Surface modification of machine-finished magnesium alloy AZ31 using a scanning cyclic press

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Abstract
A machined material has a work-hardened layer at its surface. In this study, a surface modification technique, the scanning cyclic press (SCP), was applied to machined specimens of magnesium alloy, AZ31, to investigate whether SCP can improve its fatigue properties regardless of the surface finish. During the SCP process, a vibrating indenter reciprocally scanned the specimen’s surface, and it applied cyclical low-compressive loadings to the surface for $8 \times 10^6$ cycles. After applying SCP, the surfaces of the specimens were observed using a laser scanning microscope, and the surface roughness was measured. The surface observation and surface roughness measurement showed that the changes in the surface state after applying SCP were relatively small and the surface roughness after applying SCP was more homogenous than before applying SCP. Uniaxial push-pull fatigue tests were conducted for SCP-treated specimens and untreated specimens. The test results showed that the fatigue life of SCP-treated specimens was longer than that of untreated specimens. To clarify the reason for the improvement effect, the fracture surfaces were observed using a scanning electron microscope (SEM). The SEM observation showed that the fracture morphology was different between the SCP-treated specimen and the untreated specimen. In the SCP-treated specimen, fatigue fracture origins were sub-surface, while the untreated specimen fractured at the surface. These results suggest that SCP could improve the fatigue properties of AZ31 regardless of the surface finish of the specimen before SCP.

Keywords: Surface modification, Scanning cyclic press, Magnesium alloy, Surface roughness, Improvement of fatigue property

1. Introduction
Surface severe plastic deformation (S²PD), which is a surface treatment that uses large plastic strains, improves mechanical properties, such as hardness, fatigue strength and wear resistance, on metal surfaces by creating a nanocrystalline layer on the bulk material. Many techniques based on S²PD, such as surface mechanical attrition treatment (SMA T) (Lu, K. and Lu, J., 2004; Shahrezaei et al., 2019), surface mechanical grinding treatment (SMGT) (Liu et al., 2015), and shot peening (Shiozawa and Miyazaki, 2013), have recently been studied as useful processes for nanocrystallizing the surface of metal materials. Techniques used to strike workpiece surfaces using ultrasonic vibration, such as ultrasonic nanocrystal surface modification (UNSM) (Wu et al., 2014) and ultrasonic impact treatment (UIT) (Togasaki et al., 2010), have also attracted attention as useful ways to modify surfaces. On the other hand, we developed a new surface modification technique, the scanning cyclic press (SCP), which modifies the microstructure of a metal’s surface by applying a cyclically low compressive load. Unlike S²PD, SCP uses a precise loading control based on servo fatigue testing machines. Our previous study showed that SCP modifies the surface...
layer of a mirror-polished specimen of an extruded magnesium alloy, AZ31, and improves its fatigue properties (Fujimura et al., 2017); however, the general surface finish of actual machine parts is not mirror-polished but machined, and a work-hardened layer is usually formed at the machined surface (Hikiji et al., 2004; Kakiuchi and Uematsu, 2019). To investigate whether SCP improves the fatigue properties of AZ31 regardless of the surface finish, SCP was applied to machined specimens. After applying SCP, the surfaces of specimens were observed, and uniaxial push-pull fatigue tests were conducted to clarify the effect on fatigue properties.

2. Experimental procedure

2.1 Material and specimen

The material was an extruded magnesium alloy, AZ31. The chemical components of the material were Al: 3.0, Zn: 1.1, Mn: 0.31, Si: 0.007, Fe: 0.002, Cu: 0.001, Ni: 0.001, and Mg: Bal. (wt. %). The supplied material was a 16 mm diameter round bar extruded at a temperature of 673 K with an extrusion rate of 5 m/min. The microstructure consisted of rough and fine grains, and the average grain size was 45 µm. The 0.2 % proof stress was $\sigma_{0.2} = 197$ MPa, and the tensile strength was $\sigma_B = 224$ MPa. An hourglass-shaped specimen with a straight section of $\phi 4 \times 2$ mm was used. The specimen’s surface was machine finished.

