

Residual Stress, Surface Roughness and Microstructure on Specimen Surface Subjected to Gyrofinishing Process with Various Abrasive Media

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Gyrofinishing is a mass-finishing process used for large and/or complex workpieces. In this process, abrasive media filled in a container are accelerated by rotating the container, impacting the workpiece fixed in it and smoothing the workpiece surface. In this study, the effects of the materials and sizes of the abrasive media on the surface roughness, microstructure, and residual stress on the specimen surface developed by gyrofinishing were revealed. The surface of the gyrofinished specimen was smooth. However, the specimen surface when using the HS medium, consisting of a mixture of ceramic and small abrasive grains, was slightly rougher compared to that finished using the PS medium, consisting of ceramic. An ultra-fine grained structure was formed at the surface after gyrofinishing, regardless of medium. A flow of the microstructure was observed in the specimens gyrofinished with the HS media, indicating that shear stress occurred during gyrofinishing. All the gyrofinished specimens exhibited a significant compressive residual stress near the surface. The residual-stress profile along the depth direction differed depending on the material and size of the media. The small media shallowed the depth of the maximum compressive residual stress ($d_{\max}$), whereas the medium size hardly affected the maximum compressive residual stress ($\sigma_{\max}$). The measured $d_{\max}$ was significantly smaller than the $d_{\max}$ value estimated based on the Hertz contact theory, which is likely due to the shear stress generated by the rotation or sliding of the media on the specimen surface during gyrofinishing. The specimens gyrofinished using the HS series had a higher $\sigma_{\max}$ than those gyrofinished using the PS series. The rough surface of the HS medium is expected to introduce a high compressive residual stress through the burnishing effect. It can be concluded that gyrofinishing provides the specimen surface with a smooth, ultra-fine grained structure and significant compressive residual stress. [doi:10.2320/matertrans.MT-H2024001]

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1. Introduction

The fracture failure of metal materials is primarily caused by fatigue fractures. Fatigue cracks generally nucleate from the surface and propagate deeper into the specimen, resulting in fatal fractures. Thus, surface states such as hardness, residual stress, and roughness play an important role in the fatigue properties. Various surface strengthening processes, including carburizing, nitriding, and ball burnishing, have been proposed to improve fatigue properties of metal materials [1–3]. The shot-peening process is one of them and is widely applied to metal materials because of its usability and low cost [4–6]. In the shot-peening process, abrasive particles, several hundred micrometers in size, accelerate to several tens of meters per second and those shoot on the specimen surface. It is well known that a high compressive residual stress is introduced near the surface after the shot-peening process [7, 8]. This high compressive residual stress strongly suppresses fatigue crack opening and improves the fatigue properties [9]. Unfortunately, the shot-peening process roughens the specimen surface, causing deterioration of fatigue properties because of stress concentration at the dent [10]. Therefore, the shot-peening process has positive and negative effects on the fatigue property simultaneously, and the positive effect overcomes the negative effect in most cases. Therefore, shot peening is considered an effective way to improve fatigue properties.

However, as mentioned above, the improvement in fatigue properties due to the shot-peening process was smaller than that expected from the compressive residual stress. Kikuchi *et al.* quantitatively evaluated the effect of surface roughness and residual stress on the fatigue limit in a specimen subjected to the shot-peening process and concluded that a rough surface certainly decreases the fatigue limit [11].

Recently, the gyrofinishing process has been developed as a mass-finishing process for large and/or complex workpieces such as gears and springs [12–14]. Figure 1 shows a schematic illustration of the gyrofinishing machine.

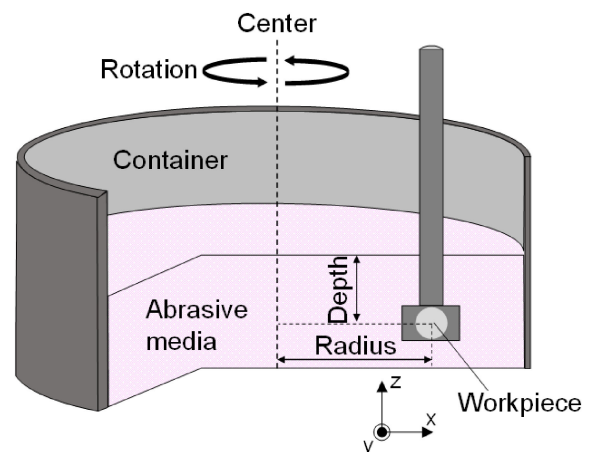


Fig. 1 Schematic illustration of the gyrofinishing machine.

