

EFFECT OF DEEP ROLLING BEHAVIOR OF SINTERED METAL ON FATIGUE LIFE TIME

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Abstract

In this study, the effect of deep rolling on the near surface properties and microstructure of sintered metal was investigated. A metal surface treatment on the surface of sintered metal was found to improve the following attributes: sub-surface hardness, compressive residual stress, and dislocation density with a reduction of surface roughness and porosities on the near surface. It was also demonstrated that the compactness and hardness are improved by increasing the deep rolling force. Compressive residual stresses and work hardening states are suggested to inhibit surface crack initiation and crack propagation, resulting in an improvement of the fatigue resistance of sintered metals.

Keywords: Sintered metal, deep rolling, fatigue, work hardening

Introduction

Recently, enhancement of mechanical properties using mechanical surface treatments has been widely applied to improve fatigue life (Wagner, 1999; Juijerm and Altenberger, 2007a). Compared to other processing methods, powder metallurgy enables us to manufacture parts with complex geometry at a reduced cost for materials (German, 1998; Beiss *et al.*, 2002; Höganäs AB, 2013). However, sintered materials have a major disadvantage because of the lower fatigue life time expectancy due to porosity (Tosangthum *et al.*, 2006; Nusskern *et al.*,

2014). On being subjected to cyclic loads, such voids will lead to crack initiation and the growth of fatigue cracks. Damage caused by fatigue is particularly serious because no sign of it is evident before it occurs.

Fatigue failure is explained through cracking which is composed of 2 steps: initiation and propagation (Halford and Gallagher, 1999). Dislocations play a major role in the fatigue crack initiation phase. It has been observed that, under high cycles of loading, dislocations pile up and form

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structures called persistent slip bands which are suggested to occur along slip planes (Glaeser and Shaffer, 1996; Papakyriacou *et al.*, 2001). This leaves tiny steps on the surface which serve as stress risers and fatigue cracks can be initiated. Subsequently, such microcracks coalesce and propagate through the material.

A mechanical surface treatment such as deep rolling is generally applied to increase the fatigue performance (Wagner, 1999; Schulze, 2005; Juijerm *et al.*, 2007b). Compressive residual stress and work hardening should occur on the surface as a consequence of plastic deformation. Positive compressive residual stress can compensate for the applied stress that occurs in the tensile-load cycles. Work hardening states, represented by the FWHM-values (full width at half maximum), can be referred to as the density of the dislocations (Nikitin *et al.*, 2005). The mobility of dislocations obviously decreases with the higher their density.

It has been reported that a macroscopic compressive residual stress and work hardening can suppress surface crack initiation and crack propagation, resulting in a fatigue resistance improvement. Besides, a reduction of material roughness can hinder the occurrence of the persistent slip bands mentioned earlier.

This research studies the effect of the deep rolling parameters on the fatigue lifetime for sintered materials where microstructural changes, sub-surface hardness, residual stress, and FWHM-value were investigated.

Materials and Methods

Metal powder NC100. 24 mixed with zinc stearate (solid lubricant) at the ratio of 99:1 by weight were used. The mixed powder was pressed with 40 tons of force to form a slab with dimensions of 20×20×186 mm³. The green compacts were sintered at 1,200°C for 75 min in a vacuum. Dumbbell-shaped specimens, as shown in Figure 1, were fabricated using a lathe. The deep rolling process was applied by using a hydrostatic spherical rolling element, illustrated in Figure 2, at a constant

rotation of 85 rpm. The applied forces were as follows: 0.125, 0.25, and 0.4 kN.

An optical microscope was used to study the microstructure and the modification of the porosities. The hardness case-depth, a hardness at various depths from the surface, was measured with a micro Vickers hardness tester. The residual stress and work hardening states were observed using a $\sin^2\psi$ X-ray diffraction technique with Cu K α radiation in a longitudinal direction of the specimens, focused on {211} planes where $\frac{1}{2}S^2 = 6.16 \times 10^{-6} \text{ mm}^2/\text{N}$ was used in an elastic constant. Work hardening was characterized by the FWHM values of the diffraction peaks. Fatigue tests were performed using a rotary fatigue tester. In the beginning, the microstructure, the hardness case depth, the residual stresses, and FWHM-values for the first group of specimens (non-treatment) were measured. Then the fatigue tests were applied with stress amplitudes of 200, 300, 400, and 500 MPa. After that, the S-N curves were determined. For the second group, after deep rolling with several forces, the microstructure,

