



Anisotropic tensile behavior and related yield point phenomena in annealed ultrafine-grained pure aluminum

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Abstract: It is found that tensile flow curves of samples of annealed ultrafine-grained aluminum AA1090 show the development of a yield point and a significant mechanical anisotropy. To rationalize the anisotropic tensile behavior, the orientation data of the annealed material were measured using electron backscatter microscopy. It is found that the inferior mechanical properties of samples tested at 45° to the rolling direction may be attributed to a strong rolling texture effect and that the anisotropic magnitude of the yield drop may be related to the proportion of grains with soft orientations (defined as those with Schmid factor greater than 0.45) in the sample. Additionally, it is found that the anisotropy in tensile ductility is in general agreement with a Considère criterion analysis and that the mechanical anisotropy in the samples is only partly explained by the crystallographic texture, where microstructural anisotropy may also play a role.

Key words: ultrafine-grained aluminum; recovery annealing; mechanical anisotropy; yield drop; ductility

1 Introduction

Aluminum with an ultrafine-grained (UFG) structure is of interest for structural applications on account of its enhanced strength compared with material with normal grain size. An ultrafine-grained structure can be introduced by the application of severe plastic deformation. Several such techniques exist, but heavy cold rolling is one of the most convenient approaches for refinement of grains. Although refinement of grains is a suitable way for improvement of strength, depending on the microstructure, deleterious characteristics, such as the early onset of plastic instability and reduced tensile elongation [1–5] may also be found in these materials. As the grain size of ultrafine-grained materials is on the sub-micrometer scale, the dislocation storage efficiency inside the individual grains is poor, and grain boundaries are thought to play an important role in plastic deformation [6,7]. This causes a lower work hardening rate and a higher dynamic recovery rate in UFG metals, thus leading to inferior mechanical properties.

It should be recognized that good ductility is required with regard to the formability of metals. To

restore some ductility in UFG metals, a post-deformation recovery annealing is usually applied [1,8]. Under certain conditions, this annealing may produce a drop in yield stress [1–3,6,9,10]. In addition, rolled aluminum exhibits a significant anisotropy in mechanical properties, as typified by different tensile flow curves when tested with the tensile axis aligned at different angles from the rolling direction [11–16]. However, the anisotropy in yield drop magnitude has not been studied, and the underlying causes of mechanical anisotropy are still not well understood. It is believed that the crystallographic texture of the material is one of the primary sources of plastic anisotropy [17–20], although other factors, such as grain shape and morphology [14,20], may also play a role. An understanding of mechanical anisotropy, and its correlation with texture, is therefore important for the development of simulations and models of formability [19,21], moreover, to help control the final mechanical properties.

The aim of the present work is not only to reveal the anisotropic mechanical behavior and related yield point phenomena in annealed UFG pure aluminum, but also to further elucidate the intrinsic mechanisms of the anisotropy, based on the analysis of both microstructure

and texture. The Considère criterion and a texture-based Schmid/Taylor factor analysis are used to rationalize the observed mechanical anisotropy, and to estimate the contribution of texture to the mechanical anisotropy.

2 Experimental

Commercial purity aluminum AA1090 was used in the present work in the form of aluminum plate cold-rolled to a thickness of 1.0 mm (~80% rolling reduction). The initial material has a UFG structure with an average boundary spacing of ~0.78 μm measured perpendicular to the rolling direction (RD). In order to investigate the mechanical anisotropy of the material, dog-bone shaped specimens with a gauge length of 10 mm were cut from the plate along four different directions, namely 0°, 30°, 45° and 90° with respect to RD. In order to determine the annealing conditions required to develop a significant yield drop and good ductility, a series of initial tests were first carried out at various temperatures and annealing durations, with the mechanical behavior for each evaluated by tensile testing only at 90° to RD. Based on the flow curves obtained, annealing conditions for the full investigation on mechanical anisotropy were chosen as 528 K (255 °C) for 4 h and 558 K (285 °C) for 2 h. All tensile tests were carried out at room temperature using a WDW-100 tensile machine with a constant crosshead speed of 1 mm/min. Tensile properties were estimated from the standard true stress–true strain plots. For each sample direction and material condition, two samples were tested to ensure reproducibility. Microstructural characterization of the material prior to tensile testing was carried out using electron backscatter diffraction (EBSD) on samples cut to reveal the transverse plane (containing both the rolling and normal directions). Samples for EBSD observations were prepared by electro-polishing using an electrolyte consisting of 90% ethanol and 10% perchloric acid. Orientation data were collected using an Oxford Instruments EBSD system attached to a field emission scanning electron microscope. The EBSD maps shown in this work were taken at an operating voltage of 20 kV, using a step size of 0.8 μm . Minimal data cleaning was carried out, consisting three iterations of the noise-reduction filter in the Channel 5 software using a setting of 5/8 neighbors.