2.2 Surface modification using the SCP

The SCP surface modification machine we developed can apply uniaxial sinusoidal compressive loading to the specimen’s surface in ambient air at room temperature, as shown in Fig. 1. A vibrating indenter contacts the surface of a rotating and feeding specimen and can apply the compressive load with a variable frequency. The maximum and minimum values of cyclic compressive loading were 29.4 N and 0 N, respectively, and the frequency was 200 Hz. The number of cyclic loadings in SCP was $8.0 \times 10^6$ cycles. The rotation speed and feed rate of the specimen were 2 rpm and 0.01 mm/sec, respectively. The indenter scanned the entire circumference of the straight section of the specimen.

![SCP system](image)

Fig. 1 SCP surface modification machine and schematic diagram of the process. A vibrating indenter contacts the surface of a rotating and feeding specimen and can apply a variable compressive load with a variable frequency. The indenter connects to a hydraulic actuator of a servo fatigue testing machine and applies a precise load.

2.3 Surface observation and surface roughness measurement

Before and after applying SCP, the surface of the specimen was observed using a color three-dimensional (3D) laser-scanning microscope (VK-9700/9710 Generation II, KEYENCE). The laser microscope allowed for measuring surface roughness to determine the quantitative change in the surface state. The areal roughness parameter (arithmetic mean roughness $R_A$) was determined from the 3D image. Two measurement points on the circumference, measuring 820 µm long and 60 µm wide, were set at the specimen’s center with an equal angular spacing of 180 degrees.
2.4 Fatigue test method and conditions

To investigate the effect of SCP on the fatigue properties of AZ31, uniaxial push-pull fatigue tests were conducted using a servo hydraulic fatigue testing machine. Sinusoidal loading was applied to untreated and SCP-treated specimens in ambient air at room temperature. The stress ratio and frequency of the cyclic loading were $R = -1$ and $f = 120$ Hz. For untreated specimens, fatigue tests conducted twice at three stress levels of 100, 120, and 150 MPa and once at 110 MPa. For SCP-treated specimens, fatigue tests conducted once at 100 and 120 MPa.

3. Results and discussion

3.1 Surface observation before and after applying SCP and quantitative evaluation of the change

Figure 2 shows the surfaces of the specimen before and after applying SCP, and Fig. 3 shows the surface profile curves at the dotted lines in the regions of the surface roughness measurement for each specimen. On the surface, before applying SCP, machining marks were observed, and there were fine and deep scratches in places (Fig. 2(a)). From the surface profile curve, as shown in Fig. 3(a), the asperity of the surface was not significant; however, the narrow valleys with about 4–6 $\mu$m depth (indicated by black arrows) were observed at the scratches. After applying SCP, the modified area changed to a glossy surface with a striped pattern (Fig. 2(b)). On the dark lines of the streaked surface shown in the magnification, there was dark abrasion powder, which adhered during the SCP process. Other than that, surface features, such as fine irregularities and scraped marks, were similar to those of the machine-finished specimen. On the surface profile curve, as shown in Fig. 3(b), the small convex and concave part were observed; however, the deference in height was about 6 $\mu$m, which was almost the same as the machined surface. The convex part shown on the right side of Fig. 3(b) corresponded to the dark line formed due to the abrasion powder that adhered to the surface. To quantitatively investigate the changes in the surface before/after applying SCP, the surface roughness was measured. Table 1 summarizes the results of the surface roughness measurement of four specimens. The surface roughness $R_a$ before applying SCP was 0.547 $\mu$m on average (standard deviation: 0.235 $\mu$m, coefficient of variation: 0.429). After applying SCP, the surface roughness $R_a$ was 0.762 $\mu$m on average (standard deviation: 0.102 $\mu$m, coefficient of variation: 0.134). These results showed that SCP caused relatively small changes in the surface state, and the surface roughness was more homogenous, because the variation of $R_a$, such as the standard deviation and the coefficient of variation, was smaller than the machined surface.

