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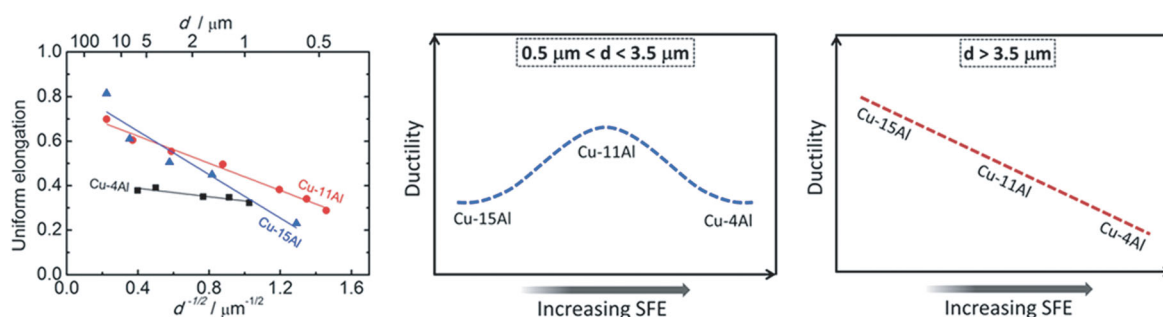
Ductility Sensitivity to Stacking Fault Energy and Grain Size in Cu–Al Alloys

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Tensile strength of Cu–Al alloy is prominently enhanced by decreasing the stacking fault energy (SFE). In contrast, the uniform elongation (UE) depends strongly on the SFE and grain size. With decreasing the SFE, the UE of the Cu–Al alloy becomes increasingly sensitive to the grain size. In the coarse-grained regime, the UE is monotonically enhanced with decreasing the SFE, but in the fine-grained regime, the Cu–Al alloy with the medium SFE displays the highest UE. Strain-hardening behavior is investigated to clarify the ductility sensitivity to the SFE and grain size in the Cu–Al alloys.



Keywords: Cu–Al Alloy, Stacking Fault Energy (SFE), Grain Size, Ductility, Strain-hardening

It is well known that strength and ductility always display a tradeoff in many metallic materials.[1] In this study, the ductility is defined as uniform elongation (UE) which describes well the capability of homogeneous plastic deformation under tension. Recent studies indicate that severe plastic deformation (SPD) can significantly enhance the yield strength but sacrifice the ductility due to the early plastic instability during tensile test.[2–4] Thus, it is significantly important to study the mechanisms for ductility enhancement. In fact, efforts on ductility improvement were made and intriguing results have been reported.[5–8]

The ductility (especially UE) is governed by the strain-hardening rate and true stress according to the Considère criterion.[9] It is frequently observed that

the UE can be improved with increasing the grain size in many materials systems.[1,10] In parallel, recent studies show that the face-centered cubic (FCC) alloys with low stacking fault energy (SFE) draw good balance of strength and ductility.[6,11–13] In FCC materials, it is known that SFE can affect the deformation mechanisms significantly.[14–16] When the SFE is high, dislocation slip in the wavy mode dominates the plastic deformation.[17] In contrast, when the SFE is low, dislocation slip in the planar mode dominates and dislocation recovery will be inhibited; besides, stacking faults (SFs) and deformation twins (DTs) prevail.[15,18] Thus SFE should impact crucially on the ductility of FCC alloys via determining the strain-hardening behavior.

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The effects of SFE on the tension/compression deformation mechanisms have been studied in different kinds of FCC materials, but the grain sizes always fell in the coarse-grained regime.[19–21] In contrast, fully recrystallized twinning-induced plasticity steels and Cu–Al alloys with grain sizes smaller than 1 μm have been fabricated by cold rolling and annealing process,[18,22,23] which makes it feasible to study the ductility and deformation mechanisms from the fine-grained regime to the coarse-grained regime.