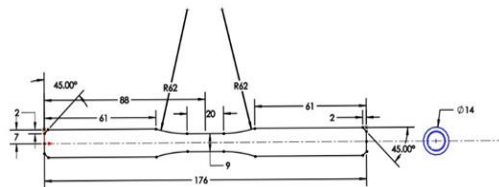


Figure 1. The specimen geometry of sintered metal



Figure 2. The compressed deep rolling setup

the hardness case depth, the residual stresses, and FWHM-values were measured; then, the fatigue test followed with stress amplitudes of 200, 300, 400, and 500 MPa for the high cycles regime fatigue test, and 550, 600, 650, and 700 MPa for the low cycles regime fatigue test. Then the S-N curves were determined and compared with each other.

Results and Discussion

The densities of the green- and as-sintered specimens were 5.40 and 5.98 g/cm³, respectively. Figure 3 demonstrates the microstructure composed of a ferrite phase matrix with distributed porosities which is consistent with the chemical composition of the metal particles. The hardness of the sintered non-deep rolled metal was measured at 53.25 HV.

After being subjected to the deep rolling treatment, the sub-surface microstructure clearly demonstrates that the particles of the deep rolled specimens (Figure 4(b)) are more tightly packed than those of the untreated specimens (Figure 4(a)). The porosities in the near surface area are reduced as the hardness increased. The hardness value also increases with an increase of the applied force; it ranges from 118.4, 159.3, and 173.9 HV for the 0.125, 0.250, and 0.4 kN condition, respectively. Also, in Figure 5, the effect of the deep rolling forces on the hardness of the near surface is shown. The thickness of the hardened layers, where the hardness is greater than or equal to 100 HV, increases with the increasing deep rolling forces. The case depths are 0.35 mm, 0.52, mm and 0.78 mm for 0.125, 0.250, and 0.4 kN of applied force, respectively.

The compressive residual stress and the FWHM-value for the deep rolled specimens increase significantly with the higher deep rolling forces, as depicted in Figures 6 and 7, respectively. This implies that the density of the dislocations shows a strong correlation with the deep rolling forces. The results show that the higher the deep rolling forces are applied, the more the specimen will be in plastic deformation together with a positive work-hardening.

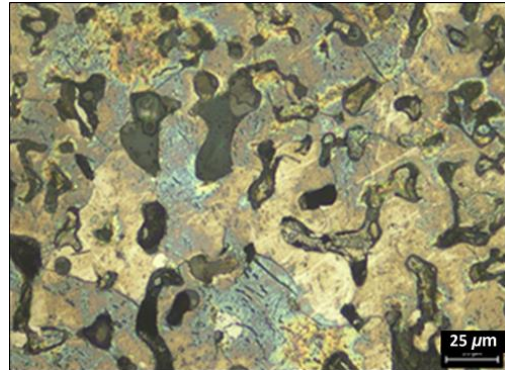
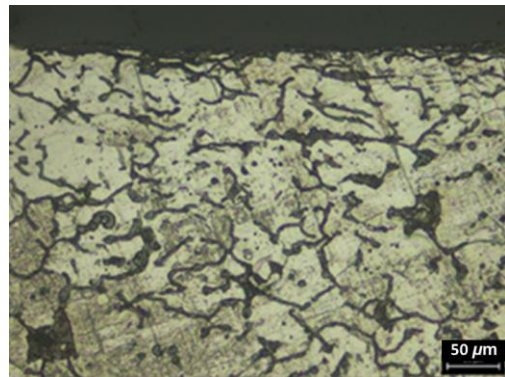
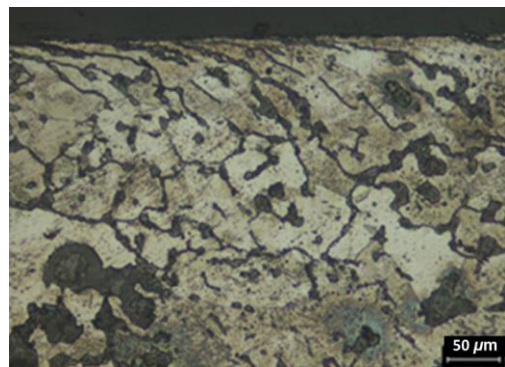