3 Results

The true stress–true strain curves for samples tested along 90° to RD after annealing at various conditions are shown in Fig. 1(a). In all cases after annealing, the strength of the samples decreases and better ductility is achieved. The flow curves at 0°, 30°, 45°, and 90° to RD

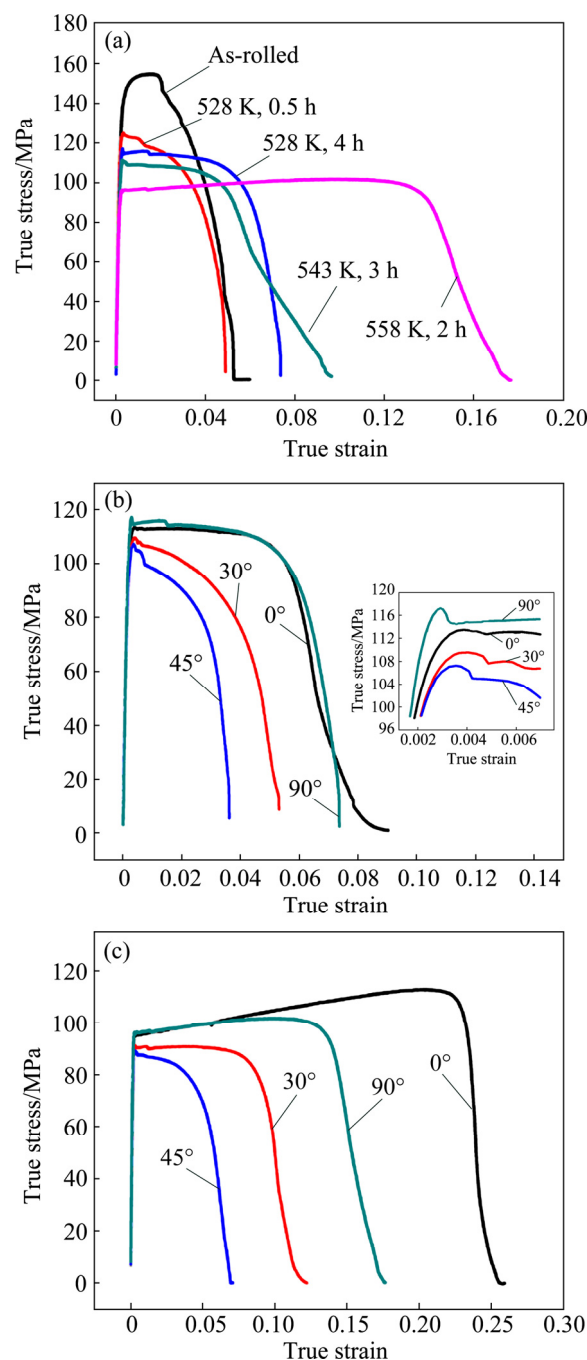


Fig. 1 True stress–true strain curves for samples: (a) Under different annealing conditions, tensile-tested at 90° to RD; (b) Annealed at 528 K for 4 h, tested along different angles to RD; (c) Annealed at 558 K for 2 h, tested along different angles to RD

for samples annealed at 528 K for 4 h or 558 K for 2 h are shown in Figs. 1(b) and (c). The differences between the flow curves for different tensile directions highlight a significant anisotropy in mechanical behavior for both annealing conditions. In terms of yield strength, the specimens tested at 0° and 90° to RD show similar values, with the lowest strength of the specimen tested along 45° to RD. A yield drop phenomenon is also

