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Enhancing strength and electrical conductivity of pure aluminum by microalloying with telluride

Zhuang Du, Jinwen Ye*, Lufei Yang and Jiteng Zhang

Center for Rare Earth and Vanadium-titanium Based Materials, School of Materials Science and Engineering, Sichuan University, Chengdu, 610065, People’s Republic of China

* Author to whom any correspondence should be addressed.
E-mail: yjw550@163.com

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Abstract

The effects of Te addition on the microstructure, strength and electrical conductivity of pure aluminum were investigated, for improving the strength and electrical conductivity of resulting alloys. It was found that the tensile strength and electrical conductivity of the studied alloys increased by 25.8% and 2.8%, respectively, compared with those for pure aluminum (58 MPa and 62.06% IACS), respectively, by adding 0.1 wt% Te. Several mechanisms may account for the observed improvement of the alloys’ strength and electrical conductivity. First, Te addition can refine the grain size of pure aluminum by introducing more nucleation sites and suppressing grain growth through boundary precipitation. Second, the precipitation morphology changes from fine-needle or sheet-like to ellipsoidal shapes, likely improving the alloys’ tensile properties. Finally, Te can purify the melts by forming Al-Te-Fe-Si intermetallics at the grain boundaries, likely reducing the lattice distortion and increasing the electrical conductivity.

1. Introduction

The ever-increasing price of copper over the past several decades has resulted in a continued increase in the copper cables’ cost. Aluminum (Al), which is cost-effective, lightweight and highly electrically conductive, is widely used as a conductor material for replacing copper [1–3]. However, pure Al with high electrical conductivity usually exhibits low tensile strength, which significantly limits its application [4, 5]. Therefore, Al alloys with high electrical conductivity and strength are very much desired.

Previous studies have reported that solution hardening and segregation enhancement can remarkably increase the tensile strength of Al, but reduce its the deformation capacity and conductivity [6–10]. Therefore, a microalloying method that uses a small amount of alloying elements to form nanosized second-phase particles was proposed to improve the tensile strength and ensure high conductivity of pure Al [11, 12]. In addition, owing to their low solubility in the Al matrix, rare-earth (RE) elements are usually selected as microalloying elements [13–15]. Previous studies reported that La, Ce and Er could improve the tensile strength of Al samples but were likely to slightly reduce their electrical conductivity [16–19]. Guan et al [20] found that the strength and electrical conductivity of alloys can be significantly improved by adding Sc. However, the high cost of Sc has prevented the use of Al-Sc alloys in this field [21]. As one of the microalloying elements, tellurium (Te) is cheaper than RE elements, and has been widely used in the metallurgy field; for example, adding in conductive copper alloy to enhance its tensile strength and electrical conductivity [22]. However, the effect of Te on the tensile properties and electrical conductivity of pure Al has not been reported.

The objective of this work was to determine ways for improving the tensile properties and electrical conductivity of Al alloys by adding Te. The influence of the microstructure of the Al–Te alloy and the relationship between the microstructure and the alloy properties were also explored and constructed.
2. Experimental

The studied Al-xTe (x = 0, 0.05, 0.1, 0.15, 0.2, 0.3, wt%) ingots were prepared in a resistance furnace (SG2-7.5) with an Al-5 wt%Te master alloy as a Te source, which was added to a premelted pure Al (99.7 wt%) at 740 °C for 40 min. After thorough stirring, the resulting alloy melt was poured into an iron mold preheated to 160–200 °C with the dimension of 110 × 100 × 40 mm³. The compositions of the alloys, assessed using an inductively coupled plasma-atomic emission spectrometer (ICP-AES), are listed in table 1. The metallurgical specimen was cut off from the middle of the casting, and the surface was etched using Keller’s solution (2 ml HF, 3 ml HCl, 5 ml HNO₃, and 190 ml H₂O) for approximately 30 s at room temperature. The phase composition was confirmed by x-ray diffraction (XRD, DX-2000) at a scan speed of 0.06° s⁻¹. The microstructure was characterized using a metallurgical microscope (4XC-E), a scanning electron microscope (SEM, JSM-7500F), a transmission electron microscope (TEM, Tecnai G2 F20 S-TWIN), and an energy dispersive spectrocope (EDS) with SEM and TEM was used for the phase composition analysis. The average grain size was estimated using the line interception method using Image-Pro Plus software [23, 24]. The grain grade formula is:

\[ G = 3.321928 \log_{10} n_a - 2.954 \]

where \( G \) represents the grade of the grain size and \( n_a \) is the number of grains in one square millimeter.

