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LETTER

Effects of short aging on thickening anisotropy of θ' precipitate and mechanical properties of severe cold-rolled 2519A aluminum alloy plate

Xin-ming Zhang · Zhi-guo Gao · Yi-sheng Zhao

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The commercial 2519 aluminum alloy is a primary material for structural components of aircrafts, helicopters, and amphibians because of its low specific density, which favors the selection of aluminum alloys in weight-critical applications [1, 2]. To promote the mechanical properties of the alloys, severe plastic deformation (SPD) processes were explored such as equal channel angular pressing and severe cold rolling (SCR) [3–8]. However, 2519A aluminum alloy for a new version of Al–Cu alloy was developed as armor material and scarcely fabricated by SPD processes. Valiev has reported that alloys produced by the SPD processes have increased strength with limited ductility [9]. The increase in strength of 5083 aluminum alloy is always accompanied by a loss in ductility [10]. A combination of equal channel angular pressing and low-temperature aging resulted in significant improvements in both ultimate tensile strength (UTS) and ductility in AA6061 and Al–10%Ag alloy [11, 12]. Short age was scarcely utilized for improving the mechanical properties of the aluminum alloy plate. In this letter, for the first time, short aging treatments are performed to balance UTS and ductility of severe cold-rolled (SCRed) 2519A aluminum alloy.

The 2519A alloy plates quenched were rolled from 10 mm to no more than 3 mm in thickness. The total thickness reduction (70–90%) was achieved in multiple passes, with about 10% reduction per pass. The aging temperature of the SCRed aluminum alloy was identified using a differential scanning calorimeter (DSC). Uniaxial tensile tests were conducted at an initial strain rate of $3 \times 10^{-4}\ s^{-1}$ on SCRed and short-aged (SA) samples along rolling direction. Microstructural observations were carried out using Tecnai G^2 20 TEM and Sirion 200 SEM.

Transmission electron microscopic (TEM) images corresponding to three considered rolling reduction rates are shown in Fig. 1. Cellular structure is observed due to high dislocation density deformed during SCR process regardless of the reduction rate. Dislocation tangle is found in SCRed plates, which were attributed to cross slide (Fig. 1a–c). In fact, there is no obvious difference between three images corresponding although to three different rolling reduction assignments of SCRed plates. However, the fracture surfaces of SCRed plates showed significant differences between each others. The increased sizes of microdimples were found with the increasing rolling reduction rates although in the existence of large dimples (Fig. 2a–c), which could be correlated to the effects of reduction rate on particle sizes.

To identify an appropriate aging temperature, DSC experiments were carried out. Figure 3 shows the DSC trace for the SCRed aluminum alloy. From the DSC curve, the onset of aging temperature has been estimated to be 458 and 503 K. For achieving stable microstructures, the SCRed samples underwent short aging treatments for 20 min.

TEM images of 2519A alloy short aged at 458 K corresponding to the three different rolling reduction rates are shown in Fig. 4. Only in the sample short aged at 458 K for 20 min corresponding to the rolling reduction rate of 70% (Fig. 4a), thickening anisotropy of θ' precipitate on $\{100\}_{Al}$ is observed. A similar result is not found in Fig. 4b and c, corresponding to the rolling reduction rate of 80 and

X. Zhang (✉) · Z. Gao · Y. Zhao
School of Materials Science and Engineering, Central South University, Changsha 410083, People's Republic of China
e-mail: xmzhang_cn@yahoo.cn