Figure 3. Pore distribution of the as-sintered specimen



(a)



(b)

Figure 4. Microstructure of (a) the as-sintered and (b) deep-rolled with applied force 0.4 kN specimens

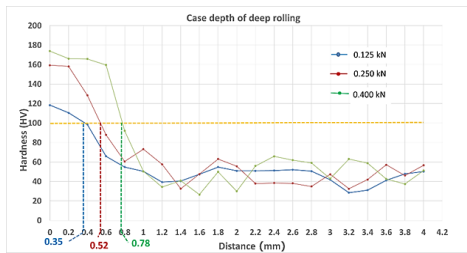


Figure 5. Hardness profiles and case depth of different deep rolling forces

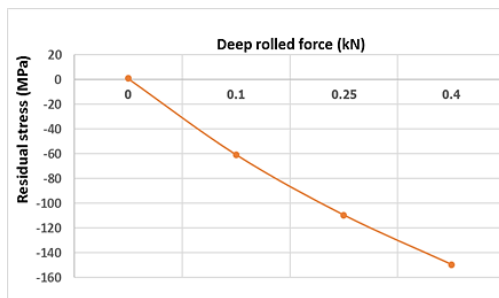


Figure 6. Effect of different deep rolling forces on the residual stresses at the near surface for sintered metal

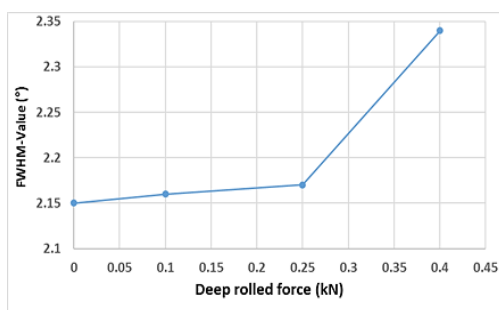


Figure 7. Effect of different deep rolling forces on the FWHM-values at the near surface for sintered metal

Although deep rolling induces plastic deformation on the surface, the material on the near surface cannot expand freely (Juijerm and Altenberger, 2007a). Therefore, it is understandable that a compressive residual stress in the

sub- surface region can be observed. In addition, the FWHM-values are in agreement with the degree of plastic déformations (Schulze, 2003).

The influence of the deep rolling process on the fatigue life time is shown in Figure 6. It is demonstrated that the higher the deep rolling force applied, the more the fatigue lifetime is prolonged. Additionally, the fatigue lifetime for the as-lathed specimens is lower than for those subjected to the deep rolling process. Regarding the stress amplitude of the 500 MPa fatigue test, the number of cycles for the untreated condition was 1,853 cycles and the number was increased to 54,354 cycles for 0.125 kN, 126,803 cycles for 0.250 kN, and 716,435 cycles for the 0.4 kN the deep rolling conditions.

Furthermore, the macroscopic compressive residual stresses and FWHM-values at the near surface region directly relate to the effect of the deep rolling on the materials. By applying a deep rolling process, the maximum compressive residual stress can be obtained at 149.40 MPa, while the FWHM-values increased from 2.15° for the as-lathed condition to 2.34° for the 0.4 kN deep rolled specimens. This indicates that the deep rolling process causes a plastic deformation in the sub- surface region. An increase of the density of the dislocations can hinder the dislocations movement. Therefore, the macroscopic compressive residual stresses and work hardening states can suppress surface crack initiation and crack propagation resulting in a fatigue performance improvement.

Conclusions

The effects of the deep rolling process on the mechanical properties of low carbon steel sintered samples were observed. The surface hardness can be significantly improved by the deep rolling process with more severe deformation. Therefore, it confirms the essence of post-sintering deformation on powder metallurgy. As regards the greater compactness on the surface, surface hardening induces compressive residual stress and work hardening causes an increase of the fatigue performance.

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