface generated a tensile surface residual stress while HTF generated a large compressive one. In addition, turning with a fresh tool imparts maximum compressive residual stresses of -638 MPa at depth of 5 µm in feed direction and -986 MPa at the surface in cutting direction but only affects residual stress in a shallow subsurface (~20 µm). On the other hand, the HTWL surface showed much deeper (>100 µm) affected depth. The maximum compressive residual stress -826 MPa for the HTWL surface occurred at a depth of 40 µm in feed direction and 30 µm in cutting direction. The peak tensile residual stress at 5 µm in the subsurface for the HTWL surface is a result of the martensitic transformation which occurred in the near surface due to high cutting temperatures results from abusive turning conditions.

GF vs. GWL surfaces

The difference between the residual stress profiles generated by gentle and abusive grinding is less dramatic than those for the hard turning cases. However, similar trends with a shift from surface compressive to tensile residual stress are observed. Gentle grinding resulted in a compressive surface residual stress that quickly attenuates at a depth of only 20 µm, while abusive grinding generated tensile residual stress throughout the measured depth of 90 µm. The magnitude and affected depth of the tensile residual stress is much greater for the GWL surface.

ROLLING CONTACT FATIGUE (RCF) LIFE TESTS

The experimental RCF setup shown in Figure 3 was used to determine fatigue life of the machined surfaces. This spindle is capable of rotating at 4000 rpm, thus allowing the test to run in a reasonable time frame. The load is applied through the rotating shaft which also houses the
slave washer. The test utilized eight chrome steel balls with an average diameter of 5.56 mm and a hardness of 63 HRc. A retainer was used to hold the ball and was constructed of nylon to minimize noisy transmission during the test. Slave washers of the same material as the test surfaces were created by turning to maintain the ball’s position during operation and provide a lower contact pressure between the ball and slave washer. The lower contact pressure in the slave washer would help ensure that fatigue failure would first occur in the test surfaces. The testing conditions are shown in Table 1.

![Experimental setup of rolling contact fatigue](image)

**Figure 3** Experimental setup of rolling contact fatigue

<table>
<thead>
<tr>
<th>Load</th>
<th>Peak Hertzian stress</th>
<th>Radius of contact circle</th>
<th>Load frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>306 N</td>
<td>4629 MPa</td>
<td>26 mm</td>
<td>173 Hz</td>
</tr>
</tbody>
</table>

In-situ monitoring of fatigue damage was accomplished using a complete acoustic emission (AE) acquisition package that is versatile in the application of fatigue damage analysis. An AE sensor was attached to the test sample with a holding fixture, while vacuum grease served as the coupling media between the sensor and test sample. The AE sensor has a 125 kHz resonant frequency and connects to an 18 bit PCI-2 data acquisition board that was incorporated into a computer. Before the data reached the computer it was passed through a preamplifier that was set at a 40 dB gain. Using the signal processing package AEWin [13], a threshold of 45 dB was used. The occurrence of surface fatigue is determined by the sharp increase of AE amplitude signal, which has been shown a reliable signal for monitoring surface fatigue [10].

The test sample is secured in a resting plate which is positioned with four rods that maintain the rig's position and rigidity. The resting plate is free to move up and down as it rests on a load cell, allowing accurate measure of the applied load. Prior to startup, a high-temperature multi-purpose lithium complex grease was evenly distributed across the test surface, slave washer track, and ball bearings. Further lubrication was added at regular intervals throughout the duration of the test. Rotational speed of the spindle and washer was monitored using an optical tachometer. Parallelism and centricity between the slave washer and test surface was set using a dial indicator gage to ensure that the pressure distribution is uniform across the test surface.
CORRELATION OF RESIDUAL STRESS AND RCF

Surface fatigue life refers to the number of stress cycles required to initiate spalling on the test surfaces. Results of the surface fatigue lives with variance are shown in Figure 4. Three fatigue tests for each surface type were conducted for data repeatability.