Y. Zhao
Shenzhen Polytechnic, Shenzhen 518055, People's Republic of China

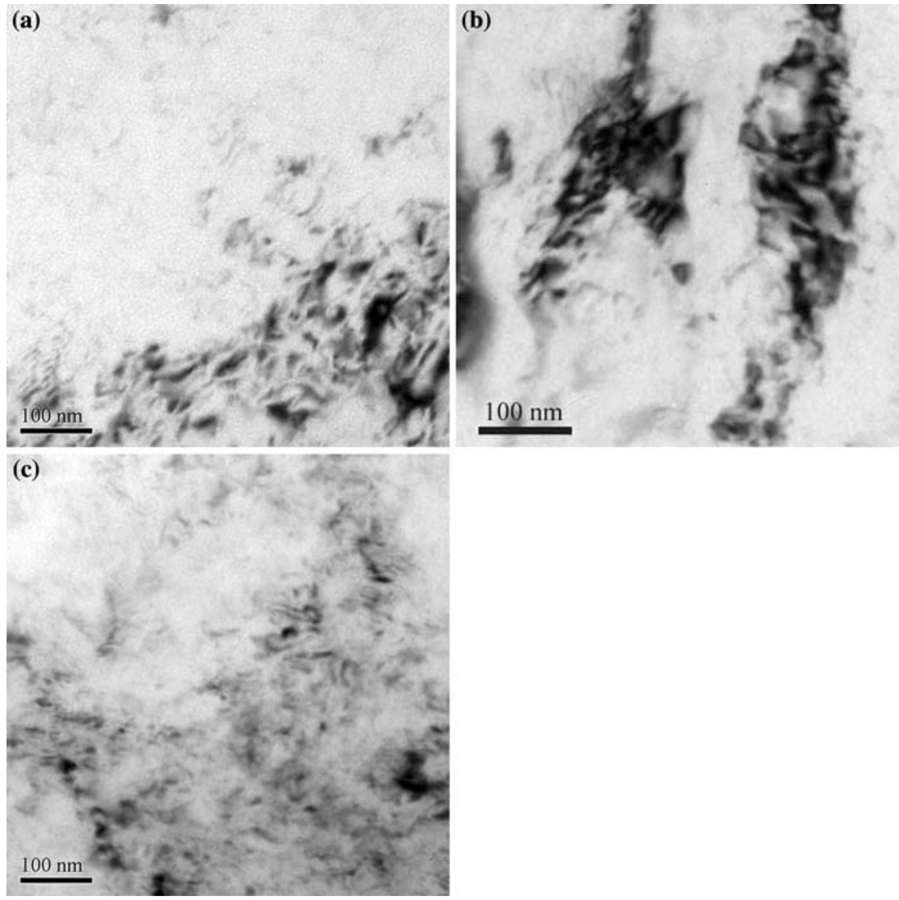


Fig. 1 TEM bright-field images of SCRed 2519A alloy corresponding to the rolling reduction rates of **a** 70%, **b** 80%, and **c** 90%

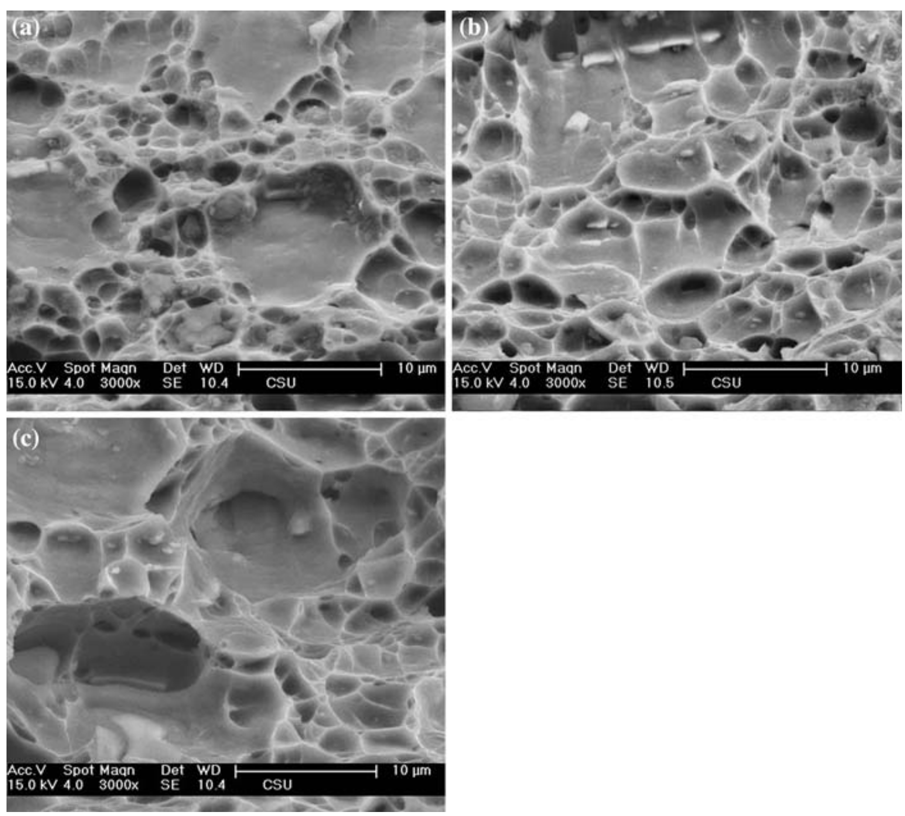


Fig. 2 SEM images of the fracture surface of SCRed 2519A alloy corresponding to the rolling reduction rates of **a** 70%, **b** 80%, and **c** 90%

