Uniform Equiaxed Grain Structure throughout Thickness of a Hot-Rolled 5083 Al-Mg-Mn Alloy Thick Plate after a Tempering Treatment at 350°C

Jun-Yen Uan*1 and Hsu-Feng Cheng*2

Department of Materials Engineering, National Chung Hsing University, 250 kuo-kuang Rd., Taichung 402, Taiwan, R.O. China

In a conventional hot-rolled 5083 Al-alloy thick plate, the crystalline structure at the central part in the thickness direction comprises primarily slender grains. However, the grain structure is always equiaxed near the surface of the rolling plate. In this experiment, the shape of the slab before hot rolling was changed to a trapezoid. The main goal is to increase the amount of plastic strain and increase the dislocation density in the central part of the plate hot-rolled from the trapezoidal aluminum slab. TEM observations indicated that the center of the plate of hot-rolled trapezoidal slab had a higher dislocation density than the center of the rectangular slab. Subsequent heat treatment caused the treated grains to become equiaxed. Therefore, an equiaxed grain structure that was uniform in the thickness direction of a hot-rolled thick plate could be obtained because the hot rolling of the trapezoidal slab caused profound lateral strain, in addition to extensive deformation in the rolling direction. The excess deformation resulted in a high dislocation density in the central region of the as-hot rolled plate, increasing the strain energy that was stored for recrystallization.

Keywords: aluminum alloy, hot rolling, equiaxed grain, dislocation, recrystallization

1. Introduction

Aluminum alloy has an excellent combination of light weight, workability, mechanical properties, and corrosion resistance, among other characteristics.1) The demand for aluminum alloy as a structural material in the ship, automobile and aeronautical industries, is increasingly.2) Rolling is one of the most widely employed metalworking processes for producing aluminum sheet with the above applications.

An aluminum alloy slab for hot rolling is typically rectangular. However, the material after hot rolling exhibits inhomogeneous plastic strain in the thickness direction. The regions near the rolling surface, which are in direct contact with the roller, exhibit a higher plastic strain, while the center of the plate has a smaller plastic strain. In a work by Yiu et al.,3) Al-Mg-Mn alloy was rolled at 480°C and a total rolling reduction of around 48% was achieved. The result clearly shows that the resultant deformation in the as-rolled metal is not uniform through the thickness of the plate; most of the rolling strain is concentrated at the rolling surface.3) Additionally, Duan and Sheppard4) analyzed 5083 Al-Mg alloy by the FEM method to determine the strain inside the material and the microstructural change due to rolling. This result suggests that during rolling, the dislocation density and stored energy drop from the surface to the center in the thickness direction through the material. Ahmed and Well studied the microstructure of the 5083 Al-Mg-Mn alloy after hot rolling and heat treatment.5) The grains at the rolling surface are equiaxed, but in the central part of the plate, the grains are relatively slender, because the surface of the hot-rolled plate, which typically experiences a higher deformation strain than the center, has a higher stored energy for recrystallization.5) Recently, high-reduction rolling process for the refinement of recrystallized grains in Al-Mg alloys were investigated.7) The rolling was performed in only one rolling pass, and the reduction ratio was varied from 50% to 88%.7) Although the research is significant in grain refining, the differences in grain size and grain morphology between the rolled surface region and the middle region can be evident.7) Sakai et al.6) introduced through-thickness shear deformation in Al alloy sheet by asymmetric rolling. Shear strain can be introduced at the middle-thickness, but the shear strain increased rapidly near the rolled surface.8) According to the studies mentioned above, a common question is that how to introduce or increase deformation strain at the middle-thickness region of a rolled sheet during rolling. The process of high-reduction rolling or asymmetric rolling may achieve the goal of increasing more deformation strain at the mid-thickness. However, for a conventional rolling process, little is known about increasing the deformation strain at the mid-thickness position. Figure 1 presents the metallographic microstructure of a longitudinal section of an as-received 10 mm-thick 5083 plate, which is commercially popular and produced by conventional hot rolling process. The 5083 plate was produced by China Steel Corp., Taiwan. Figure 1(a) indicates that the rolled plate had an equiaxed grain structure near the rolled surface. However, the grains near the center of the plate in the thickness direction were slender (Fig. 1(b)).