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In this process, the abrasive media filled in the container are accelerated by the rotation of the container, which then, impacts the workpiece fixed in the container and smooths the workpiece surface. This process is similar to the shot-peening process, although the media size and velocity significantly differ between these processes: in the gyro-finish process, the medium size is tens of times, but medium velocity is several tenths of that of the shot-peening process. Kacaras *et al.* investigated the surface microstructure and residual stress developed by stream finishing (gyrofinishing) [15]. They revealed that ultra-fine grains formed at the specimen surface, and compressive residual stress developed up to several tens of micrometers in depth by gyrofinishing. Its compressive residual stress was approximately -600 MPa, which is similar to the compressive residual stress developed by the shot-peening process. Various abrasive media have been proposed for the gyrofinishing process because controlling the material and size of the abrasive media is easy owing to the large size of the media (several millimeters). However, the effects of the material and size of the media on the surface state after gyrofinishing have not been thoroughly investigated.

In this study, the effects of the material and size of the abrasive media in the gyrofinishing process on the surface roughness, microstructure, and residual stress on the specimen surface were revealed. Furthermore, the development of residual stress on the specimen surface during gyrofinishing was discussed.

2. Experimental Procedure

2.1 Specimen and gyrofinishing process

A commercial carbon steel (Fe-0.1 mass% C) bar with a diameter of 30 mm was used in this study. The bar specimen was cut to thickness of 5 mm. The cut specimen was solution-treated at 1223 K for 0.6 ks and then water-quenched. A full martensite structure was formed from the surface to a depth of 1 mm, and in the region deeper than 1 mm, the hardness continuously decreased with depth owing to the decrease in the amount of martensite structure. The gyrofinishing process was conducted on the heat-treated specimens polished using #1500 SiC paper. The gyrofinishing machine GS-45 (Tipton Co., Ltd.) was used. The rotation speed of the container and the time of gyrofinishing were 60 rpm and 0.6 ks, respectively. The workpiece position was at a depth of 100 mm from the surface of the filled abrasive media and 100 mm in radius from the center of the container. The definitions of depth and radius in the gyrofinishing process are described in Fig. 1. In this study, the upward, radial, and circumferential directions of the container of the gyrofinishing machine are referred to as the z -, x -, and y -directions, respectively, as shown in Fig. 1. Figure 2 shows an image of the abrasive media used in this study. Spherical abrasive media consisting of ceramic (PS) and a mixture of ceramic and small abrasive grains (HS) (Tipton Co., Ltd.) were used. Furthermore, media of 4 mm and 10 mm in diameter were prepared for both PS and HS. Hereinafter, PS and HS media with 4 and 10 mm diameters are referred to as PS-4 (Fig. 2(a)), PS-10 (Fig. 2(b)), HS-4 (Fig. 2(c)) and HS-10 (Fig. 2(d)), respectively.

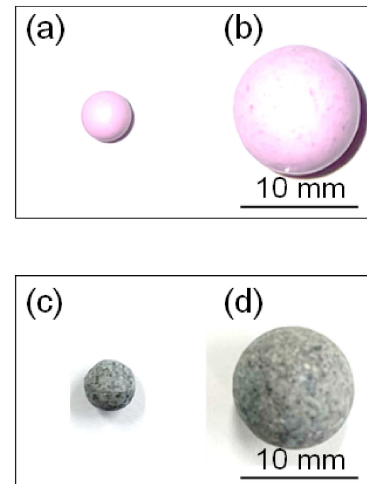


Fig. 2 Whole image of the abrasive medium of (a) PS-4, (b) PS-10, (c) HS-4 and (d) HS-10.

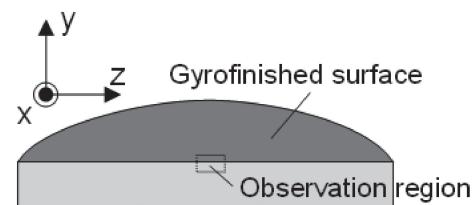


Fig. 3 Schematic illustration of microstructural observation region.

2.2 Measurement of surface roughness and hardness, and microstructural observation

Surface roughness was measured using laser microscopy (VK-X3050, Keyence Corp.). The measured region was the surface at the center of the specimen before and after gyrofinishing.

The microstructure was observed by field-emission scanning electron microscopy (SEM). The observation region was the cross-section of the specimen beneath the gyrofinished surface, as shown in Fig. 3. The specimen was cut along the y - z plane during gyrofinishing (Fig. 1). The cut specimens were polished with SiC paper and finished with a colloidal silica suspension. The specimen was plated with Ni to avoid dull edges at its outermost surface.

Micro-Vickers hardness tests were performed on gyrofinished surfaces. The load was 1 gf. In addition, nanoindentation test was conducted to measure the Young's modulus of the media. A Berkovich indenter with a three-sided pyramid was employed. The peak loading was 1000 μ N.

2.3 Measurement of residual stress profile

Residual stress was measured by a portable X-ray residual stress analyzer (μ -X360s: Pulstec Industrial Co., Ltd.). In this analyzer, residual stress was calculated by using the $\cos \alpha$ method [16], and its advantages are that it is handheld and that it has a short measurement time of approximately one minute. Furthermore, the accuracy of this method has been validated, as the residual stress measured by the $\cos \alpha$ method was found to be coincident with that measured by $\sin 2\psi$ [17]. The residual stress was intermittently measured by removing the surface using electropolishing with a mixture

of ammonium chloride, glycerin, and water, and then constructing the residual-stress profile along the depth direction of the specimen.