In the present study, the starting materials are Cu–4.4 at.%Al alloy (defined as Cu–4Al), Cu–10.8 at.%Al alloy (defined as Cu–11Al) and Cu–14.7 at.%Al alloy (defined as Cu–15Al). Their SFEs are 32, 10 and 7 mJ/m^2 , respectively, according to previous reports.[24–26] All the Cu–Al alloys were firstly cold rolled and then annealed in a salt bath to give grain sizes of 0.5–20 μm . Tensile specimens with gauge length of 10 mm, width of 5 mm and thickness of 1 mm were cut by electrical discharge machine. Tensile tests were conducted at an initial strain rate of $8.3 \times 10^{-4} \text{ s}^{-1}$ at ambient temperature. Tensile strain was accurately measured

by using an extensometer until necking. Transmission electron microscopy (TEM) characterization was conducted using a JEOL 2010 operated at 200 kV. TEM foils were cut from the tensile specimens and the observation direction is parallel to the normal direction of the tensile specimen.

Figure 1(a)–(c) demonstrate the engineering stress–strain curves of the three kinds of Cu–Al alloys. Figure 1(d) and 1(e) show the plots of the ultimate tensile strength (UTS) and UE against the inverse square root of grain size. At a given grain size, it is interesting to find that the UTS can be enhanced monotonically with decreasing SFE, as shown in Figure 1(d), which agrees well with previous reports.[15,22,27] In contrast, monotonic enhancement of the UE was not obtained, as shown in Figure 1(e), where four conclusions can be generally obtained. Firstly, the UE has a linear relationship with the inverse square root of grain size (Hall–Petch type) for each alloy, and the equations can be described as

$$\text{Cu} - 4\text{Al}: \varepsilon_{\text{UE},4\text{Al}} = 0.43 - 0.095 d^{-1/2}, \quad (1)$$