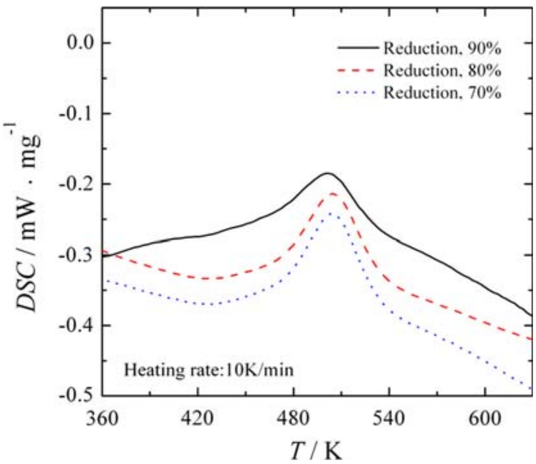


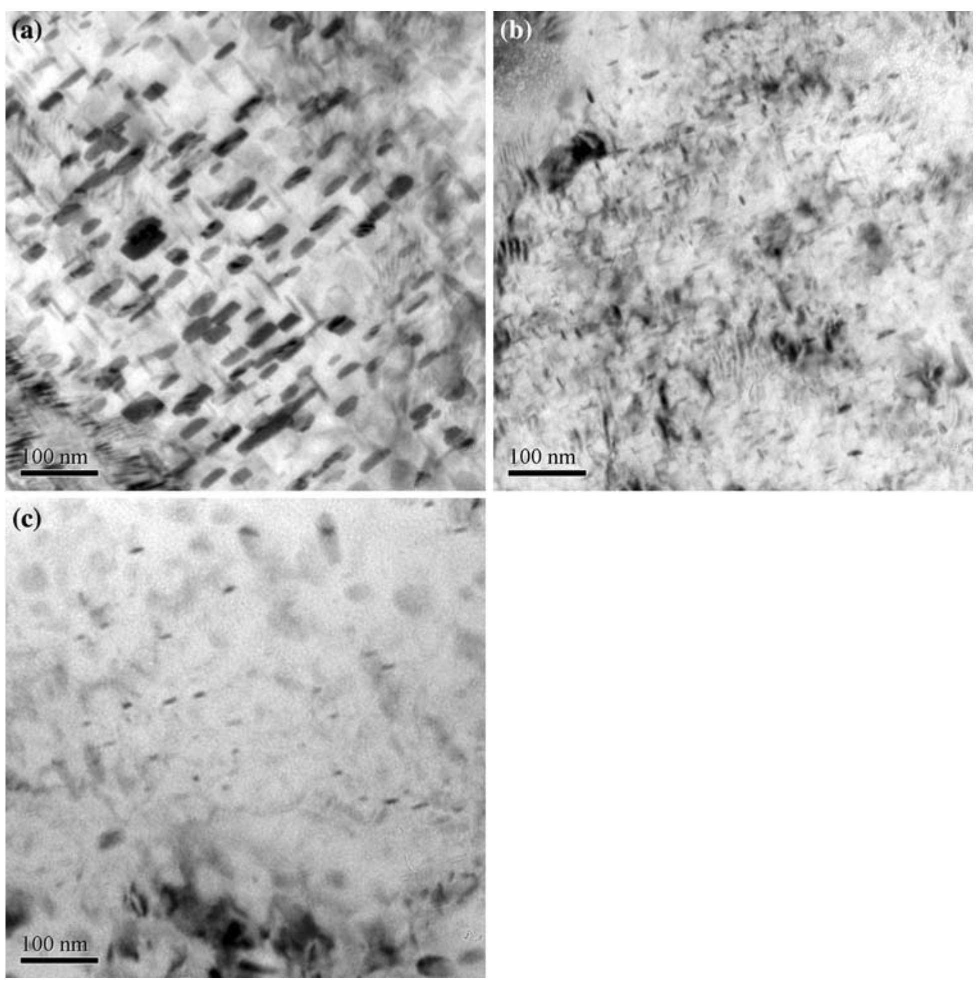
Fig. 3 DSC curve for SCRed 2519A aluminum alloy

90%, respectively. It is suggested that the increasing SCR reduction rates inhibit thickening anisotropy of θ' precipitate.

