Effect of cryogenic treatment on the residual surface stress introduced by grinding

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Abstract
Using W6Mo5Cr4V2 HSS (High-speed steel) as a sample material, effects of cryogenic treatment on residual surface stress of ground W6Mo5Cr4V2 HSS specimens were investigated. The residual stress in the ground surface and its change caused by cryogenic treatment were analyzed using both X-ray diffraction technique and finite element method. It was demonstrated that the cryogenic treatment reduced the equivalent stress Max Mises from 248.9 MPa to 114.3 MPa, and the principal stress reduced from 124.0 MPa to 91.6 MPa. The residual stress at X direction (S11) parallel to the grinding direction was tensile stress, which was reduced from the Max. 105.8 MPa to 63.48 MPa. However, the residual stress (S22) perpendicular to the grinding direction was compressive stress, which was slightly increased from 272.6 MPa to 287.8 MPa by the cryogenic treatment. The changes in both the tensile and compressive residual stress components are beneficial to material performance, e.g., wear resistance. Results from the computational and experimental analyses are consistent.

Key words : Cryogenic treatment, Residual stress, High-speed steel, Grinding, Numerical simulation, X-ray diffraction

1. Introduction

Surface residual stress is of importance to the performance of materials used in many processes, which is always a topic of interest to material researchers and engineers in various industrial sectors such as aerospace, machinery, nuclear industry and many others(Jia, 2010; Mizutani, 2010 and Liu et al, 2008). Residual stress of grinding surface has important effects on mechanical properties of materials. Depending on the type of residual stress, it may lower the fatigue strength, accelerate stress corrosion when used in environments, reduce the wear resistance and service life of the materials. Studying residual surface stress introduced by grinding and modification by cryogenic treatment has theoretical and practical significance. Grinding, often the last step of machining, occasionally leads to surface burning and cracks, which are mostly caused by residual stress introduced during the grinding process. The residual stress could be adjusted by using different ways in order to minimize or maximize its effect on the performance of materials. The residual stress can be modified by pre-stressing, changing the grinding condition, and employing shot peening, etc. Chen (Chen, 1993) proposed a method combining grinding and partial freezing to control the residual stress in ground surfaces. Yang (Yang, 1990) prestretched ground steel specimens during annealing to introduce residual compressive stress. Kobayashi (Kobayashi, 1998) investigated static compressive stress under a specific condition in order to clarify the mechanism for the introduction of compressive residual stress caused by shot peening. G. Donzella (Donzella, 2011) studied the residual stress by means of the hole drilling technology and X-ray diffraction method, which showed the
presence of a densified surface layer and residual compressive stress in specimen surface by shot peening. Xu (Xu, et al, 2004) studied the residual stress of gear surface before and after shot peening. Zhang (Zhang, 2013) dealt with sheet surface of titanium alloy with dry and wet shot peening, and researched the distribution of surface residual stress. Xu Jin(Xu, et al,2001)proposed that strong cold grinding could obtain the residual compressive stress for the workpiece surface or lower their residual tensile stress. Although these methods have been used, there are still some limitations. For instance, these methods more or less change dimensions of workpiece, which is undesired especially when high surface tolerance is required. Besides, these processes are not always easy to operate.

In this study, cryogenic treatment is demonstrated to be an alternative technique to modify residual stresses in ground surfaces, which does not change the dimensional precision of a workpiece. Cryogenic treatment is a technology that a workpiece is cooled to very low temperatures to change material microstructure. As extension of traditional heat treatment, cryogenic treatment may considerably enhance the material strength, toughness and wear resistance; it may also improve the uniformity and the stability of microstructure, prolonging the service life of treated workpieces. Cryogenic treatment is regarded as a low-cost green process without pollution issues and has considerable economic benefits and high market values (Yan, 2008 and Qiu, 2007).

This paper reports our recent studies on the effect of cryogenic treatment on residual stress introduced by grinding with the aim of exploring its effectiveness in modifying the residual stresses in ground surfaces.

2. Experimental details

2.1 Sample preparation

W6Mo5Cr4V2 HSS was used for this study. Specimens with dimensions of Ø35×10 mm were heat treated using a vacuum quenching furnace of VHQ-122-06. The cryogenic treatment was performed in a cryogenic tank of YDS-15-210. Surface grinding was achieved using a M7130 surface grinding machine. Residual stress was measured using a TEC-4000 X-ray stress analyzer made by American TEC Company. Numerical simulation of residual stress development was conducted with finite element analysis software ABAQUS.