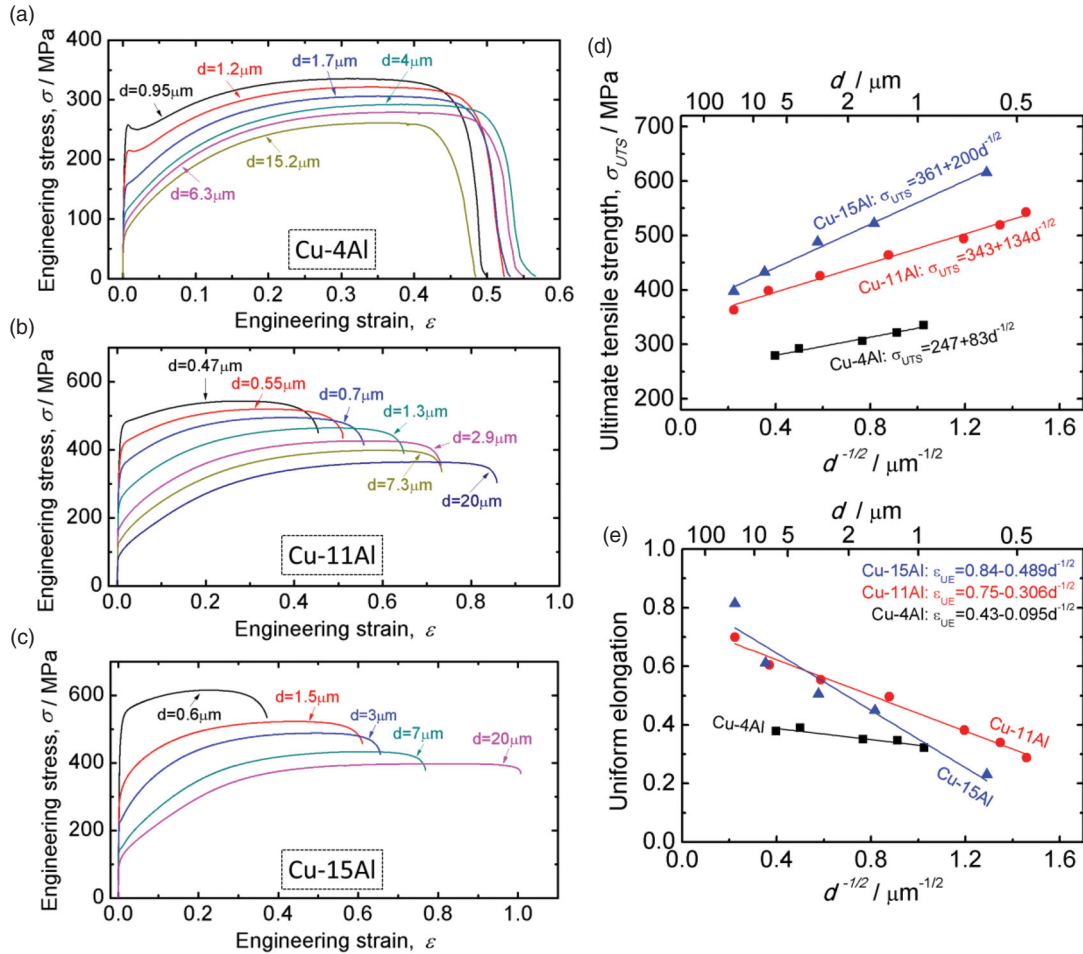


Figure 1. (a)–(c) Engineering stress–strain curves of the three Cu–Al alloys with different SFEs; Plots of (d) the ultimate tensile strength and (e) the UE against grain size for the Cu–Al alloys with different SFEs.

$$\text{Cu-11Al: } \varepsilon_{\text{UE,11Al}} = 0.75 - 0.306 d^{-1/2}, \quad (2)$$

$$\text{Cu-15Al: } \varepsilon_{\text{UE,15Al}} = 0.84 - 0.489 d^{-1/2}. \quad (3)$$

Note that the unit of the grain size d is micrometer and the unit of the slope of each line is $(\mu\text{m})^{1/2}$. Secondly, it is found that the slope of each line is sensitive to the SFE, indicating that the SFE plays a critical role in the ductility of the three Cu–Al alloys. Thirdly, the intercept values on the y axis of UE are 0.43, 0.75 and 0.84 for the Cu–4Al, Cu–11Al and Cu–15Al alloys, respectively, which are corresponding to the theoretical limits of UE of the three Cu–Al alloys. Fourthly, the Cu–11Al alloy has a higher UE than the Cu–4Al and Cu–15Al alloys when the grain size is smaller than about $3.5 \mu\text{m}$; in contrast, when the grain size is larger than about $3.5 \mu\text{m}$, the UE is monotonically ameliorated with decreasing the SFE. This gives rise to a question: what dominates the UE of Cu–Al alloys? In that case, tensile deformation mechanisms corresponding to the three Cu–Al alloys will be investigated.

Previous studies indicate that dislocation, SFs and DTs can contribute to the strength and plasticity in metals and alloys during plastic deformation.[12,13,18,20,26,28] After characterizing the microstructures after tensile tests, the deformation patterns of the Cu–Al alloys with different SFEs and grain sizes were summarized and schematically shown in Figure 2. When the SFE is higher than 30 mJ/m^2 , only dislocation configurations were detected during tensile test in this study when the grain size is larger than about $1 \mu\text{m}$. When the SFE is smaller than 30 mJ/m^2 , SFs and DTs emerge besides the dislocation slip in the Cu–Al alloy with a grain size that is larger than about $1 \mu\text{m}$. However, the deformation mechanisms are different in these low-SFE materials

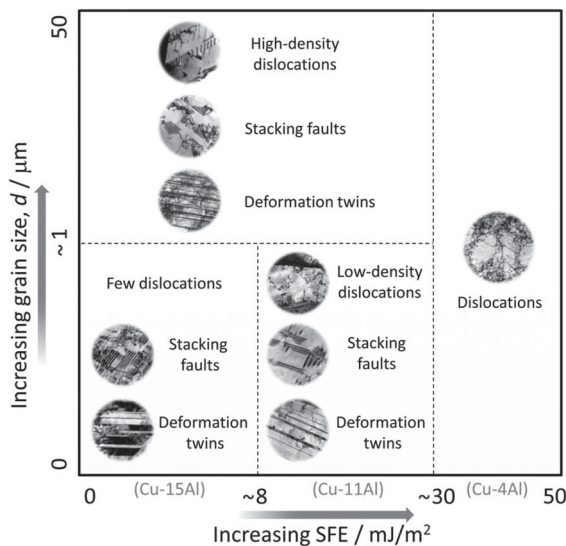


Figure 2. Tensile deformation mechanisms map of Cu–Al alloys with different SFEs and grain sizes.

when the grain size is smaller than $1 \mu\text{m}$. For example, when the SFE falls in the range of $8\text{--}30 \text{ mJ/m}^2$, low-density dislocations can still be observed besides the SFs and DTs. In contrast, only few dislocations can be detected when the SFE is smaller than 8 mJ/m^2 , but SFs and DTs play important roles in the tensile deformation process.[18] These different deformation mechanisms dominated by grain size and SFE are supposed to determine the strain-hardening behavior, thus the tensile plasticity of the Cu–Al alloys.