3. Results

3.1 Surface roughness developed by gyrofinishing with various media

Figure 4 shows the entire specimen surfaces (a) before and after gyrofinishing with (b) PS-4, (c) PS-10, (d) HS-4, and (e) HS-10. Before gyrofinishing, numerous scratches were introduced on the specimen surface by polishing it with #1500 SiC paper. After gyrofinishing, the scratches completely disappeared, regardless of the medium. In the specimen surfaces gyrofinished with PS-10 and HS-10 (Figs. 4(c) and (e)), some dents were seemingly present, whereas the specimens gyrofinished using PS-4 and HS-4 had a flat surface (Figs. 4(b) and (d)). Figure 5 shows the surface roughness maps of the specimens gyrofinished with (a) PS-4, (b) PS-10, (c) HS-4, and (d) HS-10. The specimen surface gyrofinished with PS-4 exhibited an extremely flat surface, whereas the specimen gyrofinished with PS-10 had bumps and dents with diameters of approximately 100 μm , as indicated by arrows in Fig. 5(b), although the roughness inside each bump and dent was small. The specimen surface gyrofinished with HS series (Figs. 5(c) and (d)) exhibited scratches, which tended to be parallel to the z-direction of the gyrofinishing process. The degree of surface roughness depended on the size of the HS media, with large media causing significantly greater roughness of the specimen surface. In the specimen gyrofinished with HS-10, the depth of roughness varied in the range of -2 – 2 μm . Figure 6 shows the depth-line profiles of the specimen surfaces gyrofinished with PS-4, PS-10, HS-4, and HS-10. The specimen surface gyrofinished with the PS series exhibited a smooth surface,

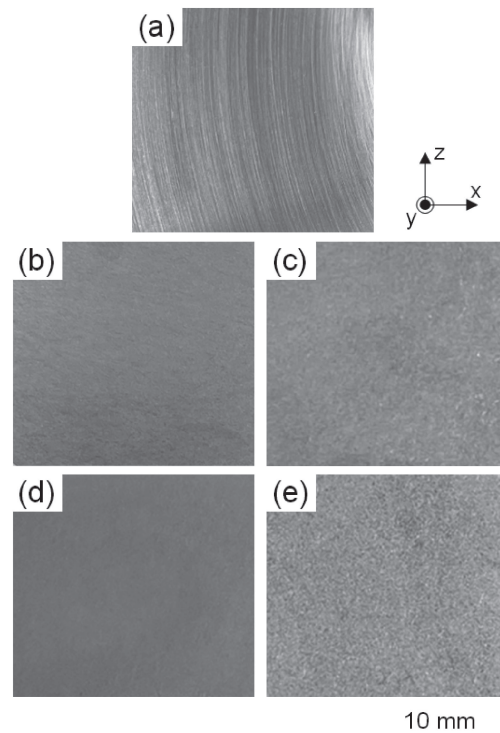


Fig. 4 Images of entire specimen surface (a) before and after gyrofinishing with (b) PS-4, (c) PS-10, (d) HS-4, (e) HS-10.

although shallow dent with a depth less than 0.25 μm was observed on the specimen surface gyrofinished with PS-10, as indicated by arrow in Fig. 6. Gyrofinishing with HS-4 produced a comparably smooth surface, whereas HS-10 significantly roughened the specimen surface. Table 1 lists the arithmetic mean heights (S_a) calculated from the surface roughness shown in Fig. 5. The S_a value for the specimen

