Hardness, microstructure and residual stress at the surface of gyro finished martensitic steel

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1. Introduction

Fatigue property is one of the most important mechanical properties for structural materials. Surface roughness and residual stress are well known influential factors for the fatigue properties in metal materials[1,2]; a smooth surface and compressive residual stress improves the fatigue property. Shot peening process has been conducted for improving the fatigue property. The process can introduce high compressive residual stress on the specimen surface, resulting in improvement of fatigue properties. However, the shot peening roughens the specimen surface, and it causes the deterioration of the fatigue properties.

Recently, gyro finishing has been developed as a mass finishing process for large or complex workpieces such as gears and springs[3]. In this process, abrasive media accelerated by rotation of container impact on the workpiece fixed in the container and smooth the surface. While, in the shot peening process, the media accelerated by high pressure air shoot on the specimen surface. Thus, the gyro finishing is similar to the shot peening. Although the size of abrasive media in gyro finishing is significantly larger than the media used in the shot peening process, it can be expected that deformation structure and compressive residual stress will be developed at the specimen surface by gyro finishing.

In this study, the microstructure, surface roughness, hardness and residual stress at the surface in the martensitic steel after gyro finishing with various abrasive media were revealed.

2. Experimental procedure

S10C steel (Fe-0.1mass%C) bar with 30 mm diameter was used in this study. The bar specimen was cut into 5 mm in thickness. The cut specimen was solution treated at 1223 K for 0.6 ks and then water-quenched. A full martensite structure was formed after heat treatment. Gyro finishing was conducted on the specimen polished by SiC paper with #1500. The rotation speed and time of the gyro finishing were 60 rpm and 0.6 ks, respectively. The workpiece position was 100 mm in depth from the abrasive media surface and 100 mm in radius from the center of the container. The ceramic spherical abrasive media (Tipton Corp.) with sizes of 1 mm, 4 mm and 10 mm diameter were used in the gyro finishing. Hereinafter, the specimens after gyro finishing with abrasive media in 1 mm, 4 mm and 10 mm diameter are referred to as CSA-1, CSA-4 and CSA-10, respectively. The surface roughness and hardness were measured using a laser microscope and a Vickers hardness test machine, respectively. The residual stress measurement was performed by the cosα method[4] using X-ray diffraction. The residual stress was intermittently measured by removing the specimen surface using electropolishing, and the residual stress profile along the depth direction was constructed. The microstructure around the specimen surface was observed using field-emission scanning microscopy (SEM). The observation was conducted on the cross-sectional plane of the gyro finished specimen.

3. Results and Discussion

3.1. Surface roughness and microstructure after gyro finishing

Table 1 shows the arithmetical mean height (Sa) values of the specimen surface after gyro finishing by various abrasive media. Although the Sa value slightly increased with increasing the media size, those values are significantly smaller than the Sa value (20 μm) in the surface after the shot peening process[5]. Thus, gyro finishing can introduce a smooth surface to the specimen surface.

Table 1 Arithmetical mean height (Sa) values of the specimen after gyro finishing with various abrasive media.

	CSA-1	CSA-4	CSA-10
Arithmetical mean height, Sa [μm]	0.051	0.063	0.11

Figure 1 shows the cross-sectional SEM image of the specimen surface after gyro finishing with CSA-10. The acicular shaped grains could be observed in the matrix, which is a typical lath martensite microstructure in low-carbon steels. On the other hand, within the region from the surface to 1 μm depth, acicular shaped grains were hardly observed and equiaxed ultra-fine grains below 500 nm were present, as indicated by arrows in Fig. 1. Similar ultra-fine grains were observed on the specimen surface after shot peening[6]. The extremely high plastic strain is introduced into the specimen surface during the shot peening, which induces such ultra-fine grains. Therefore, gyro finishing can also introduce extremely high plastic strain and ultra-fine grains on the specimen surface, similar to shot peening.

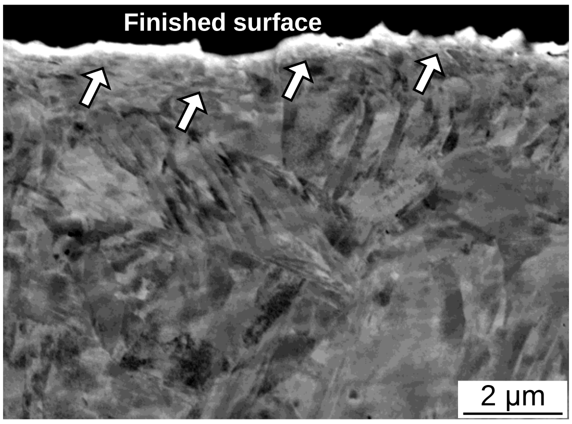

Figure 1 Cross-sectional SEM image in the specimen after gyro finishing with CSA-10.

