CHARACTERISTICS OF RESIDUAL STRESS PROFILES IN HARD TURNED VS. GROUND SURFACES WITH AND WITHOUT A WHITE LAYER

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ABSTRACT

There exists some inconsistency regarding the true residual stress profiles by hard turning and grinding AISI 52100 steel (62 HRc). This study aims to clarify the pressing issues for five surface types: hard turned fresh, hard turned with a white layer, ground fresh, ground with a white layer, and as-heat-treated. The key findings are: (i) hard turned fresh surfaces produce surface compressive residual stress and subsurface maximum compressive residual stress, while ground fresh surfaces only generate surface maximum compressive residual stress; (ii) hard turned white layer surfaces generate a high tensile stress in the white layer, but has highly compressive residual stress in the deeper subsurface than the hard turned fresh surfaces; (iii) hard turned white layer surfaces change the basic shape of residual stress profiles, while ground white layer surfaces do not; (iv) Tensile residual stress in hard turned white layer surfaces is higher than that the ground white layer surfaces. However, the residual stress for the ground white layer does not become compressive in the subsurface; and (v) Machining is the deterministic factor for the resulting residual stress compared with heat treatment.

Keywords: residual stress, white layer, hard turning, grinding

INTRODUCTION

Residual stress by hard turning and grinding has been identified as a critical factor influencing product performance such as rolling contact fatigue [1,2]. A compressive residual stress induced by hard turning and grinding was found to improve rolling contact fatigue (RCF) life [2-5]. Furthermore, deep compressive residual stress is believed to be more beneficial to bearing fatigue life than shallower residual stress of greater magnitude. Recent studies [1] have also shown that distinct residual stress patterns have little influence on the magnitudes or the locations of peak stresses and strains in subsurface. But they have a significant influence on surface deformations. It is therefore desirable to measure and identify the differences in residual stress profiles generated by hard tuning and grinding.

The most significant difference in residual stress by fresh hard turning and grinding is that hard turning may induce a relatively deep maximum compressive residual stress in the subsurface [3], while a worn tool or grinding wheel induces tensile residual stresses at the surface [6-8].

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This document was presented at the Denver X-ray Conference (DXC) on Applications of X-ray Analysis.

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Although researches [6-15] have measured residual stress by hard turning and grinding, there are considerable differences in the nature (shape, magnitude, and depth) of residual stress in the machined surfaces between different groups using nearly identical machining conditions. For example, compressive residual stress is reported in the white layer while the majority reported tensile residual stress. For this reason there is some inconsistence regarding the true residual stress profiles generated by hard turning and grinding with both gentle and abusive conditions. In addition, the reported residual stresses are limited to only residual normal stresses, residual shear stresses are poorly understood. The uncertainty or repeatability of residual stress measurement was also not addressed. Lastly, a comparison between residual stress by heat treatment and the subsequent machining will also be helpful.

The objective of this paper is to clarify the residual stress profiles generated by hard turning and grinding. This has been accomplished by determining the residual stress profiles generated in AISI 52100 steel by mild hard turning and grinding (machined surfaces free of a white layer) and abusive hard turning and grinding (machined surfaces with a white layer). X-ray diffraction with a Co source was used to determine the residual stress profiles for the four types of surfaces. The residual stress of the as-heat-treated samples was also measured and taken as the baseline data.

SAMPLE PREPARATION

Work samples of AISI 52100 steel were cut from a 3 inch (76.2 mm) diameter solid bar at 0.75 inch (19.05 mm) thickness. The test specimens were then machined to ensure parallelism and perpendicularity before heat treatment. Heat treatment consisted of austenizing at a temperature of 815ºC for 2 hours, followed by quenching in an oil bath for at 65ºC for 15 minutes. Finally, tempering was conducted at 176ºC for 2 hours which produced a final hardness of 61-62 HRC. The test samples were then machined by both turning and grinding. The machining parameters were selected to produce four unique surface types (Figure1): hard turned fresh (HTF), ground fresh (GF), hard turned with a white layer (HTWL), and ground with a white layer (GWL).