2.2 Cryogenic treatment

HSS specimens were quenched at 1220°C and cryogenic treated, and then tempered at 560 °C for 1 h followed by air cooling (See figure 1 for details). The tempering-cooling process was repeated for three times in order to eliminate or minimize residual stress in quenched steel specimen, so that the stress introduced by grinding could be determined. Details of the sample preparation and treats are given below:

(1) Specimen preparation: Bars of size Ø35×10mm were cut in CNC (Computer numerical control) wire cutting machine of XKG-10D.CNC.

(2) Heat treatment process: Vacuum heat treatment shown in figure 1 was conducted in the vacuum quenching furnace of VHQ-122-06, which is illustrated in figure 2.

(3) Cryogenic treatment process: HSS specimen was cooled to -196°C at a cooling rate of 5°C/min and was kept at the temperature for 10h, and was then returned to the room temperature. The whole process is shown in figure 3, including a liquid nitrogen cooling stage and a liquid nitrogen heating stage.

(4) Grinding process: Plane grinding in a single inverse grinding way with the grinding depth of 30 μm without coolant was used. The feed speed of workpiece was controlled at 0.42 m/s and a linear velocity grinding wheel of 35 m/s was used. Alumina grinding wheel of size 350×40×125mm and 46# are used to grind high-speed steel specimen. Ground specimens were cooled at room temperature and surface residual stress was then determined through X-ray diffraction analysis.
Fig. 1 Heat treatment procedure (in vacuum) for the HSS W6

Fig. 2 VHQ-112L-06 Vacuum quenching furnace

Fig. 3 Technological flow sheet of cryogenic treatment

3. Results

3.1 Experimental analysis of residual stress

X-ray diffraction method (Li, 2011, Rossini, et al, 2012, Lee, et al, 2012, and Gou, et al, 2011) is a nondestructive test commonly used to measure residual stress. In this study, the residual stress in specimen surfaces was measured with a TEC-4000 X-ray stress analyzer. Surface residual stresses in grinding specimens with and without cryogenic treatment were measured. The specimen size and arrangement of measuring points in surface are shown in figure 4. Each measurement was repeated three times with different specimens. Results of the residual measurement are illustrated in figure 5.

Fig. 4 Workpiece size and measurement points arrangement
As shown in figure 5 (A), the component of residual stress parallel to the grinding direction was tensile, and the maximum tensile stress reached the maximum of 128.72 MPa in the central region. After the cryogenic treatment, the tensile component became uniform with much lowered values in the range of 70 MPa. The situation is different for the component of residual stress perpendicular to the grinding direction, which was compressive with the maximum of 162.42 MPa in the central region (see figure 5(B)). Rather than decreasing the compressive stress, the cryogenic treatment increased the compressive stress from 162.42 MPa to 294.24 MPa.

Due to different thermal expansion coefficients of various phases, different orientations of grains, and mis-orientation among grains, the internal stress can be changed with temperature variations during the entire heat treatment process. The larger cooling rate results in an increase in internal stress and the residual stress is the superposition of microscopic stresses respectively introduced by grinding and cryogenic treatment, and that the cryogenic treatment introduced thermal stress in the directions opposite to those introduced by grinding. As a result, the cryogenic treatment can adjust residual stress in ground surfaces (Wang, 2012).

Fig.5 Residual stresses of ground surface measured with and without the cryogenic treatment
(A) Residual stress component parallel to the grinding direction, and (B) Residual stress component perpendicular to the grinding direction.

It is difficult to analytically reveal how the cryogenic treatment leads to opposite effect on residual stress, compared to the grinding process. However, this can be demonstrated by computational modeling, which is described in the following sections.

3.2 Numerical simulation of residual stress introduced by grinding
3.2.1 Temperature distribution at sample surface during grinding

In order to simulate the development of residual stress during grinding, the temperature field (Zhang, et al., 2009) needs to be analyzed, which requires the following information: geometry and material of the workpiece, grinding force, processing condition, the coefficient of heat transfer between the workpiece and the grinding fluid, and the boundary condition. The material under study is W6Mo5Cr4V2. For the modeling study, the sample had a size of Ø35×10mm and the environment temperature was set at 20°C. Material properties needed for the simulation are given in Table 1 (Li, 2005).