The tensile properties were tested using a universal testing machine (WDW-50E) at a rate of 3 × 10⁻³ s⁻¹ according to the GB/T 288.1–2010 standard. The geometric dimensions of the tensile specimens are shown in figure 1. At least six samples were tested for each composition. The specimens’ elongation was assessed by measuring the length change in the gauge section, before and after tension. The electrical conductivity was tested using an eddy current conductance meter (FQR7501B) at room temperature, according to the ASTM E1004 standard [25], based on the following formula:

\[ \text{IACS} = \frac{\omega_{\text{Al}}}{\omega_{\text{Cu}}} \times 100\% \]

where \( \omega_{\text{Al}} \) and \( \omega_{\text{Cu}} \) are the conductivities of the Al alloy and annealed pure copper (58 MS/m), respectively.

3. Results and discussion

3.1. Effects of Te on the microstructure of Al-Te alloys

The refining effect of Te on the as-cast Al can be observed clearly from the metallographic photos and average grain size, as shown in figures 2 and 3. The coarse columnar grains in pure Al samples (figure 2(a)) gradually disappeared and were replaced by a set of equiaxed grains as the Te content increased (figures 2(b)–(f)). When the Te content increased from 0 to 0.05 wt%, the average grain size rapidly decreased from 110 μm to 179 μm.
Further increasing the Te content to 0.1 wt%, the average grain size reduced to 158 μm. Nevertheless, the refining effect became less obvious and the grain degree remained almost the same when the amount of Te exceeded 0.1 wt%.

The primary phases in the Al-5Te master alloy are Al and Al₂Te₃, as shown in figure 4; the latter formed through the eutectic reaction of Te and Al [26]. Figure 5 shows the BSE images of pure Al samples and Al-xTe alloys, where a mass of fine white particles can be detected in the matrix after the addition of Te. The trend toward grain refinement is also observed for increasing Te contents in figures 5(b)–(d). To reveal the refining mechanism, the results of the elemental analysis of each point marked by the red arrows in figure 5 are listed in table 2 (Fe and Si are the impurity elements in these alloys). The precipitated phase at the boundary in pure Al consisted of Al, Fe and Si, while that in Al-xTe alloys was Al, Te, Fe and Si. Because the Al₂Te₃ phase crystallizes preferentially during solidification owing to its high melting point [26], and because the crystal parameters of

Figure 2. The micrographs of Al-Te alloys with different contents of Te: (a) 0, (b) 0.05 wt%, (c) 0.1 wt%, (d) 0.15 wt%, (e) 0.2 wt%, (f) 0.3 wt%.

Figure 3. The average grain size and grain degree with different content of Te.
Figure 4. XRD results for the Al-5Te master alloy.

Figure 5. BSE micrographs of the studied Al-Te alloys: (a) pure Al, (b) 0.1 wt% Te, (c) 0.2 wt% Te, and (d) 0.3 wt% Te. The insets are the high-magnification BSE images marked with blue arrows in (a) and (b), respectively.

Table 2. EDS results for each point marked by red in figure 5.

| Number | Al/\text{at}\% | Fe/\text{at}\% | Si/\text{at}\% | Te/\text{at}\% |
|--------|---------------|---------------|---------------|---------------|
| 1      | 81.95         | 17.36         | 0.70          | —             |
| 2      | 90.58         | 6.24          | 2.82          | 0.36          |
| 3      | 86.28         | 10.30         | 2.21          | 1.21          |
| 4      | 84.01         | 11.94         | 1.31          | 2.74          |
Al₂Te₃ (4.088 Å) are very similar to those of Al (4.049 Å), the Al₂Te₃ phase likely can serve as an effective nucleation point for improving the nucleation rate, which is one of the important reasons for grain refinement.

The amount of Al-Te-Fe-Si precipitations at grain boundaries increased with increasing the Te content from 0.1 wt% to 0.3 wt%, implying that the contents of Fe and Si in the Al matrix increased, compared with pure Al. This happened owing to the Te atoms segregating at the liquid-solid interface, which restricted the flow of Fe and Si solutes from the liquid phase to the solid phase during solidification. As the solubility of Te in the Al matrix is extremely low, this resulted in constitutional undercooling, which made nucleation easier [27, 28]. Therefore, Te effectively promoted nucleation and markedly refined the grains. However, a higher Te content caused serious aggregation of the Al₂Te₃ phase and decreased the number of refined grains.