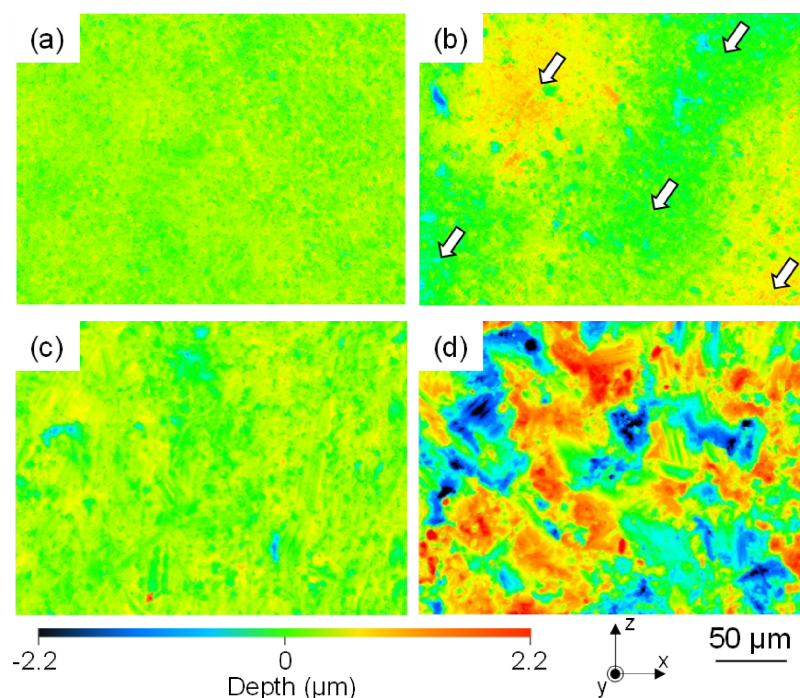


Fig. 5 Surface roughness maps in the specimens gyrofinished with (a) PS-4, (b) PS-10, (c) HS-4, (d) HS-10.

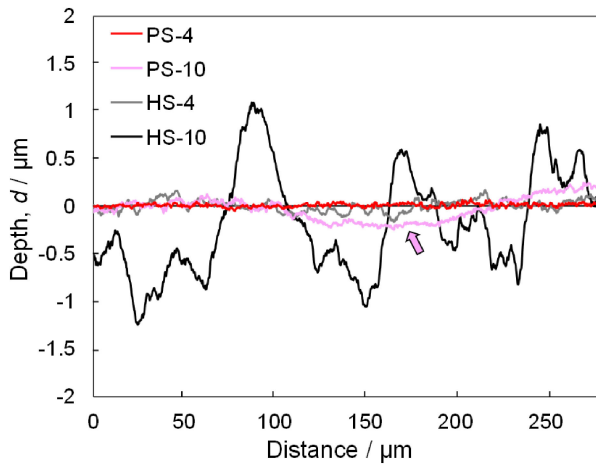


Fig. 6 Depth-line profiles on the specimen surfaces gyrofinished with PS-4, PS-10, HS-4, and HS-10.

Table 1 Arithmetic mean height (S_a) calculated from the surface roughness maps of Fig. 5.

	PS-4	PS-10	HS-4	HS-10
S_a (μm)	0.063	0.11	0.13	0.70

surface gyrofinished with HS-10 is the largest, but this value is significantly lower than $20\mu\text{m}$, which is approximately the S_a value of the specimen surface after the shot-peening process [18].

It can be concluded that the specimen surface after gyrofinishing is smoother than after shot-peening, although the surface roughness after gyrofinishing varies depending on the material and size of the media.

3.2 Microstructure developed by gyrofinishing with various media

Figure 7 shows the backscattered electron (BSE) images of the cross-sections of the specimens gyrofinished with (a) PS-4, (b) PS-10, (c) HS-4, and (d) HS-10. Acicular grains were observed in all specimens in regions deeper than $1\mu\text{m}$. This microstructure is a typical lath martensite structure. Notably, in all specimens, in the region shallower than $1\mu\text{m}$ depth, i.e., the outermost surface, equiaxed grains were detected with grain sizes finer than approximately $1\mu\text{m}$. Therefore, ultra-fine grained (UFGed) structure is formed on the specimen surface by gyrofinishing, regardless of the medium. A similar UFGed structure has been widely observed in specimens subjected to severe plastic deformation (SPD), such as equal-channel angler pressing [19], high-pressure torsion [20], and multi-directional forging [21, 22] methods. Generally, severe plastic strain induces an UFGed structure. This phenomenon is called “continuous dynamic recrystallization” [23] and has been observed on specimen surfaces subjected to working, including punching [24], drilling [25], and turning [26]. In addition, a similar UFGed structure is also developed during the shot-peening process [27, 28]. During gyrofinishing, continuous dynamic recrystallization occurred regardless of the medium, indicating that gyrofinishing introduces the severe plastic deformation into the outermost surface of the specimen.

Another interesting point in Fig. 7 is that, in the HS series, the UFGed or acicular-shaped grains continuously tilt near the surface, such that the longitudinal axis of the grains is parallel to the z-direction of the gyrofinishing, as indicated by the white dotted lines in Figs. 7(c) and (d). Such a flow of microstructure was observed on the specimen surface after the roller pitching test, in which two roller specimens were rolled while bearing a load [29, 30]. In the roller pitching test, shear stress occurs because of the difference in rotational