clearly observed in the flow curves for samples annealed at 528 K for 4 h. To show this more clearly, the yield drop region is magnified in the inset of Fig. 1(b). It is interesting to note that the magnitude of the yield drop varies with tensile direction. The variation in yield drop magnitude with angle to RD is shown in Fig. 3(a), where it is seen that testing along RD (0° to RD) results in the smallest yield drop, whereas testing along TD (90° to RD) results in the largest yield drop. In addition, a clear anisotropy in the tensile ductility is also observed. This is most evident in the tensile curves for samples annealed at 558 K for 2 h (Fig. 1(c)), where it is seen that the tensile elongation increases with tensile direction in the sequence of 45° , 30° , 90° and 0° . It can be noted that among the four testing directions, specimens tested at 45° to RD possess the worst mechanical properties, exhibiting the lowest yield strength and elongation values.

The microstructure and texture of the annealed samples are shown in Fig. 2. Under the recovery annealing conditions examined in this work, the material predominantly maintains a typical cold-rolled microstructure, showing a lamellar structure elongated along RD, even though the grains coarsen and a small number of recrystallized grains are found in the sample annealed at 558 K for 2 h. Based on line intercept measurements perpendicular to RD, the average boundary spacing in these samples are determined to be $\sim 1.8 \mu\text{m}$ for the sample annealed at 528 K for 4 h and $\sim 1.9 \mu\text{m}$ for the sample annealed at 558 K for 2 h. The crystallographic texture of the annealed samples is summarized in Table 1. In both cases, a strong rolling

texture is found, consisting mainly of S $\{123\}\langle 634 \rangle$, Brass $\{110\}\langle 112 \rangle$ and Copper $\{112\}\langle 111 \rangle$ components.

4 Discussion

4.1 Yield drop anisotropy

In body centered crystal (BCC) structure materials, the yield drop is generally associated with interactions between dislocations and solute atoms or impurities. For the case of commercial purity UFG aluminum, it is believed that the observation of a yield drop can be attributed to a lack of a sufficient density of mobile dislocations to satisfy the applied strain rate [6]. With decreasing grain size, the mean free path of dislocations is no longer determined by the dislocation structure, but is limited by the grain boundaries. In this material, the large grain boundary area can act also as effective sink for dislocations, especially in the recovery-annealed condition. This in turn reduces the mobile dislocation density, and thus a higher velocity of dislocations is required to fulfill the imposed macroscopic strain rate. Consequently, the increased dislocation velocity can be related to the raising of the yield stress. After a certain plastic strain, however, dislocation interactions eventually result in an increase in the density of dislocation sources, leading to a fall in the stress required to maintain the applied strain rate, and hence a yield drop phenomenon occurs.

To rationalize the observed yield drop anisotropy, the Schmid factor (SF) for the slip systems with the highest resolved stress was calculated for each measured crystal orientation in the EBSD map of the sample annealed at 528 K for 4 h, by taking into account of different tensile testing directions of 0° , 30° , 45° and 90° from the RD. The results are shown in Fig. 3(b), where it is seen that the 0° direction is relatively hard compared with tensile testing along either the 30° , 45° or 90° directions. The proportion of soft grains (defined here as volume fractions with $\text{SF} > 0.45$) was also calculated as a

Table 1 Proportion of each texture component in annealed samples

Annealing condition	S	Brass	Copper	Cube	Others
528 K, 4 h	46%	34%	9%	<1%	11%
558 K, 2 h	57%	22%	13%	<1%	7%