Typical true stress–strain curves and strain-hardening curves of Cu–Al alloys with different grain sizes and SFEs are compared and investigated, as shown in Figure 3. When the grain size is $0.55\text{--}0.95 \mu\text{m}$, the strain-hardening rate of the Cu–11Al alloy is slightly higher than the Cu–15Al alloy, but the flow stress of the Cu–11Al alloy is much lower, which collectively result in a higher ductility in the Cu–11Al alloy according to the Considère criterion.[9] For the Cu–4Al alloy, though the strain-hardening rate is the lowest among the three Cu–Al alloys, its ductility is comparable with the Cu–11Al alloy due to the lowest flow stress, as shown in Figure 3(a). When the grain size is increased to $1.2\text{--}1.5 \mu\text{m}$, the elongation of the Cu–4Al alloy increases slightly in contrast to that shown in Figure 3(a) due to the stable strain-hardening behavior; in comparison, the elongations of the Cu–11Al and Cu–15Al alloys are highly improved owing to the enhanced strain-hardening rate. It is valuable to note that the strain-hardening curves of the Cu–11Al and Cu–15Al alloys coincide very well at high tensile strains, thus the Cu–11Al alloy has a higher elongation than the Cu–15Al alloy due to the lower flow stress, as shown in Figure 3(b). Similar results are obtained when the grain size falls into the range of $2.9\text{--}4 \mu\text{m}$, as shown in Figure 3(c). When the grain size is further increased to $15.2\text{--}20 \mu\text{m}$, the elongation increases monotonically with decreasing the SFE, as shown in Figure 3(d). Careful inspection indicates that the strain-hardening curves move upwards with decreasing the SFE, which essentially leads to the continuous enhancement of elongation.

The mechanical properties as delineated above have clearly shown the variation of ductility with grain size and SFE. Though tensile strength and ductility are readily improved in FCC metallic materials with decreasing the SFE,[6,11–13] the ductility cannot be enhanced monotonically as shown in Figure 1(e). Thus the ductility sensitivity to the SFE and grain size was summarized and shown in Figure 4 in both the fine-grained regime and the coarse-grained regime. When the grain sizes of the Cu–Al alloys are smaller than $3.5 \mu\text{m}$, which are related to Figure 3(a)–(c), it is found that the Cu–11Al alloy retains higher ductility than the Cu–4Al and Cu–15Al alloys, as schematically shown in Figure 4(a). This