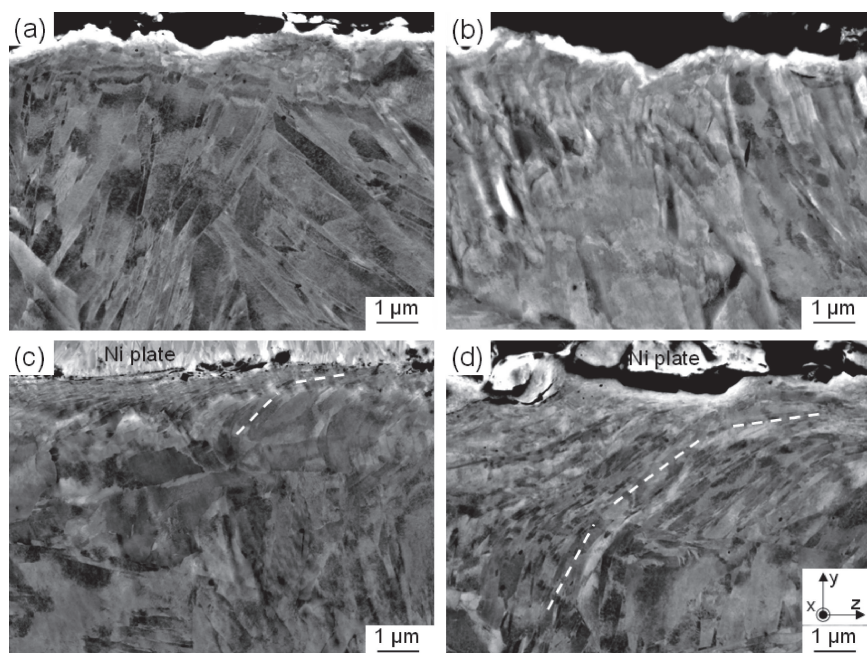


Fig. 7 Backscattered electron (BSE) image on the cross-section on the specimen gyro-finished with the (a) PS-4, (b) PS-10, (c) HS-4, and (d) HS-10.

Table 2 Vickers hardness measured from the specimen surface before and after gyrofinishing with PS-4, PS-10, HS-4, and HS-10.

	Vickers hardness (HV)
Before gyro-finishing	383 ± 25
PS-4	391 ± 12
PS-10	408 ± 27
HS-4	394 ± 14
HS-10	469 ± 28

speeds between the two rollers, and the microstructure flows in the shear stress direction. Therefore, the flow of the microstructure in the HS series suggests that shear stress occurs during the gyrofinishing process in the z-direction, that is, in the upward direction of the container of the gyrofinishing machine (Fig. 1). The media are filled in the container, and it is difficult for them to move along the x-direction, that is, the radial direction, when they impact the specimen surface; however, such restriction of movement should be weak along the z-direction owing to the existence of a free surface. Thus, the media can move easily along the z-direction on the specimen surface during gyrofinishing. Hashimoto *et al.* demonstrated this movement of media during gyrofinishing [31]. In the PS series, although the media is expected to move along the z-direction, its surface is extremely smooth, as discussed later, and hardly any flow of the microstructure was observed.

Table 2 lists the Vickers hardness measured from the specimen surface before and after gyrofinishing. The depth of the indenter was calculated to be approximately $10 \mu\text{m}$. The Vickers hardness value in the specimens gyrofinished with the PS-4, PS-10, and HS-4 increased slightly compared to that before gyrofinishing. The Vickers hardness of the specimen gyrofinished with HS-10 was significantly higher than that of the other specimens. As discussed in Fig. 7(d), gyrofinishing with HS-10 introduced high shear strain even at large depths ($\sim 4 \mu\text{m}$) from the surface of the specimen, and thus, the region work-hardened by gyrofinishing was deeper in the specimen gyrofinished with HS-10 than in the other specimens, resulting in higher Vickers hardness. On the other hand, the Vickers hardness at $200 \mu\text{m}$ depth measured from the cross-sectional plane was approximately the same among the specimens, indicating the increase of hardness is limited to the outermost surface.

3.3 Residual stress developed by gyrofinishing with various media

Figure 8 shows the residual stress profile from the surface to the inside of specimens gyrofinished with PS-4, PS-10, HS-4, and HS-10. The residual stress on the specimen surface before gyrofinishing, which was compressive and introduced during the quenching process, is also shown in Fig. 8. After gyrofinishing, all specimens had a large compressive residual stress of over -500 MPa , and these profiles clearly depended on the material and size of the media. In the specimen

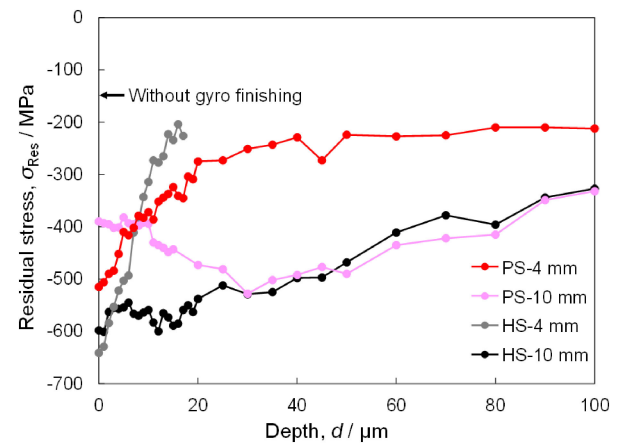


Fig. 8 Residual-stress profile from the surface to inside the specimen gyrofinished with PS-4, PS-10, HS-4, and HS-10. The residual stress in the specimen surface before gyrofinishing is also shown.