The insets in figure 5 show the morphology evolution of the second phase with the addition of Te, where the size of the second phase decreased significantly and its morphology changed from fine-needle-like to ellipsoidal-like when the added Te content reached 0.1 wt%. The morphology of the second phases can be estimated using the two-phase equilibrium formula (3) [29]:

$$\cos \left( \frac{\theta}{2} \right) = \frac{\sigma_{\alpha\alpha}}{2\sigma_{\alpha\beta}}$$

where $\sigma_{\alpha\alpha}$ is the surface tension of the Al melt, and $\sigma_{\alpha\beta}$ is the interfacial tension between the Al matrix and the second phase. Adding Te to an Al alloy as a surface-active element can effectively reduce the value of $\sigma_{\alpha\alpha}$. The value of $\sigma_{\alpha\beta}$ depends mainly on the stability of the second phases. Moreover, the larger Te atomic radius (1.60 Å) compared with those of Fe (1.27 Å) and Si (1.34 Å), results in the formation of a highly stable Al-Te-Fe-Si compound. Thus, $\sigma_{\alpha\beta}$ increases dramatically owing to the addition of Te, which increases the value of $\theta$. Therefore, the second phase tends to grow ellipsoidal.

Figure 6 shows the XRD patterns of pure Al and Al-0.1Te. It can be seen that the pure Al and Al-0.1Te spectra are composed of diffraction peaks of $\alpha$-Al phases, while minor phases were not detected in these XRD spectra because the amount of Fe, Si and Te were low. The diffraction peaks slightly shift to right following the addition of Te at 0.1 wt%, implying that the contents of Fe and Si in the Al matrix increased, compared with pure Al. Since the atomic radius of Te is larger than that of Al, the solubilization of Te atoms in the Al matrix increases the lattice constants. So, by contradiction we conclude that the added Te was not completely dissolved in the Al matrix. It was previously reported that Fe and Si would form a pseudo-solid solution in the Al matrix, owing to non-equilibrium solidification. The decrease of the d value means that there are fewer solution-related Fe and Si atoms [23], which is consistent with the XRD analysis results.

The EDS maps of the pure Al and Al-0.1Te alloys are shown in figure 7. It can be observed that the distribution of Fe and Si elements is more obvious around Te compared with pure Al, indicating the absorptive effect of Te on Fe and Si, which promotes the formation of Al-Te-Fe-Si precipitates during the nucleation formation and growth of $\alpha$-Al. Thus, combined with XRD and BSE mapping, Te acts to purify the Al matrix.

To further validate the proposed analytical results, the TEM morphology of the Al-0.1Te alloy is shown in figure 8. Evidently, fine black ellipsoid phases are discontinuously distributed at their grain boundaries (figure 8(a)). The size of the precipitate is 300–500 nm. At the same time, a small number of dislocation entanglements exist around the precipitates (figure 8(b)). Figure 8(c) indicates that the crystal pattern of the
precipitated phase is very close to that of the FeAl2 phase, based on the selected electron diffraction pattern. Combining the EDS results in figure 8(d), it is observed that Te forms complex intermetallics with Fe and Si. Thus, these results validate the previous analysis.

3.2. Effects of Te on the tensile strength and elongation of pure Al.
Figure 9 shows the engineering stress-strain curves for the studied alloys with different Te contents. Figure 10 illustrates the tensile properties of casting Al alloys with different Te contents. The tensile strength initially increased and reached a maximum value of 73 MPa at 0.1 wt% Te, about 25.8% higher than that without the Te addition, and then decreased with further increasing the Te content. Simultaneously, the elongation of the
as-cast alloys with different Te contents showed a similar trend, and the highest elongation was obtained at 0.05 wt% Te.

The strengthening mechanisms in polycrystalline materials, including solid-solution hardening, grain-boundary hardening, dislocation hardening, and precipitation hardening operate independently, and the yield strength can be expressed as a simple summation of the following individual contributions \[32\]:

\[
\sigma_y = \sigma_0 + \sigma_{gs} + \sigma_p + \sigma_s + \sigma_d
\]

where \(\sigma_y\) is the yield strength, \(\sigma_0 \approx 10\) MPa is the Peierls–Nabarro stress \[32\], \(\sigma_{gs}\) is the contribution of the fine crystal reinforcement, \(\sigma_p\) is owing to the precipitation-related hardening, \(\sigma_s\) is owing to the solution strengthening, and \(\sigma_d\) is the dislocation strengthening. TEM observations indicated that the dislocation density was very low in the Al matrix; thus, the dislocation strengthening term was sufficiently small and could be ignored. Meanwhile, based on the Hall–Petch formula where \(\sigma_{gs} = Kd^{-1/2}\) and \(K = 0.10\) MPa m \(^{1/2}\) \[32\], the fine crystal-related reinforcement was calculated to be \(\sigma_{gs} = 8\) MPa (Al-0.1Te). In addition, plastic deformation is related to the dislocation motion of the Al alloy \[33\]. Precipitation in the matrix can hinder the dislocation motion and can improve the alloy’s strength. Furthermore, compared with the needle flake phase, the ellipsoidal shape phase can effectively reduce the stress concentration. Thus, \(\sigma_s\) and \(\sigma_d\) can be estimated using equation \(3\), and the value increases with the increase of the Te content (table 3). The findings indicate that the strength...
The increase of the alloy is mainly owing to the grain refinement-related strengthening, solution-related strengthening and precipitation-related strengthening.

