Abstract:

In conventional hot rolling Aluminum thick slab, its crystalline structure at the central part along the thickness direction are mainly of slender grain, however, at the rolling surface, the structure is equiaxed grain. In this experiment, the slab shape before hot rolling is changed to be trapezoid. The major reason is to make the different parts of materials have the same amount of strains during the rolling process so that the amount of plastic strain in the central part of trapezoidal Aluminum slab is increased and in turn higher dislocation density. The experimental result shows that after heat treatment, the trapezoidal Aluminum alloy slab has its crystalline structure arranged in equiaxed way if we observe the metallographic structure in the horizontal section surface along the rolling thickness direction, no matter in the rolling surface part or the slab central part; on the contrary, Aluminum alloy slab rolled in conventional rectangular shape shows obvious slender grain in the central part. According to TEM microstructure observation result, trapezoidal rolled slab has an obvious higher dislocation density in the central part than that of rectangular rolled slab. Therefore, if we take the central part of as-rolled slab to make pulling test rod, the strength of trapezoidal slab is thus higher than that of rectangular slab. The above mentioned results tell us that trapezoidal slab helps to enhance the dislocation density in the central part of the hot rolled slab. Later heat treatment can move the

recrystallized grain in that portion to equiaxed shape. Finally, crystalline grain shape along the thickness direction becomes more homogeneous.

1. Preface:

Aluminum alloy has advantages such as: light weight, good workability, good physical and mechanical property, strong anti-corrosive property, etc., besides, the density of Aluminum is only 1/3 as compared to that of steel or copper alloy【1】. As energy saving and light weight become the mainstream, there is a dramatic increase in the quantity demand of the use of Aluminum alloy as structural materials in ship, automobile and aeronautic industry.

Aluminum alloy rolling slab has its appearance mainly in rectangular form, however, in the rolling process, the inner part of the material has inhomogeneous plastic strain at different parts along the thickness direction; in the neighborhood of rolling surface which has direct contact with roller shows higher plastic strain, however, the central part of the slab shows an obvious smaller plastic strain【2】. In a study by Yiu et al. 【3】, Al-Mg-Mn alloy is rolled at a high temperature of 480°C, the total rolling reduction is about 48%, the experimental result clearly shows that strain distribution along plate thickness direction is inhomogeneous; most of the rolling strains concentrate on the rolling surface. In addition, Duan and Shppard 【4,5】use FEM method to analyze 5083 AL-Mg alloy for the inner material stain and microstructural change in the rolling process; the result shows that in the rolling process, the dislocation density, stored energy and sub-grain, etc., all get reduced as the central part of the material thickness is approached. The microstructure of 5083 Al-Mg alloy after hot rolling and heat treatment can be seen in the studies by H. Ahmed, M.A. Well【6】, etc., they use a rolling temperature of 448°C and a rolling reduction of 52%, 500°C and 40min of heat treatment is added after hot rolling. From the microstructure we can see that grain structure on the plate rolling surface is equiaxed, but that on the central part of the plate is of slender shape relative to the rolling surface. This is because the surface of the plate which generally experienced higher strain of deformation than the center would have a higher stored energy for recrystallization【7】, which would account for the recrystallizated surface layer found frequently in hot rolled aluminum plate. Figure 1 is the metallographic microstructure of longitudinal section of thick plate (10mm) of Al-Mg alloy 5083 commonly available in the market; we can see from the figure that rolled plate has equiaxed grain structure close to the rolling surface, this is as shown in figure 1(a); figure 1(b) shows that the grain structure close to the thickness center of the plate is of slender shape. Therefore, how to increase the strain dislocation density at the central part of the thickness of as-hot rolled plate is the key research topic of this study.

