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Shear deformation and grain refinement in pure Al by asymmetric rolling

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Abstract: Asymmetric rolling(ASR), as one of severe plastic deformation(SPD) methods, was widely used to make ultra-fined materials with enhanced performance. Internal marks were used to show the shear deformation during asymmetric rolling with pure aluminium as a model material. Effects of reduction ratio and mismatch ratio on the shear deformation were studied. With the observed shear deformation results, equivalent strain was calculated. For lager shear deformation, rolling equipment was modified to increase friction between specimen and the rollers. Consequently, extremely fine grains with size of 500 nm are obtained in pure aluminium. With improved asymmetric rolling, the ability of grain refinement of ASR is greatly improved.

Key words: asymmetric rolling; shear deformation; pure aluminum; equivalent strain

1 Introduction

It is well known that strength and toughness of metallic materials can be improved through decreasing grain size. So, continuous efforts have been devoted to developing new techniques for grain refinement. Recently, severe plastic deformation(SPD) has become the most promising method[1]. Through SPD, grain size of metallic materials can be refined to sub-micrometer range, or even to nanometer range. A variety of SPD methods, such as equal channel angular pressing(ECAP), torsion straining under compression and accumulative roll-bonding[2] have been proved to be feasible to produce sub-micrometer or nanometer sized grains in bulk form. However, a weakness of almost all these techniques is that they are conducted to specimens with limited dimensions, which greatly affects their potential for industrial productions.

Severe plastic deformation can also be attained through asymmetric rolling. In asymmetric rolling, sheet is rolled between rollers that either have different diameters, or rotates at different speeds. Under these circumstances, the material is subjected to an extra shear deformation in addition to compression deformation. With increased shear deformation as well as the compression, it has been suggested that high-angle boundaries develop with increasing strain, and ultrafine grains are formed by continuous recrystallization[3−5] or by discontinuous recrystallization[6−9]. Thus, it is the most promising one to fabricate large scale structural materials.

It is reported that shear deformation plays a critical role in the grain refinement of materials processed by ECAP as well as by asymmetric rolling(ASR)[10]. And many simulations and analytical studies have been done to these techniques, especially in the ASR[11−14]. The shear deformation of ECAP was directly observed by SHAN et al[15]. Yet similar work has rarely been performed to ASR, except that mentioned by CUI et al[3]. Therefore, for better understanding of asymmetric rolling and its mechanism of grain refinement, it is necessary to conduct a systematic study on shear deformation in ASR, especially through direct observation.

Extensive research on ECAP shows that for aluminium and its alloys, grain sizes in the range form

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300 to 1 000 nm can be obtained with this method. With asymmetric rolling, CUI et al[3] produced a 2 μm grain size in high purity aluminium, while JIN et al[4] got a 1 μm grain size in AA5754 alloy. These sizes are obviously larger than those got through ECAP method. In this work, the grain structure of commercially pure aluminium after asymmetric rolling was examined.

2 Experimental

The material used in present study is a kind of commercially pure aluminium with dimension of 100 mm×20 mm×4 mm. In this specimen, a slot with dimension of 20 mm×5 mm×4 mm was made, in which a block with the same dimension was inserted. And with a steel pen, perpendicular lines were scratched on the side face of the block. These marks served as internal marks during rolling and chalk was used to make them less erasable. Asymmetric rolling as well as conventional rolling was carried out using a rolling mill with upper and lower roller diameter of 130 mm. The upper and lower rollers were driven by two independent motors. The upper one rotated with a fixed speed of 33 r/min, and speed of lower roll was from 0 to 33 r/min. No lubrication was introduced to rollers.

The specimens with blocks inserted were symmetrically and asymmetrically rolled, respectively to final reduction of 10%, 20%, up to 90% in one pass or 10% reduction per pass. For further study, this work has been repeated with three mismatch ratios, 1.27, 1.5, and 2.1. Similar work has been done with improved rolling machine in order to increase friction.