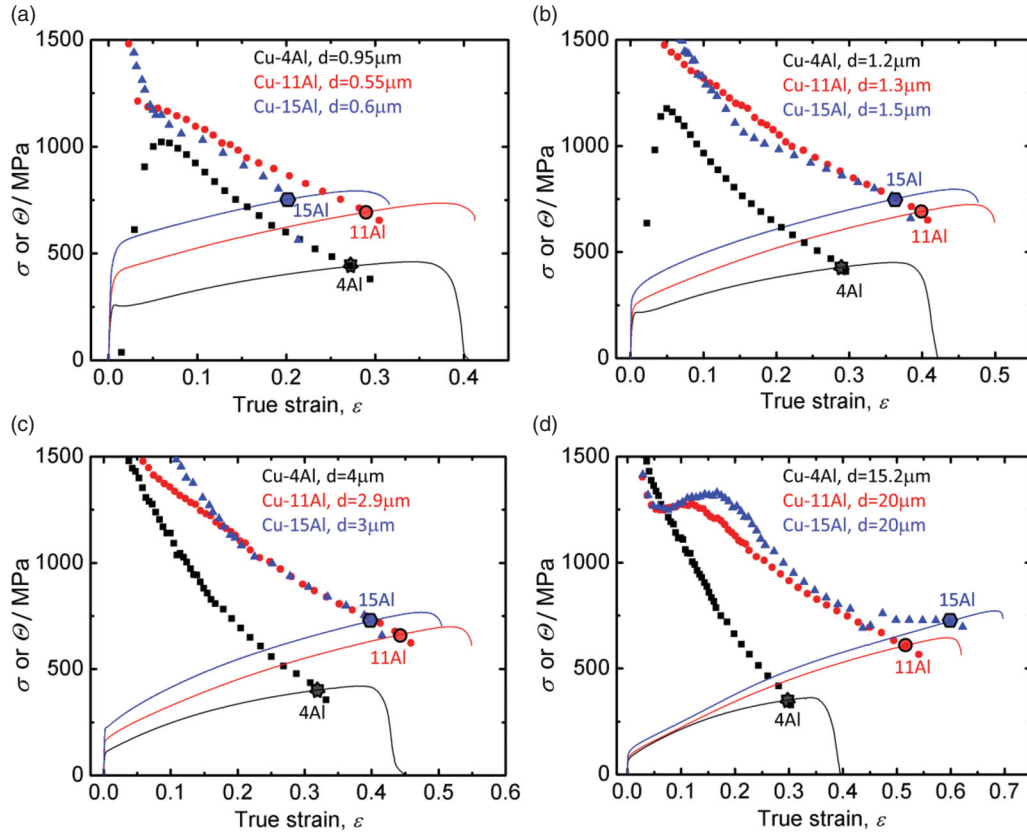


Figure 3. (Colour online) Typical strain-hardening curves and true stress-strain curves of Cu-Al alloys with different SFEs and grain sizes. The necking points are indicated. σ : true stress, Θ : strain-hardening rate.

result is unexpected since the SFE of the Cu-11Al alloy is medium among the three Cu-Al alloys, which will be discussed based on the strain-hardening curves and tensile curves. Firstly, the tensile deformation behavior will be compared between the Cu-4Al alloy and Cu-11Al alloy. For the Cu-4Al alloy with the highest SFE, the plastic deformation is dominated by dislocation slip and the strain-hardening rate decreases with strain, which is similar to pure Cu.[29] In addition, the strain-hardening curves keep stable with increasing the grain size, and the strain-hardening rate is always much smaller than the Cu-11Al alloy as shown in Figure 3(a)–(c), inducing a lower elongation in the Cu-4Al alloy than the Cu-11Al alloy.[27] Secondly, the tensile deformation behavior will be compared between the Cu-11Al alloy and Cu-15Al alloy. The strain-hardening rate of the Cu-15Al alloy is slightly lower than the Cu-11Al alloy when the grain size is about 0.6 μm , as shown in Figure 3(a), and the plastic deformation is largely undertaken by SFs and DTs since only few dislocations were detected in the Cu-15Al alloy.[18] When the grain size is further increased to 1.5 and 3 μm , it is found that the strain-hardening rates especially at the later tensile process are comparable between the Cu-11Al and Cu-15Al alloys, as shown in Figure 3(b) and 3(c), which may be related to the

dominating deformation modes of SFs and DTs.[18,27] It is observed that the flow stress of the Cu-15Al alloy is much higher than the Cu-11Al alloy as shown in Figure 3(a)–(c), thus resulting in a lower ductility in the Cu-15Al alloy though comparable strain-hardening rate is achieved. For the Cu-11Al alloy with a medium SFE, the high strain-hardening rate and medium flow stress collectively harvest the highest ductility among the three Cu-Al alloys. Note that all the materials discussed above are related to fully recrystallized materials with grain sizes larger than about 0.5 μm . When the grain size is further decreased, a sharp transition of the ductility may occur.[1,30,31] Take interstitial free steel as an example, when the mean grain size is 0.95 μm , a promising UE of 0.11 is obtained, but early plastic instability occurs when the grain size is further decreased to 0.85 μm , resulting in a drastic decrease of UE to 0.01.[31] However, it is reported that in Cu-Zn alloys with ultrafine-grained or nanocrystallized structures after high-pressure torsion processing, there exists an optimal medium SFE yielding the best ductility, which is consistent with the present results in the fine-grained regime.[3] In this study, fine-grained Cu-Al alloys are analyzed only when the grain size falls into the range of 0.5–3.5 μm since the ductility will be negligible when the grain size is smaller than