From the above mentioned result, we know that for rectangular shape slab, the plastic strain along the thickness direction after rolling is inhomogeneous; most of the strains are concentrated on the neighborhood of rolling surface, this leads to the inhomogeneous grain shape along the thickness direction; that is, it is equiaxed shape on the material surface and it is slender shape on the central part. However, there is no related research available for improving such phenomenon. In this study, the slab outer shape is changed, it is a trapezoidal shape with an oblique edge, all the other rolling conditions are kept the same, the whole rolled slab is found to have more homogeneous plastic strain, especially in the central part of the material; it is also found that the central part has higher dislocation density and stored energy as compared to that of rectangular slab. After heat treatment, we find that the trapezoidal rolled slab has equiaxed grain shape both on the rolling surface and the central part.

2. Experimental:

This study uses general commercial 5083 Aluminum alloy with Mg content about 4.5%. Rolling Aluminum slab comprises of two main shapes, their shape and dimension are as shown in figure 2. Figure 2(a) is a rectangular Aluminum material with dimension of width 70mm, thickness 32mm, length 105mm. Figure 2(b) is a trapezoidal Aluminum material with upper bottom width of 40mm, low bottom width of 70mm, thickness of 32mm, and length of 105mm. Hereafter, **5083HR-O** is used as the rectangular Aluminum material number before rolling (Figure 2(a)), and **5083HR-40** is used as the number of trapezoidal Aluminum material before rolling

(Figure 2(b)). Before hot rolling, both **5083HR-40** and **5083HR-O** slab are homogenized for 45 hr at 500°C in furnace and furnace cooled to room temperature. During hot rolling, all the Aluminum material temperatures are fixed at 320°C. Each rolling reduction is 1.5mm, the whole rolling reduction is 68%, the final thickness of hot rolling plate. After the above hot rolling, **5083HR-40** and **5083HR-O** materials are kept at 350°C for 3 hours before they are air cooled to room temperature. The heat treatment is a typical O-temper treatment for 5083 alloy【8】.

For optical metallography, the alloy was annealed at 150℃ for 48 hours in order to decorate grain boundary with Al_3Mg_2 particle【9】. These samples were polished in colloidal silica, and then etched in 10% phosphoric acid at 50°C【10】. Fore the observation of dislocation generated after plastic strain, the central part of the material after rolling is taken for the preparation of TEM sample. Thin foils for TEM observation were prepared by a twin-jet electron polisher using a mixture of 25%HNO_3+75%CH_3OH at an applied current range of 1.5 A to 2 A and at 243 K. The microstructure of the sample was examined using a JEOL JEM-1200 EXⅡ at 120K. Dislocation structures were photographed with [011] zone axis and {111} two-beam condition, satisfying condition for dislocation visibility. After hot rolling of 5083HR-40 and 5083HR-O, the pull test property of the as-rolled material (along the rolling direction) is tested. In addition, the above as-hot rolled specimen is kept at

350°C constant temperature for 3 hours for annealing treatment, we also perform pull test to find out the mechanical property along the rolling direction. Tensile sample with a 20 mm gauge length and 4 mm diameter were machined directly from hot rolling plates; the loading axis was parallel to the rolling direction. Since the final thickness of hot rolling plate is 10mm, therefore, the gauge length location of the pull test specimen is at the central part of the back side of the rolled plate. Tensile test was performed at room temperature and each sample as tested in a initial strain rate of $8 \times 10^{-4} S^{-1}$. Each data is obtained from a test of at least three rods of specimen and then average is taken.

3. Experimental results

3-1. The plate horizontal sectional change after rolling

Figure 3 shows the width changes of the horizontal section of the Aluminum plates of two different shapes before and after rolling, the whole rolling reduction of two plates is 68%. Figure 3(a) shows the width change on the horizontal section of 5083HR-O after rolling, from figure 3-(a) we can see the rolling result of rectangular shape, that is, both the upper and lower rolling surfaces become wider while the width of the central part does not show obvious change after rolling. Figure 3-(b) is the horizontal sectional width change of 5083HR-40 material before and after rolling, we can see from the figure that the upper bottom changes from 40mm to 53mm and the central part of the horizontal section changes from 55mm to 61mm. Therefore, in addition to the extension in the rolling direction, we can observe 5083HR-40 from cross section that both the upper bottom rolling surface and the central part have obvious wider plastic strain. If we observe from the appearance, in the same rolling conditions, the central part of 5083HR-40 has obvious wider plastic strain as compared to that of 5083HR-O.