<table>
<thead>
<tr>
<th>Table 1 Material properties of W6Mo5Cr4V2</th>
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<tr>
<td>Density [kg/m³]</td>
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<tr>
<td>Heat conductivity [W/m · °C]</td>
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<tr>
<td>specific heat [J/kg · °C]</td>
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<tr>
<td>Heat expansion coefficient [°C⁻¹]</td>
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<tr>
<td>Elasticity modulus [N/m²]</td>
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<td>Poisson's ratio</td>
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A specimen model was built with ABAQUS6.11 shown in figure 6; the specimen was meshed with implicit linear
heat conduction unit using DC3D8 of 8 nodes. For simulation, the time of finish grinding was: 
\[ t = \frac{L}{v_w} = 0.078 \text{s}, \]
where \( L \) is the grinding length and \( v_w \) is the specimen feeding speed, and the whole process was divided into 10 time steps, each of which took \( \Delta t = \frac{t}{10} = 0.0078 \text{s} \). After a number of loop iterations and loading step by step, temperature distribution of grinding zone could be obtained.

![A model of ground specimen: (a) unmeshed and (b) meshed](image)

In order to calculate the temperature field, the wheel speed \( v_s \) was set as 35 m/s and the specimen feeding speed \( v_w \) set as 0.42 m/s. The grinding depth \( a_p \) was 30 \( \mu \)m and grinding width \( b \) was 0 ~ 35 mm. Other input parameters of the grinding model were calculated using formula given in literature [Liao, et al., 2009], where the grinding contact length \( L_c \) was 3.5mm, tangential grinding force \( F_t \) was 60.49N, grinding heat distribution coefficient \( R_w \) was 0.76, and the heat flux density \( Q \) was 13.135 W/mm².

Figure 7 illustrates the temperature distribution on the ground surface at \( t = 0.078 \text{s} \). As shown, the surface temperature increased along the direction of the grinding. When moving heat source, the place temperature formerly heated was higher than those not heated in the process of grinding, heat conducted from high temperature to low temperature, which was equivalent to a preheating process. Therefore, when moving heat source to preheating area and heating with the same heat flux density, the temperature of post-grinding area became higher, thus it was formed that the surface temperature increased along the direction of the grinding.

![Temperature field at a sample surface during grinding](image)
Fig. 8 Distribution of surface temperature.

In figure 8 (t = 0.078 s) which illustrates the distribution of surface temperature, one may see that the grinding temperature formed a larger temperature gradient in surface layer.

3.2.2 Numerical simulation of residual stress on ground surface

Based on the temperature distribution of each time step and applied load, thermal stress was analyzed in the result file of transient temperature data "grinding temperature.odb". Residual stress inside the specimen was produced during the heat treatment. Grinding residual stress (Wang, et al., 2008; Niu, et al., 1999; Qi, et al., 1997; and Lee, 2004) was produced by superposition of heat treatment and heat caused during grinding. The residual stress of heat treatment here was imported directly as initial grinding stress when numerical simulation was preceded, and the simulation flow of the stress field was shown in figure 9.

Fig. 9 Calculative flow chart of stress field
The thermal stress nephograms after grinding at different time steps are shown in figure 10.

Fig.10 Heat residual stress field of grinding
(A)t=0.023s  (B)t=0.051s  (C)t=0.071s  (D)t=0.078s

Numerical simulation result of grinding residual stress parallel to the grinding direction (S11) is shown in figure 11(A) and the residual stress perpendicular to the specimen is shown in figure 11(B). Most area of ground surface in the grinding direction was stressed in tension, while in the perpendicular direction the surface was stressed in compression. The modeling results are consistent with the experimental measurement.

Fig.11 Residual stress
(A) in the grinding direction and (B) perpendicular to the grinding direction

3.3 Simulation of cryogenic effect on the residual stress

Material properties of HSS such as thermal conductivity, specific heat, coefficient of thermal expansion, and elastic modulus required for numerical simulation were chosen from the literature (Chen,2008 and Han,2007).

Two-step loads were set according to a pre-determined curve to fit cryogenic treatment as consistent as possible. Step 1: set up the environment temperature at 20℃ and end temperature at -196℃; Step 2: set the environment temperature at -196℃ and end temperature at 20℃. Temperature contour maps during the process of cryogenic treatment are given in Fig12.

As shown, the marginal area had the largest temperature variation, followed by specimen surface, and the center of specimen had the slowest heat transfer. The difference in temperature between inside and outside regions was small in the liquid nitrogen cooling stage with a maximum around 30℃.Corresponding cooling rate was low, since the vapor membrane of liquid nitrogen was produced continuously, the coefficient of surface heat change was small and relatively stable in the cooling stage. In liquid nitrogen temperature stage, the difference in temperature inside and outside the specimen was larger with the maximum at 100℃. The temperature gradient in cryogenic treatment process was
opposite to temperature gradient generated in grinding, thus eliminating or minimizing the residual stress introduced by grinding.

(A) liquid nitrogen cooling and (B) liquid nitrogen to heat up

Fig.12 Temperature field

Figure 13 illustrates equivalent stress Mises distribution in a specimen. As shown, the residual stress introduced by grinding is significantly reduced by cryogenic treatment.

