Effect of Incremental Shrinking Process on Mechanical Properties and Microstructure of Alloy through Electron Backscatter Diffraction Analysis

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Abstract. In recent years, the incremental shrinking process has been widely used in the forming process of aluminum alloy components for the railway vehicles. The effect of the incremental shrinking process on the performance and microstructure of 6082-T6 aluminum alloy was investigated through mechanical tests and electron backscatter diffraction (EBSD) analysis. The tensile test specimens prepared in different rolling orientations (0°, 45° and 90°) along the original and deformed sheets exhibited the mechanical anisotropy. After the incremental shrinking process, the average microhardness, tensile strength, and yield strength of this alloy were respectively increased by nearly 8.78%, 2.26%, 2.72%, while the Elongation was decreased by almost 31.67%. By analyzing the EBSD data, the strength of the material is increased by the incremental shrinking process and its mechanical anisotropy is improved, whereas its plasticity is greatly deteriorated.

Keywords: Incremental shrinking process, aluminum alloy, mechanical properties, microstructure, texture.

1. Introduction
Lightweight design has become an inevitable trend under the energy and sustainable development in the railway vehicles. Then choosing the applicable light materials is a relatively mature lightweight technology to effectively facilitate energy conservation and emission reduction [1, 2]. As a typical light metal, the 6xxx aluminum alloys have been widely used as structural materials in railway vehicles due to their superior mechanical properties, excellent extrusion and good weld ability [3, 4]. In the past few decades, the 6082-T6 alloy have been extensively studied in terms of microstructure evolution within thermo-mechanical processing, welding as well as grain refinement [5, 6]. However, few studies have been conducted on cold forming of this material [7].

As an emerging cold forming method, driving, in contrast to the deep-drawing or pressing, needs to gradually achieve the required shape while forming [8, 9]. The forming process is carried out with a relatively small and economic C-frame press, called Kraftformer machine and parameters should be adjusted accordingly [10, 11]. Figure 1. (a) shows the simulation of the incremental shrinking process.
The schematic views of the mechanism inside the shrinking tool is shown in Figure 1. (b). Meanwhile, a specific shrinking toolset, FWA 1306 X, was utilized in this paper.

More researchers have devoted attentions to the automation of the incremental shrinking process in small batch production [12]. However, few researchers, except X. Jing and H. Hoffmann, have focused on the effect of the material properties after this forming process. Their research showed that this incremental shrinking process locally improved the mechanical properties of the commercial AZ31 by modifying the microtexture of its shear edge [13]. Therefore, relevant research in this area has valuable significance for the study of material processing technology and material properties.

The aim of the present work was to investigate the effect of the incremental shrinking process on the mechanical properties, microstructure, and texture of the 6082-T6 aluminum alloy. The microhardness tests, uniaxial tensile tests, and electron backscatter diffraction (EBSD) analysis were conducted to analyze the changes of this alloy before and after the incremental shrinking process.

![Figure 1. The simulation operation diagram of the incremental shrinking process and (b) the schematic representations of the mechanism inside of the incremental shrinking tool.]

2. Experimental Procedure

2.1. Experimental Material

The experimental material was the 6082-T6 aluminum alloy sheet with a thickness of 4 mm. The chemical composition of this alloy was listed in Table 1. And it was employed in the cross-beam structure on top of the railway vehicles, as indicated by the red arrow in Figure 2. (a). Besides, the stroke infeed and the stroke frequency were set to 35 mm and 300/min, respectively. Finally, the obtained deformed 6082-T6 aluminum alloy was shown in Figure 2. (b).

![Figure 1. The simulation operation diagram of the incremental shrinking process and (b) the schematic representations of the mechanism inside of the incremental shrinking tool.]