2. Experimental Procedure

Commercial 5083 aluminum alloy with 4.5% Mg and 0.7% Fe (mass%) was the tested material. The aluminum slabs used in hot rolling experiment had two shapes, which are presented with the dimensions in Fig. 2. Figure 2(a) depicts a rectangular block with a width of 70 mm, a
thickness of 32 mm and a length of 105 mm. Figure 2(b) depicts the trapezoidal shape of a 5083 Al block with a top width of 40 mm, a bottom width of 70 mm, a thickness of 32 mm and a length of 105 mm. Before hot rolling, both slabs are homogenized for 48 h at 500 °C, and then furnace-cooled. Hot rolling was performed at 320 °C. The thickness reduction per rolling pass was 1.5 mm. The total rolling reduction in thickness is 68%. The final thickness of the hot-rolled plate was 10.5 mm. Hereafter, the sample from the rectangular Al slab (Fig. 2(a)) after hot rolling will be denoted 5083HR-0, and the sample from the trapezoidal slab after hot rolling will be 5083HR-40.

The microstructures of the as-received 10-mm-thick commercial 5083 Al alloy plate: (a) microstructure at the position near to rolling surface, and (b) microstructure at the central region of the plate.

Fig. 1

Fig. 2 The illustrations of the shape and dimension of slab before hot rolling: (a) the rectangular shape of 5083 Al block with 70 mm in width (hereafter, denoted as 5083HR-0); and (b) the trapezoidal shape of 5083 Al block with the top width in 40 mm and bottom width in 70 mm (hereafter, denoted as 5083HR-40).

Al$_3$Mg$_2$ particles to reveal more clearly the grain boundary. The samples were polished using colloidal silica, and then etched in 10% phosphoric acid at 50°C. Thin foils for TEM observation were prepared by a twin-jet polisher using a mixture of 25%HNO$_3$ + 75%CH$_3$OH at an applied current of 1.5 A to 2 A at -30°C, to study the microstructures after hot rolling. The TEM microstructure of the sample was examined using a JEOL JEM-1200 EXII at 120 Kv. Dislocation structures were photographed with a [011] zone axis and the {111} two-beam condition, satisfying the conditions for dislocation visibility.

Tensile characteristics of the as hot-rolled 5083HR-0 and 5083HR-40 were also investigated. Tensile samples with a gauge section of length 20 mm and a diameter of 4 mm were machined directly from the as hot-rolled plates. The loading axis was parallel to the rolling direction. Since the final thickness of the hot-rolled plate was 10.5 mm, the gauge section of the tensile test specimen was at the center of the rolled plate. A tensile test was conducted at room temperature, with an initial strain rate of 8 × 10$^{-4}$ s$^{-1}$. Each point was a mean result from at least three specimen rods.

Differential thermal analysis (DTA) was performed by using Linseis STA PT1600 thermogravimetric analyzer. Samples for the DTA analysis were taken from the center of the as-hot-rolled 5083HR-0 plate and the as-hot-rolled 5083HR-40 plate, respectively. During the experiments each sample was heated to 350°C by a heating rate 10°C/min, and then held at 350°C for 3 hours.
3. Experimental Results