TEM images of 2519A alloy short aged at 503 K corresponding to the three different rolling reduction rates are shown in Fig. 5. Only in the alloy short aged at 503 K for 20 min corresponding to the rolling reduction rate of 70% (Fig. 5a), thickening anisotropy of θ' precipitate on $\{100\}_{Al}$ is again observed. Figure 5b and c shows slight thickening anisotropy of θ' precipitate on $\{100\}_{Al}$, corresponding to the rolling reduction rate of 80 and 90%, respectively. This demonstrates that $(100)_{Al}$ precipitate thickening, whose fast crystallographic growth directions are aligned with the fast geometric thickening direction, have a thickening advantage over other crystallographic planes of $\{100\}_{Al}$, and the planes will determine the final thickening orientation of the precipitate. Thickening anisotropy is expressed in terms of the thickness ratio, R ($\geq$1), of the θ' precipitates on two different visible crystallographic planes. The determined R is listed in Table 1. The greater the reduction rate, the lower the R value. The higher the considered short-age temperature, the quicker the thickening anisotropy of θ' precipitate.

Tensile tests were carried out on the SCRed and SA samples. The determined mechanical properties of the

Fig. 4 TEM bright-field images of 2519A alloy short aged at 458 K corresponding to the rolling reduction rates of **a** 70%, **b** 80%, and **c** 90%



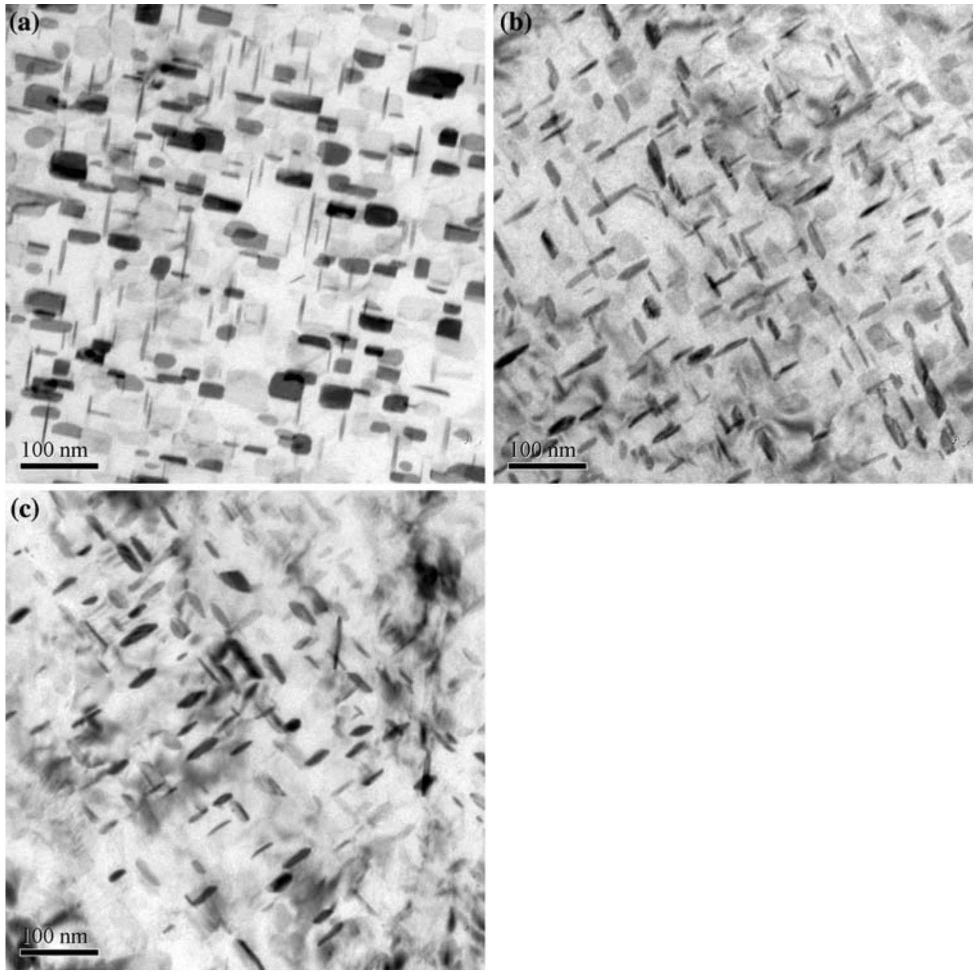


Fig. 5 TEM bright-field images of 2519A alloy short aged at 503 K corresponding to the rolling reduction rates of **a** 70%, **b** 80%, and **c** 90%