3 Results and discussion

After rolling, the inserted mark can be easily taken out, and the lineation scratched on its side face can be clearly observed (Fig.1). From Fig.1(b), it is apparent that during asymmetric rolling, the lineation that is perpendicular to the rolling plane before rolling tends to incline towards the rolling direction. The larger the reduction ratio is, the larger the inclination is. From Fig.1, when the reduction of asymmetric rolling is 61.6%, the inclination (θ/(˚)), defining the θ of inclination as the angle between the inclinations before and after rolling, is also larger than 56˚. This is remarkable, since the inclination of lineation represents the additional shear deformation of asymmetric rolling. By contrast, in symmetric rolling, shown in Fig.1(a), no inclination of lineation is observed even when the reduction ratio increases to 50%. When the reduction continues to increase, the scratches tend to bend to ")" symbol shape. This shape implies that during traditional rolling no additional shear deformation exists.

The relationship between inclination of lineation and reduction ratio is shown in Fig.2. In Fig.2, during asymmetric rolling process, inclination of lineation increases to 68.7˚ when the reduction ratio is up to 79.3%; while in conventional rolling, the inclination is still negligible. When the reduction of material still goes on, the lineation scratched on the side face of internal mark block becomes vague and illegible. However, the trend that the inclination increases with reduction ratio is obvious. And this represents the fact that shear deforma-

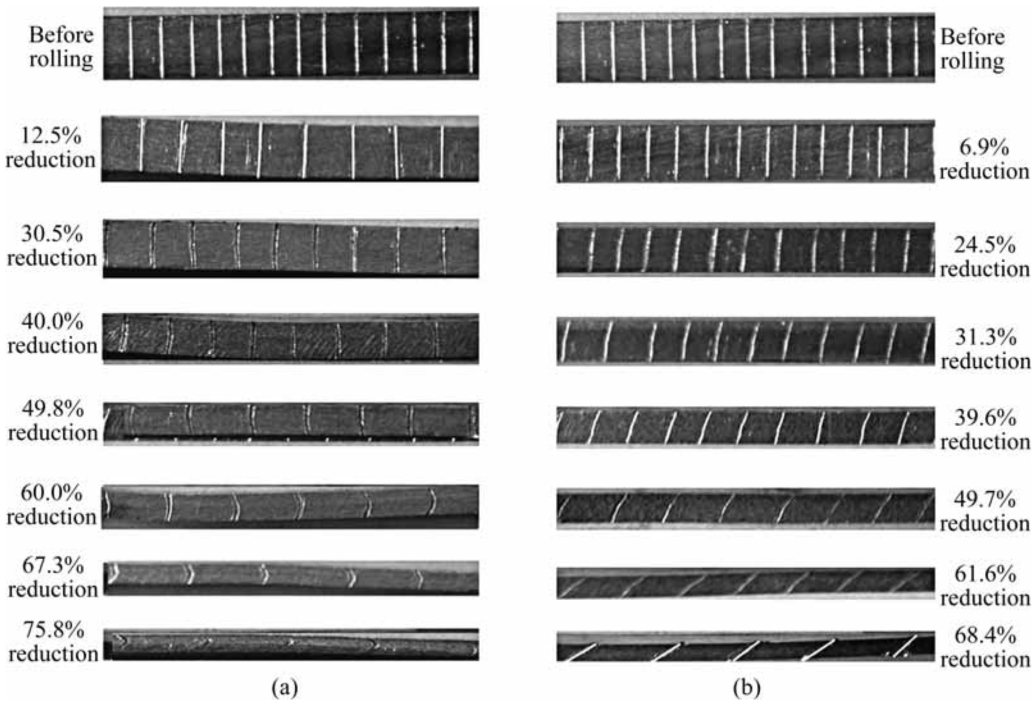

Fig.1 Lineation of internal mark during rolling: (a) Symmetric rolling; (b) Asymmetric rolling

