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Investigation on Work Softening Behavior of Aluminum and Its Alloys with Iron

F.-Z. Li, Z.-J. Liu, Q. Jin, Z.-M. Yu, and E. Liu

Work softening in aluminum and its alloys (Al-2Fe) was investigated at room temperature. Work softening was noticed in aluminum with a purity of 99.996%, in an Al-2Fe alloy with a purity of 99.996% in the aluminum matrix, and in an Al-2Fe alloy with a purity of 99.96% in the aluminum matrix, when the reduction in thickness of samples after rolling is more than 80%, 60%, and 90%, respectively. Work softening was mainly related to the recovery at room temperature. The addition of iron to aluminum purifies the aluminum matrix. The dispersed second phases formed by aluminum and iron may promote the recovery.

Keywords
recovery, reduction in thickness, work softening

1. Introduction

WORK hardening takes place in most pure metals and their alloys during plastic deformation and has been successfully used in industry. However, work softening occurs under some special conditions; namely, when the plastic deformation in metals or alloys increases to some extent, the strength of the materials no longer increases or even decreases. Since the 1970s, investigations on the mechanisms of work softening of metals and alloys have been reported (Ref 1-9).

Aluminum and its alloys have excellent characteristics. The quantity of products derived from them ranks only next to steel. Most of the products from aluminum and its alloys are produced by rolling, punching, forming, and so on. Like most other metallic materials, work hardening significantly increases the strength of aluminum and its alloys, which accounts for their wide applications.

Work softening in aluminum and its alloys also occurs when the plastic deformation reaches a certain extent (Ref 1-11). This phenomenon is extremely important to the theory of plastic deformation. This paper deals with the work softening of aluminum and Al-2Fe alloys.

2. Experimental Details

Samples, denoted I to VI (Table 1), were made from aluminum and Al-2Fe alloys of different purity levels. After being smelted at a temperature above 1073 K, the materials were solidified into bulks of 200 by 140 by 30 mm^3 in an inert atmosphere. The bulks, after homogenization annealing for 24 h at 673 K, were rolled into 6 mm thick plates. The plates were then intermediately annealed for 1 h at 673 K and finally were rolled at room temperature to reductions in thickness of 20, 40, 60, 80, 90, and 95%, respectively.

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A microhardness indenter (71H) was used to measure the hardness of the samples after rolling. Six measurements were performed at different positions on each sample, from which an average value was derived. The error of the hardness measurements was approximately 1.5%.

Specimens for tensile testing were taken along the rolling direction. Three specimens corresponding to each reduction in thickness were tested (Model 1-5-2; Changchun Experimental

Table 1 Composition of aluminum samples

Sample No.	Composition, % Al	Fe	Si	Cu	Total impurities
I	≥99.996	≤0.0015	≤0.0015	≤0.001	≤0.004
II	≥99.96	≤0.015	≤0.015	≤0.005	≤0.04
III	≥99.6	≤0.25	≤0.20	≤0.010	≤0.4
IV	98% (sample I) + 2% Fe				
V	98% (sample II) + 2% Fe				
VI	98% (sample III) + 2% Fe				

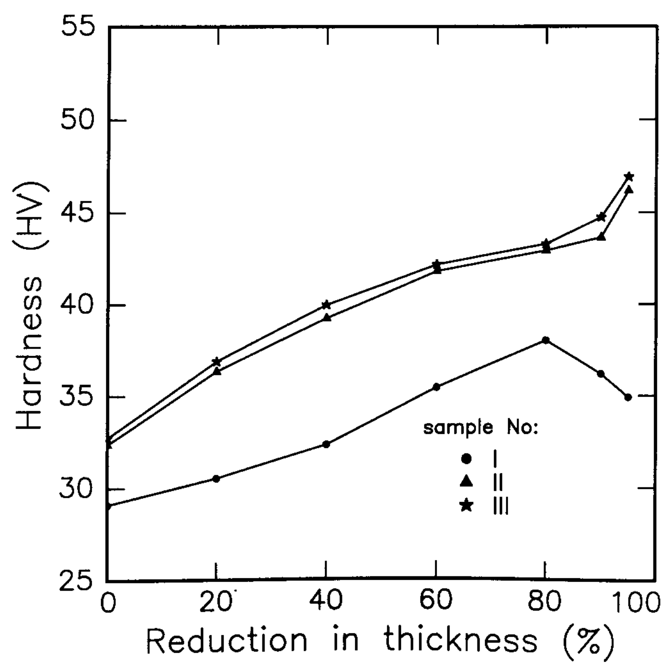

Fig. 1 Hardness versus reduction in thickness of aluminum

Equipment Company, China), and an average tensile strength was deduced. The strain rate in the tensile tests was 1.67×10^{-2} mm/s.