![Cross-sections of the machined surfaces](image)

Fig. 1 Cross-sections of the machined surfaces (a) hard turned fresh (HTF), (b) ground fresh (GF), (c) hard turned with a white layer (HTWL), (d) ground with a white layer (GWL)
The turned samples were created by face turning with a constant cutting velocity as the cutting tool moved from the outer edge to the center of the workpiece. A fresh round CBN cutting tool insert was used for the HTF sample and was rotated a few degrees after each sample was completed in order to use a fresh cutting edge in each cutting test. The turned white layer was produced using a worn tool (flank wear 0.5 mm) and higher cutting speed. Face grinding operation was performed using a vitrified Al₂O₃ wheel which was dressed prior to machining and ample coolant was used to prevent excessive heat at the machined surface for the GF samples. In order to generate the GWL surface, an increased depth of cut and no coolant was used. Three samples were prepared at identical machining conditions for the repeatability of residual stress measurement.

In order to measure the residual stress profiles of the machined samples, the test specimens were made small enough to fit in the x-ray test chamber using an abrasive cutter and ample coolant. Noting the orientation of the cutting and feed directions (Figure 2), it was possible to align the samples so that the residual stress could be measured in the desired directions.

Subsurface measurements were made by subsequent etching of surface layers in 5 µm increments for the first 20 µm and then 10 µm increments thereafter. Before etching, the samples were wrapped in lead tape, leaving only a narrow strip (4 mm wide across the sample) on the surface exposed to the 20% nital etching solution. This was done in order to have a reference height to measure the layer removal depth after each etching. After conducting multiple preliminary tests, it was discovered that this etchant concentration produced a material removal rate of approximately 1 µm/min as shown in Figure 3. After etching, the samples were thoroughly rinsed with distilled water, air dried, and cleaned with a cotton swab and methanol.

Fig. 2  Orientations of measured residual stresses  Fig. 3  Etched depth vs. time

RESIDUAL STRESS MEASUREMENT PROCEDURE

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 (ψ = 0°, ±10°, ±20°, ±30°, and ±40°) at each of three rotation angles (φ = 0°, 45°, and 90°) which were treated separately. The x-ray was generated using 35 kV and 20 mA and passed through a 0.8 mm collimator. Each scan was 15 s which was determined to be adequate for good peak intensity and definition. The gravity peak location method with 10% threshold value was used to calculate typical (211) peak positions for
steels using DIFFRAC plus stress software [18]. The change in lattice spacing $d$ at different $\psi$ angles resulted in a corresponding peak shift. The residual strain was derived from the slope of both the linear and elliptical fit between the fractional change of the plane spacing (i.e., strain) and $\sin^2 \psi$ (Figure 4). The Young’s modulus ($E$) and Poisson’s ratio ($\nu$) for AISI 52100 steel were taken as 201 GPa and 0.27, respectively. For repeatability, three measurements at different locations at each depth were made and the results were averaged to give the residual stress profiles. Residual stresses were corrected to compensate etching induced relaxation [16,17].

CHARACETERTICS OF RESIDUAL STRESS PROFILES

The residual stress profiles were measured in the feed, cutting, and shear directions for the two hard turned and two ground surfaces. Residual stresses for an as heat treated sample were also measured to serve as baseline data. The resulting residual stress profiles for the five sample types are discussed as follows:

HTF surface

*Feed Direction:* The surface residual stress in the feed direction, Figure 5, of the HTF sample is compressive with a magnitude of -400 MPa at the surface. As the depth increases, the maximum compressive residual stress of -638 MPa occurs at the depth of 5 µm. This “hook” shaped profile has also been identified by previous residual stress investigations of hard turning. Beyond 5 µm, the residual stress decreases in magnitude with depth and becomes insignificant at about the depth of 20 µm.
Cutting Direction: The maximum residual stress in the cutting direction, Figure 6, occurred at the surface and had a measured value of -986 MPa. When compared to the feed direction, residual stress in the cutting direction has a larger magnitude at the surface and subsurface to a depth of 20 µm. The major difference between the feed and cutting directions is the lack of the “hook” profile for the cutting direction. However, due to gentle turning conditions used, residual stresses were only present to a depth of 20 µm.

GF surface

Feed Direction: The residual stress profiles generated by gentle grinding with ample coolant reveal a very shallow depth of residual stress. The compressive residual stress has a very shallow depth (~ 4 µm) and the maximum of -164 MPa occurs at the surface. Compared to the hard turning, the magnitude of residual stress is more than two times lower and decreases more rapidly and becomes negligible at only 15 µm.