3-2. As-hot rolled TEM microstructure

After the material is hot rolled, the location where larger strain occurred will show higher dislocation density. The TEM microstructure of the as-hot rolled

5083HR-O and 5083HR-40 are included in Figure.4 and Figue.5. Images were taken with the same zone axis [011] and two-beam condition {111}. Figure 4 shows the TEM microstructure at the central part of 5083HR-O after 68% hot rolling. And figure 5 shows the TEM microstructure at the central part of 5083HR-40 after hot rolling. After 68% hot rolling reduction, we can see from figure 4 that the central part of 5083HR-O show dislocation after rolling, the black clustered part in the figure is an accumulation of dislocation. Figure 5-(a) shows that a lot of dislocations are generated in the central part of 5083HR-40 after rolling. Relative to the dense dislocation accumulation in the strained 5083HR-O as shown in figure 4, we can see that 5083HR-40 has a much higher dislocation than 5083HR-O. Meanwhile, in figure 5-(b) we can see that non-strained recrystallized grains are generated at the central part of 5083HR-40, that is, massive plastic strains are generated at high temperature, the dynamic recrystallization is generated during the rolling process.

3-3 Pull test

Figure 6 is the tested result of pull test of the central part of 5083HR-O and 5083HR-40 after rolling but before heat treatment. After rolling, the central part of 5083HR-O hot rolled plate (the sampling position on the specimen is as illustrated on the upper part illustration of the figure) has an average of 0.2% yield strength of 199MPa, and the average of 0.2% yield strength at the central part of 5083HR-40 is

216MPa.

3-4. Observation of metallographic structure after heat treatment

Fig.8 is the metallographic structure at the longitudinal section of rolled 5083HR-O Aluminum material kept at 350°C constant and then air cooled to room temperature. The observed part is as shown in the upper part illustration of figure 8. Fig. 8 (a) is the metallographic structure close to the rolling surface of 5083HR-O rolled plate, and Fig. 8(b) is the metallographic structure close to the central part of the rolled plate. From figure 8(a) we can see that after heat treatment, the grain shape close to the rolling surface of 5083HR-O Aluminum plate material is equiaxed, its size is about 20μm. But at the central part of 5083HR-O, the grain structures, although heat treated at the same conditions, are mostly elongated as shown in figure 8(b), most of the grains are of slender structures; the grain size is about 100μm in the long axis direction. From the metallographic structure observation we know that the rectangular rolled plate after heat treatment in this experiment shows equiaxed crystal close to the rolling surface but slender crystal close to the central part. This result is very similar to inner grain structure of the 5083 Aluminum alloy available in the market (as shown in Fig.2). Fig.9 shows the metallographic structure of the longitudinal section of 5083HR-40 rolled Aluminum after 350°C constant temperature for 3 hours and air cooling heat treatment; the observed portion is as shown in the upper part illustration of figure 9. Fig.9(a) shows the metallographic structure close to the rolling surface of the upper bottom of 5083HR-40 rolled plate, we can see that after heat treatment the crystalline structures are all of equiaxed forms, the grain size is about 20μm. And Fig9(b) shows the metallographic structure of the central part of 5083HR-40 rolled plate, we can clearly see that the grain structures are mostly of equiaxed forms, the grain size is about 25μm.

4. Discussions

Before the hot rolling of Aluminum alloy, its outer shape is mostly rectangular shape (for example, 5083HR-O of this study as shown in figure 2-(a)). In this study, the rectangular plate is changed to narrower upper bottom and wider lower bottom trapezoidal plate (such as 5083HR-40 for this study as shown in figure 2-(a)). After hot rolling on this trapezoidal plate at 350°C, the dislocation density at the central thickness position of the hot rolled plate is obviously higher than that of conventional rectangular hot rolled plate (as shown in figure 4 and 5). After heat treatment at 350°C for 3 hours, the grain shapes at the central part of the trapezoidal hot rolled plate are all equiaxed (as in figure 8-(a)). On the contrary, the hot rolling results of conventional rectangular plate in the central part of its thickness all show the formation of elongated grains (as in figure 7-(a)) along the rolling direction.