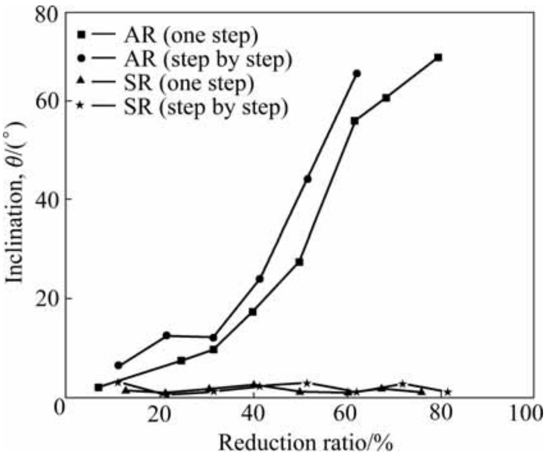

Fig.2 Relationship between reduction ratio and inclination under different rolling modes (AR: Asymmetric rolling; SR: Symmetric rolling; One step: One pass to the final reduction; Step by step: Each pass of 10% reduction up to final reduction)

tion that is believed to be the critical reason of grain refinement[3] also increases with reduction ratio.

Another interesting phenomenon also found in this study is that along the thickness direction, shear deformation that can be vividly depicted by inclination is not uniform. As shown in Fig.3, the inclination of the specimen near to the upper face is much larger than that near to the lower face, and the inclination in the middle of the bulk specimen is the smallest. This also illustrates the phenomenon that the grain size of asymmetrically rolled AZ31 is not uniform, and the grain size of the upper face is the smallest, and then the lower face, and in the middle of the specimen the grain size is the largest[6].

Fig.3 Shape of lineation after asymmetric rolling

It is well believed that the mechanism of SPD comes from its large equivalent strain, which is composed of compressive strain and additional shear deformation. By directly observing and depicting the later, equivalent strain can be easily calculated. From elastic-plastic mechanics, the equivalent strain is readily given by

$$\varepsilon_{\text{eq}} = \left\{ \frac{2[\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2 + (\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2)/2]}{3} \right\}^{1/2} \tag{1}$$

As conventional rolling, asymmetrical rolling is also a planar strain, that is, $\varepsilon_x=\varepsilon_y$, $\varepsilon_z=0$, $\gamma_{yz}=0$, $\gamma_{zx}=0$. Then Eqn.(1) can be refined as

$$\begin{cases} \varepsilon_{\text{eq}} = \left[\dfrac{2(\varepsilon_x^2 + \varepsilon_y^2 + \gamma_{xy}^2/2)}{3} \right]^{1/2} \\ \varepsilon_y = -\ln \dfrac{d}{d_0} \\ \gamma_{xy} = \tan\theta \end{cases} \tag{2}$$

where d_0 and d are the thicknesses of the sheet before and after asymmetric rolling, and θ is the apparent shear angle at a given position of the element perpendicular to the surface of the sheet before rolling. According to the calculation above, we can transfer the inclination into equivalent strain and then contact the total strain with reduction. Such results are shown in Fig.4, in which three kinds of mismatch ratios are carried out. The ratio means the rotating speed ratio of the upper roller to lower roller. This reveals that the inclination of scratches tends to be much smaller when the mismatch ratio is 1.5. The reason why mismatch ratio of 1.5 is less capable of bringing shear deformation than that of 1.27 and 2.1 is not yet understood.