Figure 11 shows the fracture morphology of the tested samples. Figure 11(a) shows that pure Al exhibited intergranular microporosity fractures with dimples. When the Te content was 0.05 wt%, the fracture behavior of the alloy was mainly dimple gliding. As the Te content increased from 0.1 wt% to 0.2 wt%, many irregular spheroidal particles (indicated by the red arrows) were observed in figures 11(c)–(e). The magnified image and the EDS result in the inset of figure 11(c) show that these spheroidal particles are oxidized inclusions, which can contribute to the crack initiation and reduced elongation. Further increasing the Te content to 0.3 wt%, a mass of banded structure oxide inclusions (the EDS results in the inset of figure 11(f)) agglomerated together to form coarsened clusters. The stress concentration effect became serious, resulting in a rapid decrease in the alloys’ tensile properties.

### 3.3. Effects of Te on the electrical conductivity of pure Al

Figure 12 shows the electrical conductivity of the studied alloys, for different Te contents. The electrical conductivity initially increased with the Te addition, achieved the highest value of 63.79% IACS at 0.1 wt% Te (which is 2.8% higher compared with that for pure Al), and then decreased. Defects in metallic materials could lead to electron scattering, which would significantly affect the electrical resistivity of alloys [34]. The Matthiessen’s rule can be expressed as:

\[
\rho = \rho_{\text{pure}} + \rho_{\text{ss}} + \rho_{\text{ppt}} + \rho_{\text{gb}} + \rho_{\text{mix}}
\]

where \(\rho_{\text{pure}}\) is the resistivity of pure Al, \(\rho_{\text{ss}}\) is the resistivity owing to the solution atoms, \(\rho_{\text{ppt}}\) is the resistivity of the precipitated phase, \(\rho_{\text{gb}}\) is the resistivity of dislocations, \(\rho_{\text{gb}}\) is the resistivity owing to the grain boundaries, and \(\rho_{\text{mix}}\) is the resistivity owing to inclusions. It should be noted that \(\rho_{\text{ss}}\) has a marked influence on the resistivity of Al.
alloys \[35, 36\], and the influence of dislocation on resistivity $\rho_d$ is negligible. In particular, the increased resistivity caused by solid solution atoms is much greater than that of the precipitated phase \[37\]. According to the previous analysis, the Fe and Si atoms form precipitation phases at grain boundaries owing to the Te addition, decreasing the dopant solid solubility and lattice distortion. Thus, the dominant factor $\rho_{ss}$ decreased significantly. On the other hand, the grains gradually refined and the second phase increased with the Te addition, causing $\rho_{gb}$ and $\rho_{ppt}$ to increase slightly. Based on the interaction of all these factors, the electrical conductivity was concluded to be the highest at 0.1 wt% Te. Therefore, the proper amount of Te addition is critical for improving the electrical conductivity of Al-Te alloys. A comparison of the tensile strength and electrical conductivity of the Al-0.1Te and other Al alloys reported in the literature \[3, 16, 17, 38\] is shown in figure 13, indicating that a good balance between the tensile strength and conductivity was achieved by adding 0.1 wt% Te.

4. Conclusion

In this work, the effects of Te addition on the tensile strength and electrical conductivity of Al were investigated. It was found that Te addition can refine the grain size of pure Al, improve the morphology of the precipitate, and purify the melt. The average grain size of $\alpha$-Al decreased from 1100 $\mu$m to 158 $\mu$m after adding 0.1 wt% Te. The morphology of the second phase changed from fine-needle to ellipsoidal shapes, and Te alloyed with impurity...
elements such as Fe and Si, forming Al-Te-Fe-Si intermetallics at the grain boundaries rather than a solid
solution in the Al matrix. By adding 0.1 wt% Te, the tensile strength and electrical conductivity improved from
58 MPa and 62.06% IACS to 73 MPa and 63.79% IACS, respectively.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Jinwen Ye https://orcid.org/0000-0002-0409-250X

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