In this study, trapezoidal shape is used for rolling, therefore, the central part of the trapezoidal rolled plate has larger plastic strain. From figure 3-(a), we can see that the horizontal section of rectangular plate before hot rolling is about 70mm, and the width at the central part after hot rolling is almost not changed, the central part of the horizontal section is still 68mm. But from figure 3-(b), the width of the central part of horizontal section of trapezoidal plate before rolling is about 55mm; but after hot rolling, the width of the central part of the horizontal section the hot rolled plate clearly becomes wider, it changes from original 55mm to 61mm. We thus know that under the same rolling reduction of 68%, the strain in the horizontal section of the central part of 5083HR-40 plate is obviously larger than that of the 5083HR-O plate. From the TEM microstructure observation (Fig.4 and Fig.5 for comparison), we know that the dislocation density at the central part of 5083HR-40 plate is obviously larger than that of 5083HR-O plate (see Fig.4 及 Fig.5(a)). In addition to observing dislocation density using TEM microstructure, we can also prove it by using pull test 【11】; the higher the dislocation density, the higher the pull strength of the material. The pull test results show that for 5083HR-40plate after hot rolling, its 0.2% yield strength at the central part is higher than that of 5083HR-O hot rolled plate. This can explain that under the same rolling conditions, higher dislocation density is generated at the central part of 5083HR-40 rolled plate than that of 5083HR-O rolled plate, this also leads to higher central strength in the 5083HR-40 plate. It is generally recognized that the density of dislocation and stored energy are the important elements of recrystallization【12】. Therefore under heat treatment of the same temperature and time, the recrystallization driving force at the central part of the 5083HR-40 plate is higher than that of 5083HR-O. Therefore, after heat treatment, if we compare the grain structures at the central parts of two rolled plates of different shapes (Figure 4(b) and figure 5(b)), it shows that the grain size of 5083HR-O is obviously of slenderer shape than that of 5083HR-40, besides, the grain size of 5083HR-40 is equiaxed and homogeneous. Therefore, the 5083HR Aluminum alloy plate rolled by using trapezoidal shape plate will show higher plastic strain and higher dislocation density at the central part of the plate, this can help to enhance the driving for recrystallization. And finally, the bad equiaxed grain shape at the central part of hot rolled plate can thus be improved.

References:

1. M. Mizuno and H. Nagaoka, International Metal Review, 1979, no.2, pp.68-81.
2. N . H . Polakowski. J . Inst. Met. Vol. 76. pp. 755-757, 1949-1950
3. Yiu H L, Fine J M, Timothy S P, Rogers S and Ricks R A 1990 *Hot Deformation of Aluminum Alloys* ed T G Langdon, H D Merchant, J G Morris and M A Zaidi (Detroit, USA) pp 509–25
4. Duan X and Sheppard T 2002 *Comput. Mater. Sci.* submitted
5. Duan X and Sheppard T 2001 *Aluminum Transac.* **5** 2001
6. H. Ahmed, Materials Science and Engineering A 390 (2005) 278-290.
7. J.G Kaufman, Introduction to Aluminum Alloy and Tempers, ASM International, Materials Park, Old, USA, 2000, P.58.
8. R. Kaibyshev Materials Science and Engineering A 342 (2003) 163-177
9. R. M. Cleveland Materials Science and Engineering A 351 (2003) 228-236
10. I YA Tarnovskii, AA Pozdeyev and V B Lyashkov, “Deformation of Metals During Rolling”, translated by M de O Tollemache Pergammon, 1965
11. Duan X and Sheppard. Modelling Simul. Mater. Sci. Eng. 10 (2002) 363-380
12. M. Verdier Scripta Materialia 37 (1997) pp 449-454