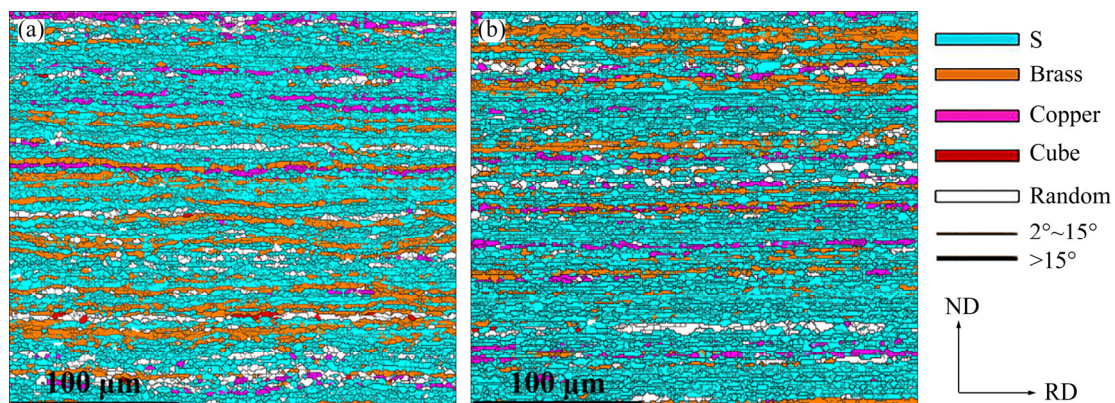


Fig. 2 EBSD maps of samples: (a) Annealed at 528 K for 4 h; (b) Annealed at 558 K for 2 h (Colors represent specific texture components defined by a tolerance angle of 15°)

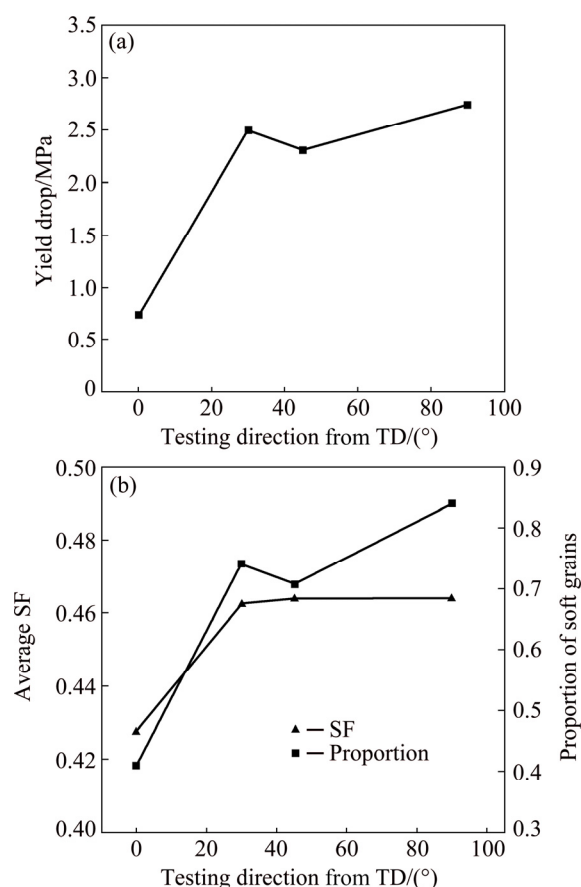


Fig. 3 Yield stress drop (a) and average Schmid factor (SF) and proportion of soft grains (with SF>0.45) (b) as function of tensile testing direction for samples annealed at 528 K for 4 h

function of test direction, and is shown in Fig. 3(b). This plot shows a similar trend to that for the drop in yield stress as a function of tensile test direction, suggesting that the magnitude of the yield drop may be related to the proportion of soft grains in the sample. It is easy to understand that more dislocations will be active in the sample if it possesses more soft grains when being subjected to a certain stress; therefore, a larger increase in the mobile dislocation density at yield may lead to a larger subsequent yield drop.

4.2 Inhomogeneous ductility

Both tensile curves for the two different annealing conditions show clear anisotropy in tensile ductility. Moreover, the tensile elongation after annealing at 558 K for 2 h shows a continuous increase in tensile ductility as the tensile axis is varied in the sequence from 45° to 30° to 90° and to 0°. As work hardening is often limited in UFG structures due to the limited dislocation storage efficiency of fine grains, the early presence of plastic instability (necking) is strongly associated with material failure. The onset of plastic instability during the tests can be predicted based on the Considère criterion, which is expressed by