3.1 Shape-change of cross-sectional section after hot rolling

Figure 3 compares the morphologies of the cross-sectional section before and after hot-rolling. It presents schematic profiles of the actual sample. Figure 3(a) depicts the morphological change of 5083HR-0 due to rolling. As shown in Fig. 3(a), the dotted line displays the cross-sectional rectangle of the original slab, while the solid line depicts the shape of the cross-section after hot rolling. The actual profile in Fig. 3(a) was obtained by rolling a 5083HR-0 plate to a final thickness of 10.5 mm and shows obvious concavity. The widths of the center of the rectangular slab before and after rolling are 70 mm and 69 mm, respectively, indicating almost no discrepancy (Fig. 3(a)). Figure 3(b) presents the horizontal sectional change of the 5083HR-40 slab before and after rolling. The figure shows that the width of the top surface changes from 40 mm to 53 mm and the center of the horizontal section changes from 55 mm to 61 mm. Therefore, not only is the deformation extended in the rolling direction, but also both the top rolled surfaces and the central part of the hot-rolled 5083HR-40 had lateral plastic flow in the direction of the width.

3.2 As-hot-rolled material—microstructure, tensile strength, and stored energy

Figures 4 and 5 present the TEM microstructures of the as-hot rolled 5083HR-0 and 5083HR-40, respectively. TEM images were captured with the same zone axis [011] under the two-beam condition [111]. Figure 4 shows a TEM image of a typical microstructure from the central part of the 5083HR-0. The top plot in Fig. 4 shows the location from which the TEM sample was taken. Figure 5 displays a TEM microstructure at the center of the 5083HR-40 after hot rolling. The top plot in Fig. 5 also depicts from where the TEM sample was taken. Figure 5(a) shows that numerous dislocations were generated in the center of 5083HR-40. The 5083HR-40 sample (Fig. 5) had a much higher dislocation density than the 5083HR-0 sample (Fig. 4). Meanwhile, as presented in Fig. 5(b), dynamically recrystallized grains are present because of the massive plastic deformation at 320°C at the central part of the 5083HR-40 plate.

Figure 6 compares the tensile yield stress of the as-hot rolled 5083HR-0 and 5083HR-40 samples. The insert in Fig. 6 presents that tensile samples were obtained from the center of hot-rolled plates. The tensile direction was parallel with the rolling direction. As indicated in Fig. 6, the average yield stress of the sample the as-hot-rolled 5083HR-40 was around 216 MPa, while the sample from the as-hot-rolled 5083HR-0 had a lower yield stress (~199 MPa).

Figure 7 shows the isothermal annealing DTA curves of the as-hot rolled 5083HR-0 and 5083HR-40 samples. The DTA samples were taken from the center of the as-hot-rolled plates. As depicted in Fig. 7, both the samples exhibited exothermic reaction at 350°C, while much larger energy release of the curve of 5083HR-40 was seen. This result is
consistently with TEM dislocations density observations (c.f., Figs. 4 and 5) that the center of as-hot-rolled 5083HR-40 had substantially higher dislocation density than that in the 5083HR-0 plate.

3.3 Observation of metallographic structure following heat treatment

The as-hot-rolled plates (5083HR-0 and 5083HR-40) were tempered at 350°C for 3 hours, followed by air cooling to room temperature. Their microstructures near the rolling surface and in the center of the plate were examined, as presented at the top of Figs. 8 and 9. Figure 8(a) depicts a typical microstructure near the rolling surface of the 5083HR-0 plate, and Fig. 8(b) presents that of the center of the 5083HR-0 plate. As shown in Fig. 8(a), the microstructure near the rolling surface of 5083HR-0 comprises equiaxed grains. However, the grain morphology of the microstructure in the center of the 5083HR-0 was fairly elongated, as presented in Fig. 8(b).

Figure 9 shows the metallographic structures of the 5083HR-40 plate following the tempering treatment at 350°C. The top plot of Fig. 9 approximately presents the positions from which Figs. 9(a) to (c) are taken. Figure 9(a) is an image of from a position near the rolling surface of 5083HR-40, while Fig. 9(b) displays a typical microstructure in the center of the 5083HR-40 plate. The grain structure near the bottom rolling surface was equiaxed (as presented in Fig. 9(c)). As displayed in Fig. 9, all of the microstructures at various positions in the plate reveal equiaxed grains.