gyrofinished with PS-10, the maximum compressive residual stress did not occur on the surface but inside the specimen, at a depth of approximately $30 \mu\text{m}$, which is similar to the residual-stress profile generated by the shot-peening with coarse media [32]. The compressive residual stress was at its maximum at the surface of the specimen gyrofinished with PS-4. The maximum residual stress was equal for the specimens gyrofinished with PS-4 and PS-10. Gyrofinishing with the HS series introduced a higher compressive residual stress into the specimen than gyrofinishing with the PS series. In the specimen gyrofinished with HS-10, the compressive residual stress was approximately constant until a depth of $20 \mu\text{m}$ from the surface, whereas that in the specimen gyrofinished with HS-4 was maximum at the surface and decreased sharply with increasing depth. The maximum compressive residual stress was slightly higher in the specimen gyrofinished with HS-4 than in the specimen gyrofinished with HS-10. The compressive residual stress in specimens gyrofinished with PS-4 and HS-4 continuously decreased from the specimen surfaces and leveled off at approximately $20 \mu\text{m}$ depth, whereas, in the specimens gyrofinished with PS-10 and HS-10, the decrease in residual stress with increasing depth was small, and high compressive residual stress was maintained even at a depth of $100 \mu\text{m}$. The residual-stress profile for depths greater than $30 \mu\text{m}$ was approximately identical for the specimens gyrofinished with PS-10 and HS-10, although the residual-stress profile near the surface was different. The residual stress disappeared at the depth of $200 \mu\text{m}$ in the specimen gyrofinished with PS-10, and thus, it can be concluded that the modified layer by gyrofinishing was approximately $200 \mu\text{m}$ depth in maximum in this study because hardness also hardly increases at $200 \mu\text{m}$ depth as discussed in Section 3.2.

The effects of the material and size of the media on the residual stress developed by gyrofinishing can be summarized as follows: The size of the media primarily affected the depth of the region where the residual stress is introduced and hardly affected the maximum compressive residual stress. The material of the media primarily affected the maximum residual stress.

4. Discussion

The residual stress developed by the shot-peening process can be predicted based on the Hertz contact theory. Ogawa *et al.* proposed that the maximum compressive residual stress ($\sigma_{\max}$) developed by the shot-peening process can be predicted using the following equation [33]:

$$\sigma_{\max} = 0.619(1 - \alpha\beta)(\sigma_s - 0.519\rho^{\frac{1}{3}}E^{*\frac{4}{3}}V^{\frac{2}{3}}). \quad (1)$$

Here, α is a constant, β is the ratio of the true plastic strain to the strain in the part that exceeds the yield strain in the apparent elastic strain, σ_s is yield stress, ρ is the density of the media, E^* is the composite Young's modulus between the media and the specimen, and V is the velocity of the media. According to eq. (1), the size of the media is not related to $\sigma_{\max}$. As shown in Fig. 8, in the specimens gyrofinished with the PS series, $\sigma_{\max}$ was equal, irrespective of the size of the media. Thus, based on the Hertz contact theory, it is reasonable that the media size hardly affected the $\sigma_{\max}$ developed by the gyrofinishing.

Ogawa *et al.* also derived the depth of the maximum compressive residual stress ($d_{\max}$) introduced by shot-peening based on the Hertz contact theory as follows [33]:

$$d_{\max} = 0.316\rho^{\frac{1}{3}}DE^{*-\frac{1}{3}}V^{\frac{2}{3}} \quad (2)$$

Here, D is the diameter of the media. Equation (2) indicates that the size of the media, i.e., D , affects $d_{\max}$ more significantly than other factors, and a small D yields a shallow $d_{\max}$, which is qualitatively consistent with the results for the PS series (Fig. 8). Table 3 lists the ρ , D , E^* , V , and $d_{\max}$ value calculated from eq. (2) during gyrofinishing. The Young's modulus of the PS media was measured using the nanoindentation test, and the same value was used for the HS media because the nanoindentation test could not be conducted on the HS media owing to their rough surfaces. The effect of E^* on $d_{\max}$ is weak, as shown in eq. (2). Thus, if the true E^* in the HS media differs from that in the PS media, the change in $d_{\max}$ is small. The velocity was calculated assuming that the velocity of each medium was equal to the rotational speed of the container. Under all conditions, the estimated $d_{\max}$ values were significantly deeper than the measured values (Fig. 8). For example, the measured $d_{\max}$ for the specimen gyrofinished with PS-10 was approximately 30 μm (Fig. 8), whereas the estimated $d_{\max}$ exceeded twice this value (Table 3). Ogawa *et al.* confirmed that the measured $d_{\max}$ for the specimen subjected to the shot-peening process is approximately equal to the $d_{\max}$ estimated from eq. (2), if $d_{\max}$ is below 40 μm [33]. This conflict may be due to the several differences between shot peening and gyrofinishing, one of which is friction. In the Hertz contact

theory, friction, that is, shear stress, is ignored. However, in gyrofinishing, shear stress occurs, as discussed in Section 3.2. The effect of shear stress on stress distribution during the roller pitching test was simulated using finite element analysis, and the position of the peak stress was found to shift toward the specimen surface with increasing shear stress [34]. Therefore, shear stress is one of the reasons for the smaller $d_{\max}$ in the gyrofinished specimens. In addition, it is possible that the velocity of the media is much slower than the rotational speed of the container, which also reduces $d_{\max}$.