Fatigue life of HTF vs. GF surfaces

The HTF surfaces had an about 40% higher average fatigue life than the GF ones. The reason for the fatigue difference may be due to several factors such as distinct patterns of the residual stress profiles. By comparing the residual stress profiles and fatigue life, it is clear that the life difference is concurrent with the HTF surfaces with large compressive residual stress at the surface and the maximum compressive residual stress in the subsurface. If fatigue cracks initiate from stress concentration due to surface asperities, the large surface compressive residual stress may impede crack initiation at the surface. Fatigue cracks may also be driven by the subsurface maximum shear stress experienced by the test surfaces in rolling contact. In this case, the maximum compressive residual stress in the subsurface may serve to delay the initiation of subsurface cracks.

Because both surfaces have equivalent surface roughness (0.16 µm Rₐ), the fatigue life is not likely to be significantly affected by surface finish. However, an important aspect of the surfaces is that the measured skewness of the GF surfaces (-0.127) is less than that of the HTF ones (-0.051). Negative skewness is an index to the surfaces ability to trap lubricant, as it signifies the presence of more valleys on the surface. For small or medium loads below shakedown limit, the valleys may act as reservoirs to trap lubricant and may increase fatigue life by decreasing friction between the balls and sample surface as they are in contact with one another during rolling. However, for large loads (above the shakedown limit) such as the 4.6 GPa peak Hertzian stress used in these tests, the valleys may act as notches and can promote crack growth due to the wedge effect.
Surface hardness could be another factor to contribute the difference in fatigue life since the GF surfaces are slightly harder than the HTF surfaces [11]. However, the effect of hardness alone cannot be separated from the compound effects of other surface integrity factors.

**Fatigue life of HTWL vs. GWL surfaces**

The surface fatigue life comparison chart for the gentle and abusive turned and ground surfaces in Figure 4 show that a white layer on the HTWL and GWL surfaces is very detrimental to fatigue life. In the case of hard turning, the HTF surfaces had a 760% longer average fatigue life than the HTWL surfaces. Similarly, the GF surfaces had a 780% longer fatigue life than the GWL ones. However, the HTWL surfaces had a 65% longer fatigue life than the GWL ones.

Compared with residual stresses of the HTF surfaces, HTWL surfaces have two significant changes. Surface residual stress shifts from high compression to high tension. The subsurface maximum compressive residual stress becomes more compressive and deeper in both cutting and feed directions. Obviously, the surface tensile residual stress leads to much earlier fatigue damage than the surface compressive residual stress. However, the increased subsurface maximum compressive residual stress seems not to effectively delay fatigue cracks initiation and propagation. Thus, the compound effects of deep compressive residual stresses in the subsurface and tensile residual stress at the surface may not be more beneficial to fatigue life than shallower compressive stress of greater magnitude. It implies that fatigue cracks tend to initiate from surface rather than in the subsurface in rolling contact.

For the GWL surfaces, the bulk residual stress is in tension and the peak tensile residual stress is in the very near surface (~6 μm). Fatigue cracks induced by surface tensile residual stress are further facilitated by the peak tensile residual stress in the near subsurface. This may explain why the GWL surfaces have the shortest average fatigue life.

In addition to residual stress, the high hardness of white layer [3,14] may also contribute the shorter fatigue life of the HTWL and GWL surfaces. But the hardness effect alone is very difficult to isolate from that of residual stress.

**CONCLUSIONS**

The key findings for machining induced residual stress and its effect on rolling contact fatigue may be summarized as follow:

- Hard turning with a fresh tool generates a “hook” shaped residual stress profile characterized by surface compressive residual stress and subsurface maximum compressive residual stress. While gentle grinding only generates maximum compressive residual stress at the surface and a shallow subsurface zone of compressive residual stress. The “hook” shaped residual stress profile with surface compressive residual stress contributes to a longer fatigue life of a machined surface.
- A white layer surface by turning generates a high tensile stress in the area of the white layer, but becomes more highly compressive in the deeper subsurface than the turned one.
without a white layer. The high tensile residual stress at the surface leads to a much shorter fatigue life.

- A ground white layer only shifts the residual stress to tension but hardly affect the basic shape of the profile for a ground fresh surface. The surface tensile residual stress coupled with near surface peak tensile residual stress produces the shortest fatigue life.
- Machining is the deterministic factor for the resulting residual stress magnitudes and profiles compared with the minor influence of initial residual stress by heat treatment.

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