Table 1 Determined *R* of θ' precipitate in samples short aged at 458 and 503 K

Short aging	Reduction rate (%)	Determined *R*
At 458 K for 20 min	70	2.0
	80	–
	90	–
At 503 K for 20 min	70	3.0
	80	1.5
	90	1.1

SCRed and SA samples as functions of reduction ratio are shown in Fig. 6. Inevitably, short aging and thickening anisotropy of θ' precipitates lead to changes in mechanical properties of 2519A alloy. Figure 6a shows that SCRed samples have exceeding UTS (528–579 MPa, corresponding to black bar). With increasing reduction rate, UTS value increases sharply, while the ductility decreases. Figure 6b shows that the ductility (4.3–2.2% elongation, corresponding to black bar) of SCRed samples is poor. UTS (536–548 MPa) and ductility (10–12.6% elongation) of SA samples as functions of reduction rate are shown (corresponding to red bar) in Fig. 6a and b, respectively. Short aging at 458 K for 20 min leads to a good combination of UTS and ductility due to dynamic recovery. Hence, SCR by 80% followed by short aging at 458 K for 20 min are believed to be a promising way to obtain a good combination of UTS and ductility. For short aging at 503 K for 20 min, the corresponding UTS (429–445 MPa) and ductility (7–9% elongation) was shown in Fig. 6 (corresponding to blue bar). These results were not expired due to thickening anisotropy of θ' precipitate and the disappearance of SCR texture. The semi-coherent θ' precipitate transformed gradually into coherent θ phase.

The researched results identified that the higher the considered short aging temperature, the quicker the thickening anisotropy of θ' precipitate. The rolling reduction rate of 70% was more prone to thickening anisotropy of θ' precipitate than the others. Short aging at 458 K for 20 min is believed as a desired process for gaining a good combination of UTS (540 MPa) and ductility (12.6% elongation) of SCRed 2519A alloy followed by 80% reduction

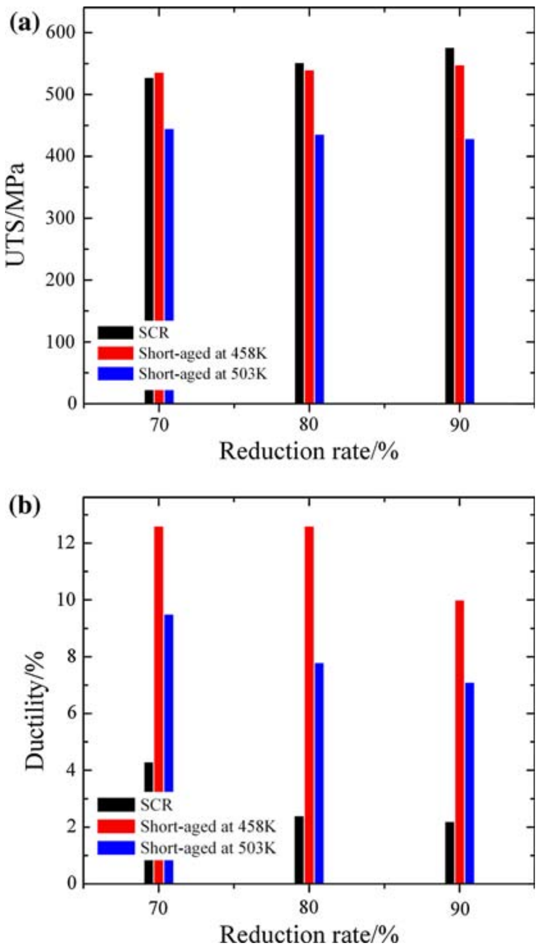


Fig. 6 **a** UTS and **b** ductility of SCRed and SA samples as functions of reduction rate

rate. Short aging at 503 K led to the bad mechanical properties of 2519A alloy due to thickening anisotropy of θ' precipitate regardless of reduction rates.

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