|    | Mg   | Si   | Fe  | Cu  | Mn   | Cr  | Zn  | Ti  | Al   |
|----|------|------|-----|-----|------|-----|-----|-----|------|
|    | 0.6-1.2 | 0.7-1.3 | 0.5 | 0.1 | 0.4-1.0 | 0.25 | 0.2 | 0.1 | Balance |
2.2. Tensile Test and Microhardness Test
Tensile test specimens were prepared in three different directions of 0˚ (rolling direction, RD), 45˚ (inclined direction, ID), and 90˚ (transverse direction, TD) of the original and the deformed 6082-T6 aluminum alloys, respectively. Figure 2. (c) shows the tensile test specimens from the deformed 6082-T6 aluminum alloy. Besides, it is necessary to notice that the deformed 6082-T6 aluminum alloy has a rough surface with the irregular indentations. This indicated that the incremental shrinking process had a certain degree of damage on the material surface. The geometry and dimensions of the specimens were cut as per GB/T 16865-2013 which shown in Figure 2. (d). Tensile tests were performed using a Zwick-Z100 materials testing machine (Guangzhou, China) and an MTS extensometer, which conducted at a velocity of 1 mm/min. These tensile specimens were split into 6 groups and designated as 0-RD, 0-ID, 0-TD, 1-RD, 1-ID and 1-TD, respectively. The “0” and “1” represented the original and the deformed 6082-T6 aluminum alloy respectively. Three samples, at least, were tested in each group to ensure the repeatability of the test results. The microhardness (HV) of the original and deformed 6082-T6 aluminum alloys was measured by Digital Microhardness Tester (HVS-1000ZDT, Shanghai) with an experimental force of 0.98 N and a loading time of 15 s. Then 10 points of each microhardness test samples were measured and the average value was selected for description.

2.3. In-plane Anisotropy (IPA)
IPA was used to evaluate the anisotropy of the tensile properties of the aluminum alloy in different orientations. In this paper, it was determined by tensile properties along with three rolling directions (0˚, 45˚ and 90˚). The IPA factors can be expressed as shown in (1).

\[
IPA = \frac{2X_{\text{max}} - X_{\text{mid}} - X_{\text{min}}}{2X_{\text{max}}}
\]

Where the X represents the tensile properties, then \(X_{\text{max}}\), \(X_{\text{mid}}\) and \(X_{\text{min}}\) refer to the maximum ultimate tensile strength (UTS), intermediate yield strength (YS), and minimum elongation (E%) of the tensile tests in the three directions of the aluminum alloy, respectively [14].

2.4. Microstructure and Texture Test
The analysis of the microstructure and the texture was designed to explain the mechanical properties changes of the 6082-T6 aluminum alloy before and after the incremental shrinking process. The evolution of microstructure and texture was investigated by electron backscatter diffraction (EBSD), which performed in an SEM (VEGA 3 XMU, TESCAN, Czech) equipped with an Oxford Instruments
NordlysNano EBSD detector. The working distance was 15 mm and an acceleration voltage of 20 kV. There were two sources of EBSD samples: one was directly from the original and deformed aluminum alloys, and their observation surfaces were both RD×ND zones; the other was from the vicinity of the fracture of the tensile specimens, and their observation surfaces were RD×ND, ID×ND and TD×ND zones, respectively. The terms “ND” correspond to the through-thickness direction. All the EBSD samples were electrochemically polished with perchloric acid-ethanol solution (1:10). Besides, the EBSD data was collected and analyzed by AZtec and Channel 5 software. The texture of the plates was evaluated on a large area maps taken with a step size of 10 µm.

3. Result and Discussion

3.1. Mechanical Properties and Anisotropy

It is well known that materials present greater microhardness and yield strength after intense deformation. The reduction of grain size and the building-up of a well-developed dislocation microstructure will in turn affect dislocation slip during further plastic deformation [15].

3.1.1. Microhardness and tensile strength. Figure 3. (a) shows the microhardness distribution of specimens from the original and the deformed 6082-T6 aluminum alloys. The average microhardness were 105.45 HV and 114.71 HV, respectively. The average microhardness of the deformed alloy rose by almost 8.78% than the original alloy. Moreover, the curve of the deformed alloy fluctuated greatly which implied that there was a certain gap between 10 test points. We might conclude that the force received by the 6082-T6 aluminum alloy wasn’t uniform during the incremental shrinking process.