$$(\partial\sigma/\partial\varepsilon)_\varepsilon \leq \sigma \quad (1)$$

where σ and ε are true flow stress and true strain, respectively. Although the Considère criterion is traditionally obtained from solid mechanics considerations, recently, it has been shown that it can also be derived following the intrinsic evolution laws for dislocation density [22]. Values for the critical stress at the onset of necking for different tensile directions, calculated using the Considère criterion, are given in Table 2. It is found that the anisotropy in elongation is in general agreement with the variation in critical stress for necking, suggesting that the early occurrence of plastic instability may severely limit the desirable elongation in this material. Even though the coarsened microstructure and a few recrystallized grains in the matrix contribute to the ductility, for the 30°, 45°, 90° testing directions, the material still fails soon after necking because of the lacking of efficient mechanisms to disperse the plastic flow. It can be seen that significant work hardening in the 0° testing direction sample accompanies the total elongation, and this is discussed further in the next section.

Table 2 Critical stresses for different testing directions predicted by Considère criterion based on tensile curves of samples annealed at 558 K for 2 h

Testing direction/(°)	0	30	45	90
Critical stress/MPa	94.3	93.6	87.5	94.1

4.3 Texture effects on mechanical anisotropy

In order to determine the effects of crystallographic texture on the mechanical anisotropy, both the SF and the Taylor factor, M , have been calculated as a function of tensile testing direction for the sample annealed at 558 K for 2 h. The SFs under uniaxial tension were calculated as described in Section 4.1. Taylor factors for each testing direction were calculated using the in-built capability of the Channel 5 post-processing software. To take into account the different tensile directions and to avoid the limitation in the software that the M can only be calculated along a direction parallel to one of the EBSD map axes, the orientation data were exported, then rotated about the sample normal direction by a certain angle and re-imported to the Channel 5 software, to allow the determination of the M along directions of 0°, 30°, 45° and 90° from the RD. The calculated M values were additionally checked by a manual calculation based on the Bishop and Hill method. Figure 4 shows the distribution of SF and M values for each direction, and the average SF and M values for different directions are summarized in Figs. 5(a) and (b). The calculations show that the 45° direction is a soft direction, with large SF