Fig.13 Distribution of the Mises stress

Residual stresses at X, Y direction after cryogenic treatment are illustrated Fig14. Compared to the residual stresses introduced by grinding, the magnitude of surface stress was clearly changed by the cryogenic treatment. Residual stresses in X and Y directions along the grinding path (Fig14) were also compared to those in specimens experienced grinding (Fig11), which showed obvious, changes in the residual stress magnitude.

(A) X-direction and (B) Y-direction

Fig.14 X-direction and Y-direction stress field

Further analyzing numerical data shown Fig11, in comparison with those given in Fig14, one may see that the distribution of residual stress caused by grinding was similar to that by cryogenic treatment but the stress magnitude markedly varied. As illustrated in Fig15, the residual stress S11 in the X direction (parallel to the grinding direction)
was tensile stress at the surface with the maximum in the central region. Residual stress S22 in the Y direction (perpendicular to the grinding direction) was compressive with lower magnitude in the central inner region. The tensile component residual stress was reduced by the cryogenic treatment. However, the cryogenic treatment resulted in an opposite effect on the compressive residual stress component.

\[ \text{(A)} \text{ the residual stress } S_{11} \text{ at direction } X \text{ and (B) the residual stress } S_{22} \text{ at direction } Y \]

Fig.15 Comparison of the residual stress $S_{11}$ and $S_{22}$ in the path AB at direction $X$ and $Y$

Fig.16 gives comparison of measured residual stress states caused by three processes: quenching tempering, grinding, and cryogenic treatment + grinding. As shown, the specimen experienced quenching tempering exhibited the minimum residual stress. Grinding introduced considerably higher residual stress, which was however reduced significantly by the cryogenic treatment.

Quantitative values of residual stresses in ground specimens before and after cryogenic treatment are listed below. The cryogenic treatment reduced the equivalent stress of Max. Mises caused by grinding from 248.9 MPa to 114.3 MPa, corresponding to a decrease by 54%; the principal stress was reduced from 124.0 MPa to 91.6 MPa (by 26%); the residual stress in $X$ direction ($S_{11}$) was in a tensile state and Max. $S_{11}$ was reduced from 105.8 MPa to 63.48 MPa (by about 40%); the residual stress in $Y$ direction ($S_{22}$) was compressive and the Max. $S_{22}$ was increased from -272.6 MPa to -287.8 MPa by the cryogenic treatment.

Fig.16 Residual stress of HSS in different treatment

It has been noted that the residual stress component perpendicular to the grinding direction was compressive, while that parallel to the grinding direction was tensile. These are explainable. Liu (Liu, 1950) calculated the stress distribution when a surface force combining tangential and normal components was applied to a target surface. The stress distribution is schematically illustrated in Fig.17. As shown, tensile stress occurs right behind the applied load,
which is a cause for wear (Hutchings, 1992 and Nakasa, et al, 2005) or grinding. When the grinding force is removed, residual tensile stress could exist in the grinding direction. As for the compressive residual stress, since the grinding force can be decomposed into normal and tangential components, the normal component mainly results in abrasive extrusion deformation, which should be responsible for the generation of residual compressive stress perpendicular to the grinding direction.

![Fig.17 Schematic contours of maximum principal stress caused by a combination of elliptical distribution of tangential and normal loads](image)

The computational study of the effect of cryogenic treatment of residual stress in ground surfaces is consistent with experimental measurements. The values from the finite element analysis are somewhat smaller than those from the experimental measurements with errors in the range of 11 ~ 26%. The errors may come from experimental error and simplification of the finite element model.

4. Conclusions

Residual stress in surface layer of a workpiece resulting from machining could considerably affect its performance. In this study, residual stress in the ground surface was analyzed experimentally and computationally with particular interest in the effect of cryogenic treatment on the residual stress. It was demonstrated that the cryogenic treatment reduced the equivalent stress of Max. Mises from 248.9 MPa to 114.3 MPa (by 54%), reduced the principal stress from 124.0 MPa to 91.6 MPa (by about 26%), reduced the maximum residual tensile stress component parallel to the grinding direction (S11) 105.8 MPa to 63.48 MPa (by about 40%), but increased the desired residual compressive stress (S22) perpendicular to the grinding direction from -272.6 MPa to -287.8 MPa. Such changes in residual stress are beneficial to the surfaces, e.g., improving their resistance to wear. Results from the computational and experimental analyses are consistent.

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References


C. K., Liu, Stresses and deformation due to tangential and normal loads on an elastic solid with applications to contact stresses (1950), PhD thesis, University of Illinois.