Cutting Direction: The residual stress in the cutting (grinding) direction is compressive and maximum at the surface with a value of -280 MPa. Similar to the characteristics of residual stress profile in feed direction, the depth of compressive residual stress is also shallow (~ 8 µm), which is slightly larger than that in the feed direction.

HTWL surface

Feed Direction: Hard turning with a worn tool and higher feed rate generates a high tensile stress in the near surface (<12 µm). Surface residual stress was tensile with a value of 357 MPa. At depths greater than 12 µm, the residual stress becomes compressive, reaching a maximum value of -826 MPa at a depth of 40 µm. The compressive residual stress remains a large magnitude throughout a depth of nearly 100 µm at which point it becomes stable. The abusive turning conditions generate higher temperatures and more broad deformation which affect the workpiece to greater depths.

Cutting Direction: The surface residual stress had a value of 102 MPa, but a sharp gradient was present that quickly attained a residual stress value of 1029 MPa at 5 µm below surface. This value is reasonable due to the presence of martensitic white layer with very high hardness formed in the near surface. Beyond this depth, the residual stress again sharply declines, becoming compressive at only 12 µm. A maximum compressive stress of -834 MPa was measured at a depth of 30 µm. The residual stress remains compressive and gradually decreases throughout the measured depth of 110 µm.

GWL surface

Feed Direction: The surface residual stress is tensile having a magnitude of 196 MPa and the maximum residual stress (496 MPa) is located at 5 µm below surface. In contrast to the HTWL profile, the residual stress of the GWL sample is tensile throughout the measured depth of 90 µm.

Cutting Direction: Surface residual stress in the cutting direction was slightly compressive (-46 MPa), but the residual stress quickly becomes tensile and reaches the maximum value of 497
MPa at the depth of 5 µm below surface. Beyond this depth, the residual stress gradually decreases and becomes stable (> 200 MPa) for the duration of measured depth.

**Shear stress**

Shear stresses in Figure 7 were calculated using an elliptical curve fitting method for non-linear $d_{\psi\psi}$ vs. $\sin^2 \psi$ data. In comparison with the normal stresses induced by hard turning and grinding, shear stresses are much lower in magnitude. For all cases except HTWL, shear stress remains low (< 200MPa). When compared to grinding, the shear stress magnitude is larger in the near surface for the hard turned surfaces due to the larger Hertzian stress and deeper subsurface deformation generated by hard turning. The residual shear stress is about -520 MPa at the surface and reaches -920 MPa at the depth of 5 µm and quickly decreases to the level of -200 MPa at the depth of 40 µm.

**As-heated-treated surface**

Residual stresses in two orthogonal directions have similar level which is around 140 MPa at the surface and quickly decreases to about -100 MPa at the depth of 5 µm and then reduces to negligible values at about 30 µm. Shear residual stress has an even lower value of 50 MPa at the surface and oscillates in the subsurface.

**Measurement repeatability**

Figure 8 shows the typical variation between three measurements at each location in all three directions analyzed in this study for the HTF and GF samples, respectively.
Although there is some variation, the difference in the measurements is small enough (≈10%) to demonstrate good repeatability for the x-ray diffraction technique. It should also be noted that it is expected that there be some variation in the residual stress measured for different locations at the same depth. In hard turning where a single point cutting tool is used, the variation may be due to accumulated wear as the tool moves across the workpiece surface, machine/tool compliance, slight variations in cutting speed as the tool moves to the center of the workpiece, and statistical variations due to grain and second phase particle orientations. In grinding, however, the cutting edge is defined by many abrasive particles with unique geometries that will lead to differences in the cutting zone/area and stress fields for each pass of the grinding wheel. This causes the residual stress measured by grinding to have a larger variation than that for hard turning. For this reason it may be necessary to perform additional x-ray scans to improve the accuracy of the residual stress profiles of ground samples.

**SUMMARY AND CONCLUSIONS**

The focus of this paper was to determine the difference in residual stress profiles generated in gentle and abusive hard turning and grinding AISI 52100 steel. X-ray diffraction method was used to calculate the residual stress profiles in the near surface (≈100 µm) for five surface types: hard turned fresh, hard turned with a white layer, ground fresh, ground with a white layer, and as heat treated. The results have revealed distinct differences in the residual stress profiles for the various machining conditions used for this analysis. The major findings are as follows:

- 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.
- 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.
- 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.
- 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.

**ACKNOWLEDGMENT**

This work has been supported by the National Science Foundation under Grant CMMI-0447452.

**REFERENCES**