$\sigma_{\max}$ in the specimens gyrofinished with HS series was larger than that in the specimens gyrofinished with PS series. This cannot be explained by the Hertz contact theory (eq. (1)); thus, friction should also be related to this phenomenon. Figure 9 shows the surface roughness maps of the (a) PS-10 and (b) HS-10 medium and their (c) depth-line profiles. The PS-10 medium had an extremely smooth surface. The surface of the HS-10 medium was rough, and its S_a was seven times larger than that of the PS-10 medium. The bump portion of the HS-10 medium reached approximately 10 μm . The rough surface in the HS-10 media grinds the specimen surface during gyrofinishing and, as a result, scratches (Fig. 5) and the flow of the microstructure (Fig. 7) appears on the surface. It is well known that grinding develops residual stress, and this phenomenon is called the “burnishing effect”. The residual stress developed by the burnishing effect is maximized at the surface [35]. Therefore, the high $\sigma_{\max}$ and small $d_{\max}$ in the specimens gyrofinished with the HS series must be attributed to the burnishing effect owing to the rough surface of the HS media.

The development of the residual-stress profile in the specimens gyrofinished with the PS and HS series is summarized schematically in Fig. 10. In both media, the

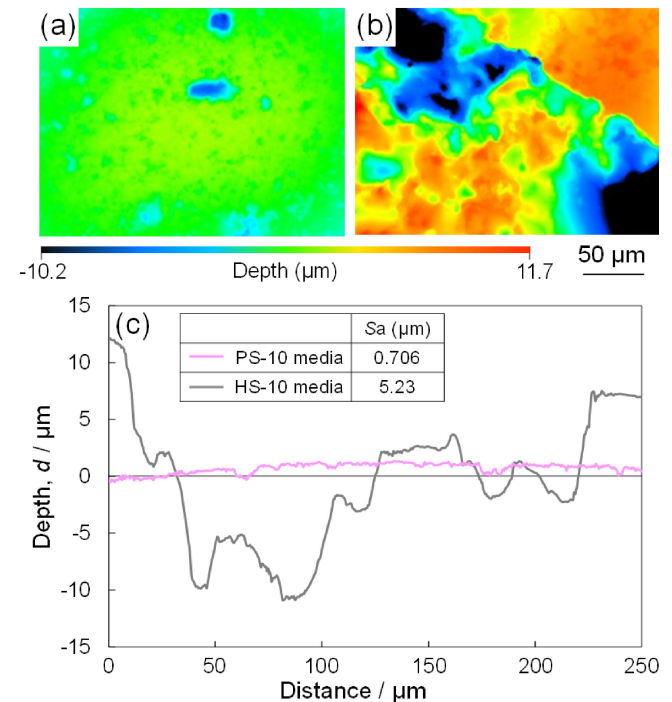


Fig. 9 Surface roughness maps in (a) PS-10 and (b) HS-10 media and (c) its depth-line profiles.

Table 3 Density (ρ), diameter (D), composite Young's modulus between the media and specimen (E^*), velocity (V), and calculated depth at the maximum residual stress ($d_{\max}$) from eq. (2) in the gyrofinishing.

	ρ (g/cm ³)	D (mm)	E^* (GPa)	V (m/s)	$d_{\max}$ (μm)
PS-4	4	4	139	0.63	32.6
PS-10	4	10	139	0.63	81.5
HS-4	1.8	4	139	0.63	27.8
HS-10	1.8	10	139	0.63	69.5