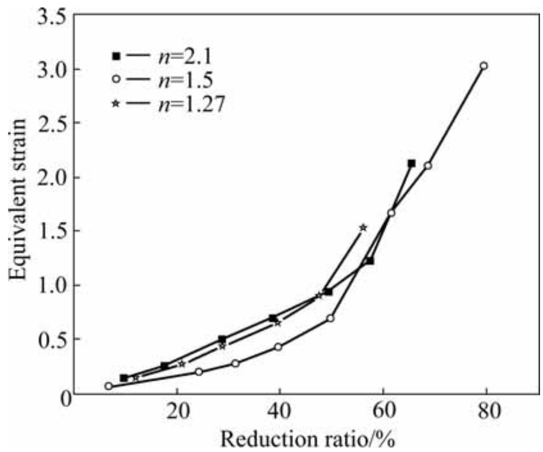

Fig.4 Equivalent total strain vs. reduction ratio

Finally, as far as the improved method is concerned, equivalent strains of both improved and conventional ones are listed in Table 1.

It is quite obvious that when the reduction is 25%, the equivalent strain of improved ASR is slightly higher

Table 1 Equivalent strain of advanced ASR and conventional ASR

Method	25% reduction	50% reduction
ASR	0.200 2	0.680 2
Improved ASR Ⅰ	0.290 0	1.084 0
Improved ASR Ⅱ	0.348 0	1.210 0

Improved ASR Ⅰ differs from improved ASR Ⅱ for even larger friction.

than that of conventional ASR, but with the increasing of reduction, the equivalent strain increases drastically. Moreover, along with the increase of friction between the rollers and specimen, the equivalent strain increases correspondingly. When specimen has undertaken even larger reduction, the lineation becomes obscure. Thus, further data about higher reduction are absent. However, it seems reasonable that in the specimens rolled with a larger amount of reduction, the equivalent strain of improved ASR should also be considerably larger than that of conventional ASR.

According to the theory of elastic-plastic mechanics, it is reasonable that the specimens with improved ASR methods have undertaken more severe plastic deformation. Supposing that the effect of grain refinement is under control of equivalent strain, the one with larger equivalent strain should have finer grain. In other words, the specimen carried out by the improved ASR should have much smaller grains. So we observed the grain size of the samples rolled by the improved ASR Ⅱ method and the result is shown in Fig.5.

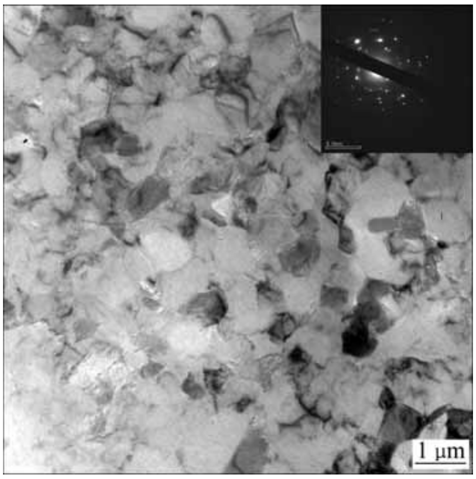

Fig.5 TEM image and diffraction pattern of 75% asymmetrically rolled commercial aluminium with improved rolling method

Fig.5 shows TEM image and diffraction pattern of the specimen that is of 75% reduction by improved ASR Ⅱ method and annealed at 150 ℃ for 1 h. It is apparent that the grain size is much smaller than 1 μm. The average grain size of this asymmetrically rolled commercial aluminium is about 0.5 μm. This indicates that the grain size of the pure aluminium is able to be refined to nano-scale by the improved ASR and seems to be a promising approach of applying the SPD in industry.

4 Conclusions

1) Shear deformation of asymmetric rolling is clearly observed by an “insert block” method. And shear deformation increases with the increase of reduction ratio.

2) Equivalent strain of asymmetric rolling were calculated. Total strain up to 3 is achieved in sample rolled to about 70%. Three mismatch ratios are chosen in asymmetric rolling, and their effects on shear deformation are observed. It is found that with mismatch ratio of 1.5 the shear deformation degree is the smallest, and the shear deformation degrees of 1.27 and 2.1 are comparable.

3) A small grain size of 0.5 μm is observed in a sample processed with the improved rolling machine.

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