In this section, the reason for the surface modification caused by the SCP process is discussed. During the SCP process, the vibrating indenter scans the surface of the specimen, as shown in Fig. 1(c). The maximum contact pressure between the indenter and the specimen under the compressive load of 29.4 N calculated using the Hersian contact stress theory was 1100 MPa when the indenter and the specimen’s surface were regarded as a sphere and cylindrical respectively. This contact pressure was higher than the 0.2 % proof stress of AZ31. Therefore, the contact surface locally deformed plastically, and the ellipse-shaped indentation may have formed during the first cycle. Because the specimen rotates during the indenter contacts the surface, a streaked pattern is formed by slightly scraping the surface, and the abrasion powder is also generated. Due to the SCP condition of this research, the displacement of the indenter during the first cycle was 2.1 $\mu$m in the rotation direction and 0.05 $\mu$m in the axial direction (Fujimura et al., 2017). Therefore, the ellipse-shaped indentation formed during the second cycle widely overlapped that of the first cycle. In addition, the second loop of the streaked pattern widely overlapped the first one. Because the indenter went back and forth many times in the modified part during the SCP process, the specimen’s surface likely became homogenous. To confirm the deformation due to the SCP process, the diameter and the mass of the SCP-treated specimen was measured. Table 2 shows the changes in the diameter and the mass of the specimen before and after applying SCP. The diameter and mass decreased by 10.44 $\mu$m and 2.09 mg on average after applying SCP. Based on the surface profile curve of the machined specimen as shown in Fig. 3(a), the depth of the narrow valleys at the scratches due to machining was about 4–6 $\mu$m. The measurement results also suggested that SCP removed the scratches with the narrow valleys because the indenter slightly scraped the surface during the process. In addition, as mentioned, the vibrating indenter scanned the specimen’s surface many times. Therefore, the surface roughness after applying SCP became more homogenous than before applying SCP.
Fig. 2  Surface observation of a machine-finished specimen before and after SCP. The upper image shows the middle part of the specimen, and the lower image is a magnification of the center of the specimen shown in the upper image.

(a) Before SCP  
(b) After SCP

Fig. 3  Surface profile curve in the region of the surface roughness measurement before and after applying SCP.

(a) Before SCP  
(b) After SCP

Table 1  Surface roughness measurement results.

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<thead>
<tr>
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<th>Surface roughness $R_a$ [$\mu$m]</th>
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<tr>
<td></td>
<td>Before SCP</td>
</tr>
<tr>
<td>Average</td>
<td>0.547</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.235</td>
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<td>Coefficient of variation</td>
<td>0.429</td>
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Table 2  Decrement of diameter and mass of specimens after applying SCP.

<table>
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<tr>
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<th>Diameter [$\mu$m]</th>
<th>Mass [mg]</th>
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<td>Average</td>
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<td>2.09</td>
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<tr>
<td>Standard deviation</td>
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<td>0.69</td>
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<tr>
<td>Coefficient of variation</td>
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3.2 Fatigue test results and fracture surface observations

Figure 4 shows the $S$-$N$ plots of the machine-finished specimens with and without SCP. In the figure, the fatigue test results of mirror-polished specimens and its SCP-treated specimens (Fujimura et al., 2017) are also shown together for comparison. Focusing on the surface finish of untreated specimens, the fatigue life of the machine-finished specimen (white diamonds) was longer than that of the mirror-polished specimen (white circles) except the stress level of 150 MPa. The slope of $S$-$N$ curve of the machine-finished specimen was gentler than that of mirror-polished specimen. As mentioned in the introduction, a work-hardened layer is usually formed at the machined surface and a compressive residual stress is introduced at the surface layer. These factors can suppress the crack initiation from the surface and improve the fatigue property. This is likely the reason for the difference between the fatigue life of each
specimen. Focusing on the effect of SCP on the machine-finished specimens, the fatigue life of SCP-treated specimens (black diamonds) was longer than that of untreated specimens (white diamonds). Regarding the fatigue life after applying SCP, the machine-finished specimen (black diamonds) was the same as the mirror-polished specimen (black circles) and there was no difference in the improvement effect of fatigue life caused by the difference of the surface finish. To clarify the reason for the improved fatigue life, fracture surfaces of machine-finished specimens were investigated using SEM. Figure 5(a) and (b) show the fracture surfaces of an untreated specimen and an SCP-treated specimen fatigued at a stress amplitude of 120 MPa, respectively. In these figures, (i) shows the crack initiation site and (ii) is a magnified view framed by a dotted square in (i). A facet, outlined with a white dotted frame and indicated with a black arrow in Fig. 5(a)(i), was located at the surface. In addition, as shown in Fig. 5(a)(ii), there was a flat region in contact with the surface (indicated by a black arrow) and following the facet. This showed that the origin of the fatigue fracture was at the surface of the untreated specimen. A surface fracture occurred in other untreated specimens except the specimen fatigued at \( \sigma_a = 100 \) MPa, in which the fracture originated in the interior (a white diamond with a slash in Fig. 4). This indicated that the fatigue strength of the surface fracture of machine-finished AZ31 was around this stress level. In mirror-polished specimens, the fracture origin located at the surface except the specimen unbroken at 80 MPa (Fujimura et al., 2017). It showed that the fatigue strength of the surface fracture of the machine-finished specimen was higher than that of the mirror-polished specimen. As mentioned, the reason for this difference was likely the work-hardened layer formed by machining. As shown in Fig. 5(b), the crack initiation site (shown by a white arrow in Fig. 5(b)(ii)) was observed in the interior of the fracture surface of the SCP-treated specimen. Internal fractures occurred in all SCP-treated specimens (black diamonds with a slash in Fig. 4). This showed that SCP changed the fracture mechanism and caused fractures to occur internally rather than at the surface. Therefore, SCP improved not only the fatigue life but also the fatigue strength of the surface fractures of machine-finished AZ31. These results suggested that SCP improves the fatigue properties of AZ31 regardless of the surface finish of the specimen before the process.