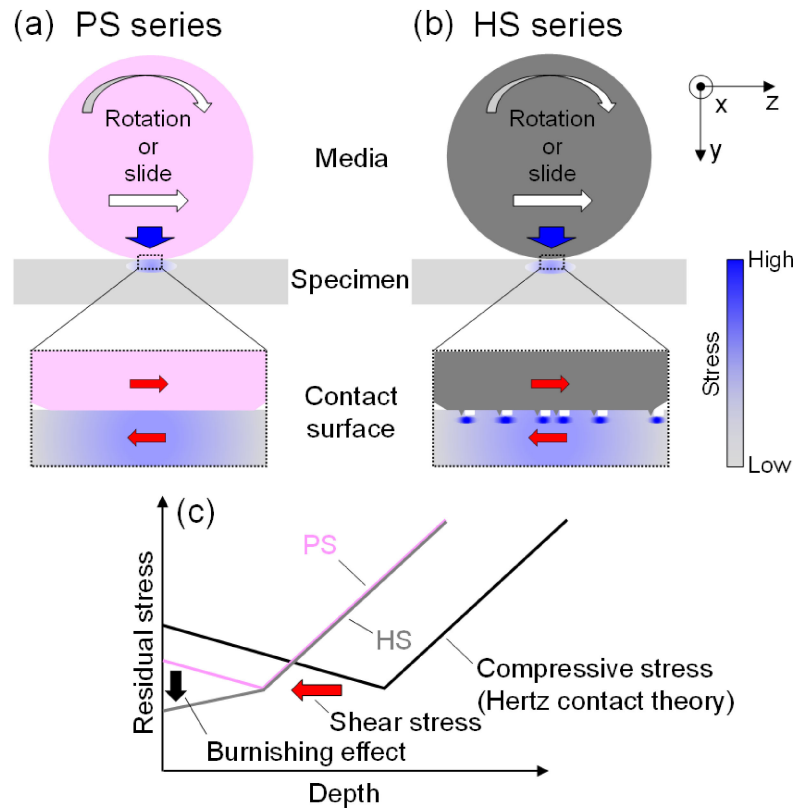


Fig. 10 Schematic illustration of the development of residual-stress profile in the specimen gyrofinished with the PS and HS series.

compressive stress generated when the accelerated media impacted the specimen surface (Figs. 10(a) and (b)) introduced residual stress into the specimen accordance to Hertz contact theory, as shown by the black line in Fig. 10(c). As discussed above, shear stress occurs owing to the rotation and/or sliding of the media on the specimen surface in the z -direction (Figs. 10(a) and (b)). Consequently, $d_{\max}$ decreases, as indicated by the red arrow in Fig. 10(c). Additionally, owing to the rough surfaces of the HS media, grinding occurred at the specimen surface, which enhanced the compressive residual stress near the surface via the burnishing effect, as indicated by the black arrow in Fig. 10(c). Thus, the specimens gyrofinished with the HS series showed a higher $\sigma_{\max}$ than the specimens gyrofinished with the PS series. The increase in residual stress owing to the burnishing effect should be limited to the shallow region near the surface; thus, the residual stress profile in the deeper region is identical between the PS and HS series (Fig. 8). The specimen gyrofinished with HS-4 exhibited the largest compressive residual stress at the surface. The reason for this is unclear; however, the frequency and amount of rotation and/or sliding, relating to the shear stress, may change depending on the size of the media. In any case, the stress state at the surface during gyrofinishing is complicated compared to that during the shot-peening process, and further investigations, such as the observation of the detailed movement of media during gyrofinishing and the measurement of the stress state when the media impact the specimen surface, are necessary for a comprehensive understanding of the development of residual stress during gyrofinishing.

5. Conclusion

The effects of the material and size of the abrasive media on the surface roughness, microstructure, and residual stress on the specimen surface after gyrofinishing were revealed. Furthermore, the development of residual stress on the specimen surface during gyrofinishing was discussed. The main results of this study are summarized as follows:

- (1) Although the material and size of the media affected the surface roughness, the arithmetic mean height was small for all the specimens after gyrofinishing with various media. Therefore, a smooth surface can be obtained by gyrofinishing.
- (2) An ultra-fine grained structure was formed at the outermost surface of the gyrofinished specimen, regardless of the medium. In the specimens gyrofinished with the HS series, the flow of the microstructure toward the z -axis, which was in the upward direction of the container of the gyrofinishing machine, appeared near the surface. This indicates that shear stress was applied during gyrofinishing.
- (3) The hardness of the specimens gyrofinished with PS-4, PS-10, and HS-4 increased slightly. Gyrofinishing with HS-10 significantly improved the hardness of the surface.
- (4) All the gyrofinished specimens exhibited compressive residual stresses. The residual-stress profiles differed depending on the material and size of the media. The small size of the media shallowed the depth of maximum compressive residual stress ($d_{\max}$). However, the effect of the size of the media on the maximum

compressive residual stress was minimal. The measured $d_{\max}$ was significantly shallower than the $d_{\max}$ estimated based on the Hertz contact theory. This is attributed to the shear stress generated by the rotation and/or sliding of the media on the specimen surface during gyrofinishing.

- (5) The specimens gyrofinished with the HS series exhibited higher compressive residual stresses than specimens gyrofinished with the PS series. The rough surface of the HS medium can introduce high compressive residual stress into the specimen surface during gyrofinishing through the burnishing effect.

Thus, gyrofinishing renders specimens with a smooth surface, an ultrafine grained structure, and significant compressive residual stress. Gyrofinishing is an effective way to improve the surface of a specimen and is highly expected to improve the fatigue properties of the specimen because the residual stress is comparable level with the specimens subjected to the shot-peening but the surface roughness is smoother than that.

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