4. Discussion

Before hot rolling, the 5083 alloy slab is mostly rectangular (usually with a slightly curved edge profile). In this
study, the rectangular slab was changed to a trapezoidal slab (Fig. 2(b)). After this trapezoidal slab was hot-rolled from original thickness of 32 mm to 10.5 mm, the as-hot-rolled plate was treated by O tempering, in which the plate was heated to 350°C for 3 hours and then cooled to room temperature. The 5083-O temper treatment work typically applied to increase the toughness and ductility of alloys used in critical structural applications, such as liquefied natural gas tanks. Following the heat treatment, the shapes of the grains in the trapezoidal hot-rolled plate were uniform, and almost all were equiaxed (Fig. 9). In contrast, the conventional rectangular hot-rolled plate yielded an inhomogeneous microstructure, with respect to grain shape, with equiaxed grains near the rolling surface but elongated grains around the center of the plate after the same heat treatment (Fig. 1 and Fig. 8).
Deforming a polycrystalline material by rolling is well known to establish a non-uniform plastic strain throughout the thickness. The result is that the regions near the rolling surface deform more than those nearer the center.\(^{14,15}\) Mandal and Baker\(^{15}\) investigated the distribution of stored energy through the thickness of cold as-rolled pure copper. The variation in stored energy as a function of the depth from the rolling surface to the center of a rolled plate shows that the surface region has more stored energy.\(^{13}\) Therefore, following the rolling processes, the dislocation density of the rolled material decreases in the direction of the thickness of the rolled plate from the surface to the center. As expected, the driving force of recrystallization in the surface region exceeds that at the center, because the deformation of the material near the surface is heavier.\(^{16}\) This fact also explains the inhomogeneity of the microstructure (as in Figs. 1 and 8, for example) in the rolled materials that had been treated by temper heat treatment. The prior studies have raised a primary question regarding how to increase the stored energy (dislocation density) in the center of an as-rolled plate. In the present work, changing the shape of the slab from rectangular (5083HR-0) (Fig. 2(a)) to trapezoidal (5083HR-40) (Fig. 2(b)) caused the dislocation density in the central region of the as-hot rolled 5083HR-40 (Fig. 5) to exceed that in the corresponding region of the hot-rolled 5083HR-0 plate (Fig. 4). According to Bever et al.,\(^{16}\) the dislocation density in the material is proportional to the stored energy. The dislocation density and stored energy are recognized to be important factors in recrystallization.\(^{17}\) The dislocation density (and so the stored energy (Fig. 7)) in the central region of the 5083HR-40 plate was increased, such that the driving force of recrystallization in the center of the 5083HR-40 plate exceeded that of 5083HR-0. Accordingly, following O-temper heat treatment, a uniform equiaxed grain structure throughout thickness of the 5083HR-40 plate was obtained.

5. Conclusions

Based on the above results and discussion, the following conclusions are drawn.

1. A trapezoidal slab of 5083 Al-Mg-Mn alloy can be hot-rolled into 10 mm-thick plate, with a total rolling reduction of 68%. Hardly any edge cracks appeared on the hot-rolled plate when the trapezoidal slab was hot-rolled from 32 mm to 10.5 mm.

2. Lateral strain (deformation in the long-transverse direction) was evident after hot rolling. Not only was the trapezoidal slab extended in the rolling direction, but also the width of the central region of the slab and the width of the top surface increased after hot rolling. In contrast, in the hot flat rolling of a conventional rectangular slab, almost no lateral deformation at the central region of the rolled slab was observed.

3. The central region in the thickness direction of hot-rolled trapezoidal plate had a much higher dislocation density (and stored strain energy) than that of the rolled plate of the rectangular slab. The two slabs were rolled in the same reduction, but since severe lateral deformation occurred during the rolling of the trapezoidal slab, the excess deformation yielded the high dislocation density in the central region of the hot-rolled plate.

4. The alloy samples underwent a 5083-O temper treatment following hot working. The rolling of a trapezoidal slab yielded a uniform equiaxed grain structure throughout the thickness of the plate.

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