3.2. Increase of Vickers hardness by gyro finishing

Table 2 shows Vickers hardness at various depths in the specimen before and after the gyro finishing. The Vickers hardness before gyro finishing was roughly identical irrespective of the depth and consistent with the Vickers hardness in martensitic steel with 0.1wt%C previously reported[7]. In the CSA-1 specimen, the Vickers hardness was approximately equal to that in the specimen before the gyro finishing. Thus, work-hardening hardly occurred during gyro finishing by CSA-1. On the other hand, the Vickers hardness of CSA-4 and CSA-10 were approximately the same and significantly higher than that before the gyro finishing. The Vickers hardness continuously decreased with increasing the depth in both CSA-4 and CSA-10. However, even at 2000 μm depth, the Vickers hardness in CSA-4 and CSA-10 was higher than that before the gyro finishing. Therefore, gyro finishing with large abrasive media can introduce high hardness within the region from the surface to several thousand μm. This result also indicates that the significant work-hardening occurred during gyro finishing with CSA-4 and CSA-10. In fact, the kernel average misorientation value corresponding to the amount of plastic strain[8] continuously increased with nearing the specimen surface.

Table 2 Vickers hardness at various depths of the specimens before and after gyro finishing with various abrasive media.

	Vickers hardness [HV]			
Depth	50 μm	600 μm	1000 μm	2000 μm
Before gyro finishing	220±9	221±10	210±6	199±4
CSA-1	226±7	221±14	216±13	221±12
CSA-4	370±5	366±1	348±4	270±10
CSA-10	404±4	379±8	361±3	283±16

3.3. Residual stress developed by gyro finishing

Table 3 shows the residual stress at the surface, 10 μm, 20 μm and 50 μm in the specimens before and after the gyro finishing with various abrasive media. The residual stress of the specimen before the gyro finishing was not 0 but significant compression and the value was maintained even inside the specimen. Thus, the compressive residual stress should be introduced during martensitic transformation. At the surface, residual stress was maximum and significantly large compressive, similar to that developed by shot peening[9], in the specimens after the gyro finishing by CSA-1 and CSA-4. While, although the maximum residual stress in the specimen after gyro finishing by CSA-10 was same level with that in CSA-1 and CSA-4, the depth of the maximum residual stress (d_{max}) was not surface but 30 μm depth. Thus, the abrasive media size hardly affects the maximum residual stress value but it affects the d_{max} in the gyro finishing. Ogawa *et al.* demonstrated experimentally and theoretically that d_{max} depends on the size of media in the shot peening process and large shot media leads to deeper d_{max}[10]. In accordance with the proposed equation for d_{max} based on Heltz theory by Ogawa, d_{max} could be estimated to 2.01 μm and 20.5 μm in CSA-1 and CSA-10, respectively. Those estimated values are approximately identical to the measured d_{max}. Furthermore, Ogawa *et al.* also reported that the maximum residual stress developed by shot peening was hardly changed by media sizes but those were changed by density, Young's modulus and velocity of media. Therefore, it can be concluded that the effect of media size on residual stress developed by gyro finishing is similar to that developed by the shot peening process.

Table 3 Residual stress at various depths in the specimens before and after gyro finished specimen with various abrasive media sizes.

	Residual stress [MPa]			
Depth	Surface	10 μm	30μm	50 μm
Before gyro finishing	-161	-144	-	-
CSA-1	-556	-205	-140	-
CSA-4	-515	-372	-251	-224
CSA-10	-390	-395	-489	-348

4. Conclusion

A smooth surface could be obtained by the gyro finishing independent of abrasive media size. Vickers hardness significantly increased by gyro finishing with CSA-4 and CSA-10, but it hardly increased by gyro finishing with CSA-1. The significantly high compressive residual stress was developed by gyro finishing independent of abrasive media size. The depth of maximum residual stress became deeper with increasing the abrasive media size, similar to that in shot peening process.

It can be concluded that gyro finishing is the effective method to provide a specimen surface with a smooth roughness, ultra-fine grains, high hardness, and high residual stress. Thus, it is highly expected that the gyro finishing improves fatigue properties of metal materials.

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