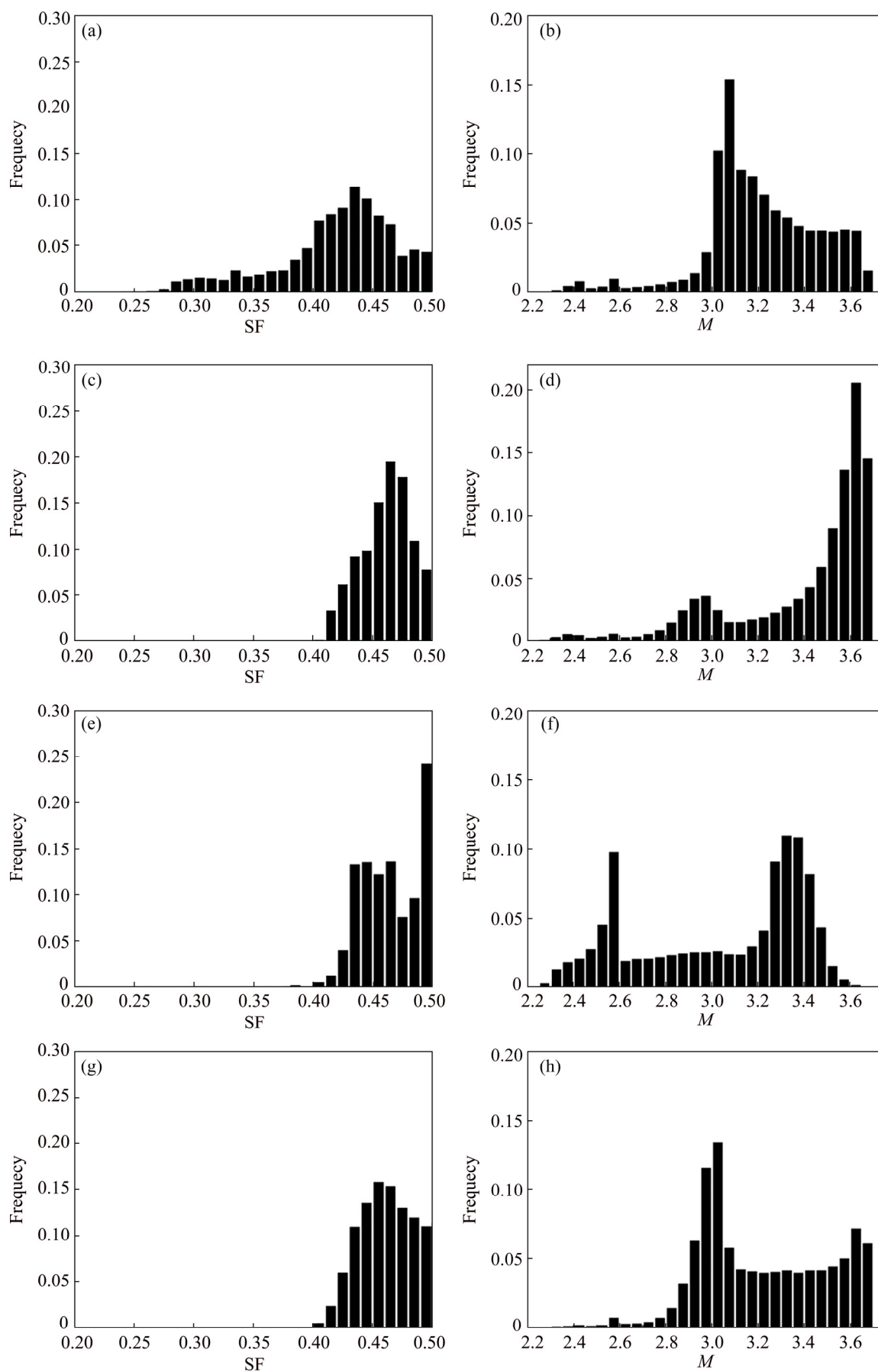


Fig. 4 Distributions of Schmid factor, SF (a, c, e, g), and Taylor factor, M (b, d, f, h), for different tensile directions of samples annealed at 558 K for 2 h: (a, b) 0°; (c, d) 30°; (e, f) 45°; (g, h) 90°