![Figure 3. (a) The microhardness distribution of the original and deformed 6082-T6 aluminum alloys specimens and (b) the true strain - stress curves of the tensile specimens.](image)

3.1.2. Tensile properties. Figure 3. (b) shows the true strain - stress curves of the tensile specimens and Table 2 presents a summary of the tensile properties. As expected, the UTS and the YS of the deformed AA6082-T6 were higher than those of the original AA6082-T6 in the corresponding direction, while E% was relatively lower. The average UTS of this alloy was increased by nearly 2.26% during the incremental shrinking process. In the same way, the average YS was increased by nearly 2.72% while the E% was decreased by nearly 31.67%. The E% had such a huge variation, mainly because the E% in the RD direction changed from 18.45% to 8.99%. Due to the different sampling directions, the mechanical properties were also discrepant, which indicated that the mechanical properties of 6082-T6 aluminum alloy were anisotropic. The UTS difference between two directions was about 13 MPa, the YS and E% properties also presented certain directional characteristics. It’s of great possibilities that the deformed AA6082-T6 had work hardening phenomenon after incremental shrinking process and the anisotropy of the deformed 6082-T6 aluminum alloy was better controlled.
Table 2. Tensile properties of the specimens along different directions

| Samples | UTS (MPa) | YS (MPa) | E (%) | n     |
|---------|-----------|----------|-------|-------|
| 0-RD    | 300.88    | 288.28   | 18.45 | 0.0618|
| 0-ID    | 305.48    | 291.11   | 16.19 | 0.0794|
| 0-TD    | 313.31    | 294.46   | 10.3  | 0.0696|
| 1-RD    | 307.223   | 297.85   | 8.99  | 0.0403|
| 1-ID    | 314.55    | 298.17   | 12.04 | 0.0703|
| 1-TD    | 318.67    | 301.55   | 9.73  | 0.0512|

3.2. IPA
The average IPA factors of UTS, YS, and E% are shown in Figure 4. It was conspicuous that the IPA factors of both the UTS and the YS of the deformed 6082-T6 aluminum alloy were lower than the original alloy. Sampling directions had a weaker effect on the YS than on the UTS, while it greatly affected the E%. It confirmed the previous inference that the anisotropy of the deformed 6082-T6 aluminum alloy was weaker than the original 6082-T6 aluminum alloy.

![Figure 4. IPA (In-plane anisotropy) factors of the tensile properties.](image)

3.3. Microstructure and Texture
The Grain orientation images on the RD × ND surfaces of the EBSD samples from the original and deformed 6082-T6 aluminum alloys are shown in Figure 5. (a) and Figure 5. (b), respectively. Figure 5. (c) represents the standard color contrast card of grain orientation image, where different colors correspond to different orientations. Apparently, there were orientation deviations in these grains. There were numerous distinct elongated grains and the grains along the RD direction were much longer than that along the ND direction. They were formed as a consequence of the establishment of an advanced dislocation substructure and deformation-induced rotations of subgrains [16]. There wasn’t evident grain refinement from the microstructure in the current work. The reason was probably that the applied plastic strain was not sufficient enough to bring about the grain refinement.
Figure 5. Grain orientation images of (a) the original 6082-T6 aluminum alloy and (b) the deformed 6082-T6 aluminum alloy, and (c) standard color contrast card of grain orientation image.

The \{111\} pole figures of the original and deformed 6082-T6 aluminum alloys are shown in Figure 6. Figure 6. (c) represents the positions of the standard texture components in FCC metals and alloys [17]. The scattered distributions displayed in Figure 6. (a) were similar to Figure 6. (b). Comparing with the standard card, there was mainly the Goss texture in the original and deformed 6082-T6 aluminum alloys. In addition, there was little Brass texture in the deformed alloys, which indicated that the stacking fault energy was low. The maximum orientation density of the deformed 6082-T6 aluminum alloy was 27.20, while the original 6083-T6 alloy was 21.64. The higher value of the orientation density means the higher strength level of the texture.

Figure 6. The \{111\} pole figures of (a) the original 6082-T6 aluminum alloy and (b) the deformed 6082-T6 aluminum alloy and (c) the positions of the standard texture components in FCC metals and alloys.