This improvement effect is the result of SCP modifying the surface layer of the machined specimen. In our previous study, we applied SCP to the surface of a mirror-polished specimen (Fujimura et al., 2017). The microstructure observation at the cross-section of the SCP-treated specimen showed that the mesh-patterned region, which was finer than the matrix (grain size: 45 \( \mu m \) as shown in Fig. 6, formed beneath the surface and its depth from the surface reached about 50 \( \mu m \). This region was not observed in the microstructure of untreated specimen. In addition, the surface hardness of the SCP-treated specimen increased by double that of the untreated specimen. These results suggested that the surface layer of the SCP-treated specimen became harder due to the formation of the mesh-patterned region. Because the SCP condition of this research was the same as that of the previous study, a similar surface layer

![Figure 4](image)

*Fig. 4*  S-N diagram of machine-finished AZ31 without (white diamond) and with SCP (black diamond). The slash shows that the fracture origin was in the interior of the specimen. For comparison, the fatigue test results of mirror-polished AZ31 without (white circle) and with SCP (black circle) are also shown (Fujimura et al., 2017).
likely formed on the machined specimen. The surface layer of the SCP-treated specimen became harder than that of the untreated specimen, and this layer likely suppressed crack initiation from the surface. Thus, the fatigue property of the machined specimen improved due to SCP.

On the other hand, as mentioned in the introduction, many useful techniques based on S2PD also provide a similar nanocrystallization and improve the mechanical properties. For example, the investigations regarding shot peening (Shahnewaz et al., 2012; Shiozawa and Miyazaki, 2013; Kakiuchi et al., 2016) have reported that the fatigue property improved due to the residual stress and the nanocrystalline introduced at the surface; however, the improvement effect was not obtained due to the notch effect caused by the increase in the surface roughness during the process. In contrast, in the SCP process, the change in the surface state was very limited, and it did not affect the improvement of fatigue property of the specimen due to SCP. As mentioned in the section 3.1, the surface roughness after applying SCP became more homogenous than before applying SCP. Therefore, at the surface, there was likely no defect which becomes the cause of the notch effect and the effect of the microstructure beneath the surface created by SCP likely
improved the fatigue property. This is an advantage of the surface modification by SCP. In addition, SCP can set process parameters, such as the magnitude of load, frequency, the number of cyclic loading, the rotating and shifting speed of the specimen. Therefore, we can investigate systematically the relationship between the process parameters and the microstructures, and as a result, we may control the microstructure for improving the mechanical properties by applying SCP under optimal conditions. Although further investigation is needed to clarify the effect of applying SCP, SCP can be regarded as a useful method for improving the fatigue property regardless of the surface finish of the specimen before SCP.

4. Conclusion

A surface modification technique, SCP, was applied to a machined specimen of magnesium alloy, AZ31, to investigate its effect on fatigue properties. Uniaxial fatigue tests showed that the fatigue life of SCP-treated specimens was longer than that of untreated specimens. In the SCP-treated specimens, fatigue fracture origins were sub-surface, while the untreated specimen fractured at the surface. The results suggest that SCP could improve the fatigue properties of AZ31 regardless of the surface finish of the specimen before SCP.

Acknowledgment

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References