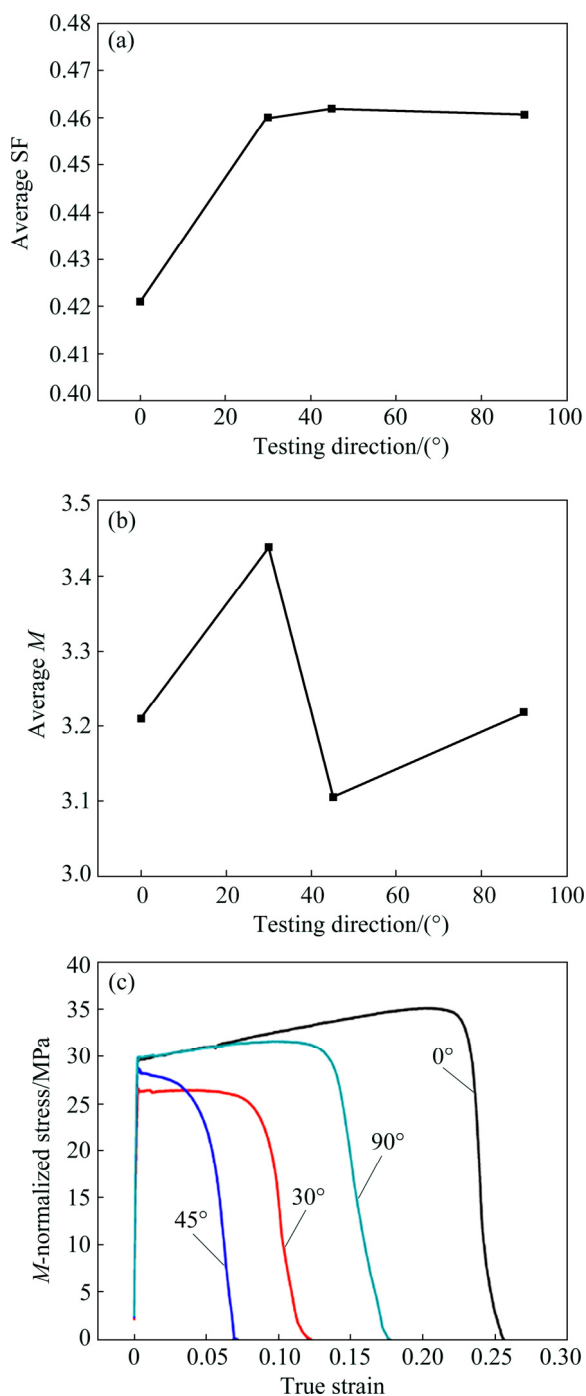


Fig. 5 Distribution of average SF (a) and average M (b) for samples annealed at 558 K for 2 h as a function of tensile testing directions from rolling direction, and M normalized flow curves for different tensile testing directions (c)

and small M values, corresponding to the observation that testing along this direction results in the poorest mechanical properties. It is suggested that the larger fraction of soft grains with SF near 0.5 in the 45° direction sample allows the spreading of plastic deformation to take place more easily in a localized manner, thus quickly leading to the sample failure by the

development of intense shear bands. Although the distributions of Taylor factor for the 0° and 90° directions are similar, the wider distribution of SF values for the 0° sample compared with the 90° sample may contribute to the difference of mechanical properties between these two directions, with the dispersion of relatively hard grains in the sample tested along 0° helping to limit the localization of plastic deformation. The presence of grains with relatively hard orientations acting as barriers to constrain the spreading of deformation may contribute to the work hardening in the 0° direction.

Although the mechanical anisotropy can be partly rationalized by the distributions of SF and M values for each sample, this does not fully account for the experimental observations. In particular, the 30° direction has larger M values and similar SF values compared with the 90° direction sample, but shows worse properties, indicating that the general texture could not be the only source for the anisotropy, and other factors such as the spatial distribution or percolation of relatively soft grains may also influence the final properties. Similarly, Fig. 5(c) replots the tensile flow curves after normalization by the mean Taylor factor, in order to remove the influence of the crystallographic texture on the anisotropy. The resulting curves still show significant differences, highlighting the fact that the crystallographic texture of the material only contributes partly to the mechanical anisotropy, and that the microstructural anisotropy should also be taken into account [23].

5 Conclusions

1) The tensile flow curves of samples annealed at 528 K for 4 h show clear development of a yield point, which is attributed to the lack of mobile dislocations. The magnitude of the observed yield drop varies with angle between RD and the tensile testing axis, and is demonstrated to be related to the relative proportion of grains with soft orientations under each testing condition.

2) A significant anisotropy with regard to ductility is found in the samples annealed at 558 K for 2 h, with the elongation increasing in the sequence of 45°, 30°, 90° and 0°. It is found that the anisotropy in elongation is in general agreement with a Considère criterion analysis.

3) It is demonstrated that the poor mechanical properties of samples tested at 45° to RD may be attributed to a strong rolling texture effect. Further analysis shows that the crystallographic texture contributes only partly to the mechanical anisotropy in the samples, and microstructural anisotropy is also needed to be taken into account.

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退火超细晶纯铝的拉伸性能各向异性及相关屈服点现象

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摘要: 经退火处理的超细晶纯铝 AA1090 在拉伸试验中表现出明显的屈服点现象及力学性能的各向异性。为进一步解释该材料的拉伸性能各向异性, 利用电子背散射衍射技术对退火处理后材料的取向信息进行分析。结果表明, 沿与轧制方向成 45° 的拉伸试样所呈现出的较差的力学性能归因于强轧制织构的作用, 并且各方向屈服下降的程度与试样中软取向晶粒(Schmid 因子 >0.45)的百分比相关。另外, 伸长率各向异性大致符合 Considère 准则; 运用晶体学织构只能解释部分的力学性能各向异性行为, 同时还需考虑显微组织结构各向异性的作用。

关键词: 超细晶铝; 回复退火; 力学性能各向异性; 屈服下降; 延展性

(Edited by Bing YANG)