Figure 7 shows the ODF sectional views of the original and deformed 6082-T6 aluminum alloys. The $F_{\text{max}}$ of the original 6082-T6 aluminum alloy was lower than that of the deformed alloy. Besides, the texture intensity of the deformed 6082-T6 aluminum alloy was stronger, revealing that the texture orientation of this alloy was more concentrated by the incremental shrinking process. This also indicated that the process didn’t arouse the intense plastic deformation.
The Schmid factor (SF) distribution calculated from the EBSD data was used to study the impact of texture on the mechanical properties and plastic deformation of 6082-T6 aluminum alloy. Figure 8 shows the corresponding Schmid maps. The average SF value of the original AA6082-T6 was higher than that of the deformed alloy. It is well known that an increase in SF indicates that the easier active slip systems exist in the material, meaning that less stress is required for plastic deformation. Moreover, there are more grains with higher SF values in the sample from the original AA6082-T6. When the SF distribution was shifted to higher values, the more grains with higher potential to slip were activated so that they were deformed easily. Therefore, it provided a theoretical basis for the fact that the UTS and YS of the deformed AA6082-T6 were higher than those of the original AA6082-T6.

The grain orientation images of the fracture specimens are shown in Figure 9. According to the color code as shown in Figure 5, (c), the orientations of 0-RD and 1-RD were deflected to (111). Similarly, the orientations of 0-ID and 1-ID were deflected to (001), as well as the orientations of 0-TD and 1-TD
were deflected to (101). When the tensile stress axis was along the RD direction, the slip mode along (111) is easier for the deformation to perform. When the tensile stress axis was along the TD direction, the deformation mode was considered to be more difficult to slip, giving rise to the higher UTS and YS in the specimens sampled along the TD direction. This exactly explained the mechanical anisotropy of the 6082-T6 aluminum alloy.

The \{111\} pole figures of the tensile fracture specimens as shown in Figure 10. Figure 11 shows the ODF sectional views of the different 6082-T6 aluminum alloy tensile fracture specimens. The scattered distributions of specimens along the same sampling direction were similar. It was because these samples were subjected to an intense unidirectional force during the tensile test that these samples had strong texture orientation. The texture intensities of 0-RD, 0-ID, and 0-TD were 32.87, 69.01, and 76.44, while the texture intensities of 1-RD, 1-ID, and 1-TD were 57.28, 48.78, and 35.69. Moreover, the texture intensity discrepancy between the tensile specimens of the deformed 6082-T6 aluminum alloy was smaller. Besides, the texture intensity of 1-RD was significantly higher than that of 0-RD, while the texture intensities of 1-ID and 1-TD were much lower than those of 0-ID and 0-TD, respectively. The $F_{\text{max}}$ of 0-RD, 0-ID, 0-TD, 1-RD, 1-ID and 0-TD were 23.52, 35.68, 84.27, 28.89, 31.35 and 47.67. The Brass texture appeared in 0-RD and 1-RD. It was the distinct deformation texture for undergoing the uniaxial tension. Then there was the stronger Cube texture in 0-ID and 1-ID, whereas the Brass, Copper and S texture existed in 0-TD and 1-TD. Their scattered distributions were relatively concentrated and the texture intensity values were relatively high.

Figure 9. Grain orientation images of the tensile fracture specimens: (a) 0-RD; (b) 0-ID; (c) 0-TD; (d) 1-RD; (e) 1-ID; (f) 1-TD.
Figure 10. The \{111\} pole figures of the tensile fracture specimens: (a) 0-RD; (b) 0-ID; (c) 0-TD; (d) 1-RD; (e) 1-ID; (f) 1-TD or more references.

Figure 11. ODF sectional views of the tensile fracture specimens: (a) 0-RD; (b) 0-ID; (c) 0-TD; (d) 1-RD; (e) 1-ID; (f) 1-TD or more references.
4. Conclusions
In conclusion, the incremental shrinking process enhanced the strength of the 6082-T6 aluminum alloy, but plasticity was greatly reduced. The IPA factors indicated that the anisotropy of the 6082-T6 aluminum alloy improved after the process. Although the average grain size of the 6082-T6 aluminum alloy decreased in the ND direction after the process, the grains with higher slip potential were fewer so that the deformation was more difficult, thereby directly causing an increase in the strength. The Brass texture appeared in 0-RD and 1-RD, whereas the stronger Cube texture in 0-ID and 1-ID. Then, the Brass, Copper and S textures existed in 0-TD and 1-TD. The discrepancy of texture intensity between the tensile specimens in the three directions of the deformed 6082-T6 aluminum alloy was smaller, indicating that its anisotropy was weaker.

Acknowledgments
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