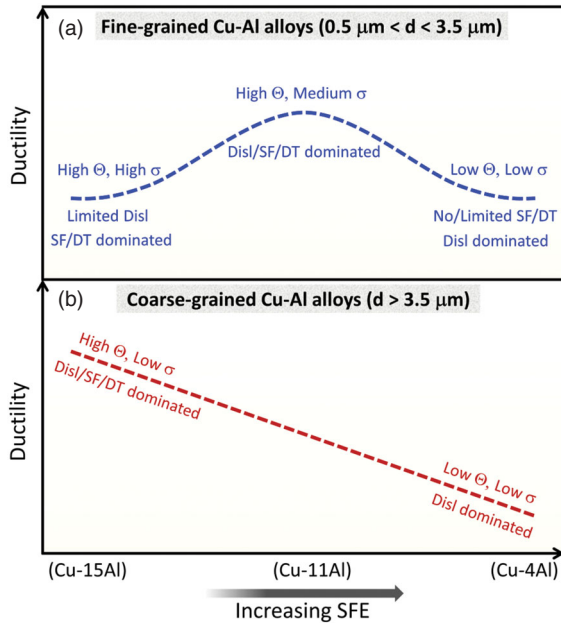


Figure 4. (Colour online) Schematic plots of ductility against SFE in the (a) fine-grained and (b) coarse-grained Cu–Al alloys with fully recrystallized structure. SF: stacking fault, DT: deformation twin, Disl: dislocation, σ : true stress, Θ : strain-hardening rate.

about $0.5 \mu\text{m}$ [15,22,25,30] in contrast to the annealed counterparts.

In the coarse-grained regime, the ductility of the Cu–Al alloys increases monotonically with decreasing the SFE, as schematically shown in Figure 4(b). Careful inspection in Figure 3(d) indicates that the strain-hardening curves shift upwards with decreasing the SFE while the tensile curves do not deviate much when the grain sizes fall into the range of $15.2\text{--}20 \mu\text{m}$. The low ductility of the Cu–4Al alloy is induced by the low strain-hardening rate owing to the dislocation-dominated deformation process. For the Cu–11Al alloy, dislocation slip governs at small strains but SFs and DTs tend to contribute with increasing the strain, as a result, the strain-hardening rate decreases more slowly than the Cu–4Al alloy, postponing the necking point to a higher strain. For the Cu–15Al alloy, the SFE is the lowest among the three alloys, indicating that dislocations can be accumulated most efficiently at small strains owing to the restrained recovery process.[15] With increasing the strains, SFs and DTs take part in the plastic deformation process and retain the high strain-hardening level.[18] Note that there is a plateau when the tensile true strain is larger than 0.45, which is supposed to be induced by twin intersections.[19] Above all, the monotonic increase of ductility with decreasing the SFE is mainly resulted from the continuous improvement of strain-hardening capability of the Cu–Al alloys.

In summary, fully recrystallized Cu–Al alloys with different SFE ($7\text{--}32 \text{ mJ/m}^2$) and grain sizes ($0.5 - 20$

μm) were fabricated and subjected to tensile tests. The tensile strength is monotonically enhanced with decreasing the SFE, while the UE depends strongly on the SFE and grain size. Firstly, grain size affects the UE significantly as shown in Figure 1(e). For the Cu–4Al alloy with the highest SFE, the ductility changes slightly with increasing the grain size owing to the stable strain-hardening behavior dominated by dislocation slip. For the Cu–11Al and Cu–15Al alloys with lower SFEs, the ductility increases remarkably with increasing the grain size due to the continuous enhancement of the strain-hardening capability. Secondly, SFE also affects the UE significantly as shown in Figure 4. In the coarse-grained regime ($d > 3.5 \mu\text{m}$), the ductility increases monotonically with decreasing the SFE, while in the fine-grained regime ($0.5 \mu\text{m} < d < 3.5 \mu\text{m}$), the ductility is the highest in the Cu–11Al alloy with the medium SFE.

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