The sample surface prepared for optical microscopy and transmission electron microscopy (TEM) analyses was parallel to the rolling plane. Optical microscopy was used to observe the morphology of the samples after rolling. The microstructure of the rolled samples was characterized by TEM (CM12, Philips), with an operating voltage of 120 kV. Foil samples were thinned first mechanically and then by double spray in electrolyte with a composition of 30% HNO_3 + 70% CH_3OH at 10 V and 200 mA. Electron probe microanalysis (EPMA) was used to measure the composition of the second phases in the samples.

3. Results and Discussion

As shown in Fig. 1 and 2, hardness and tensile strength decrease as the reduction in thickness increases above 80% for sample I, resulting in work softening, whereas the hardness and tensile strength of samples II and III increase with increasing reduction in thickness (i.e., work hardening occurs). Significant work softening occurs in sample IV as the reduction in thickness increases above 60%, as shown in Fig. 3 and 4. For sample V, work softening occurs when the reduction in thickness is greater than 90%. In contrast, sample VI shows work hardening due to the continuous increase in hardness and tensile strength with increasing plastic deformation.

Figure 5 shows crystallites elongated along the rolling direction in sample I, but no recrystallization occurs when the reduction in thickness in the sample is greater than 95%. From TEM analysis (Fig. 6), the substructure tends to polygonize and further forms equiaxed subgrains once work softening occurs. Dislocations forming the boundaries of subgrains are clearly visible, whereas no dislocations could be observed inside the subgrains.

Figures 7 and 8 show a great number of tangled dislocations with clear orientation in substructure for samples II and III. The subgrains are unequiaxed in shape.

As shown in Fig. 9, large equiaxed subgrains are present in sample IV rolled at a reduction in thickness of 95%. The dispersed second phases are visible, but no dislocations could be resolved in the grains.

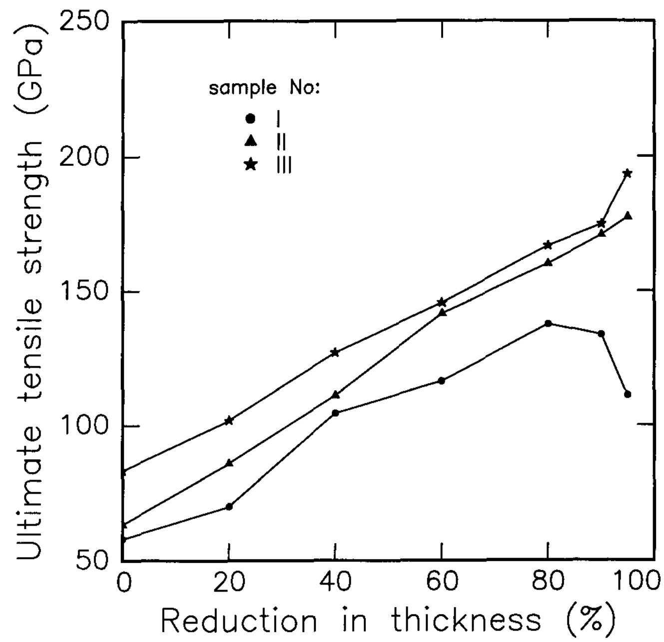

Fig. 2 Ultimate tensile strength versus reduction in thickness of aluminum

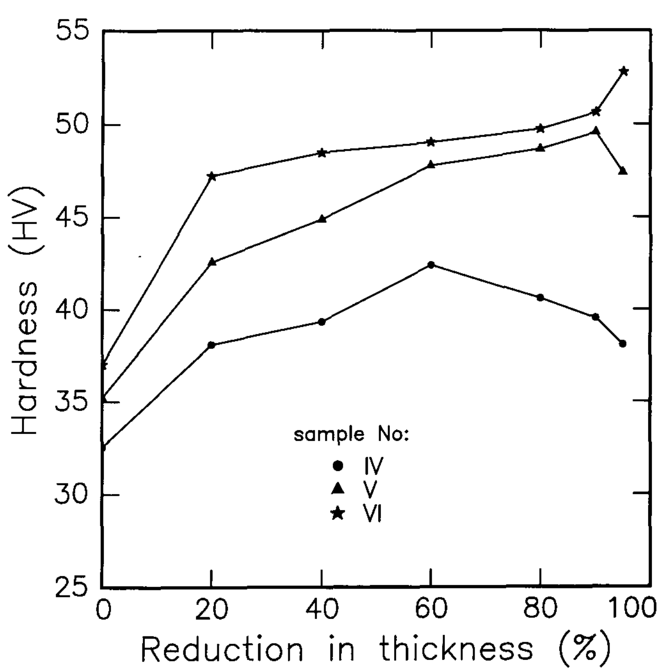

Fig. 3 Hardness versus reduction in thickness of Al-2Fe alloys

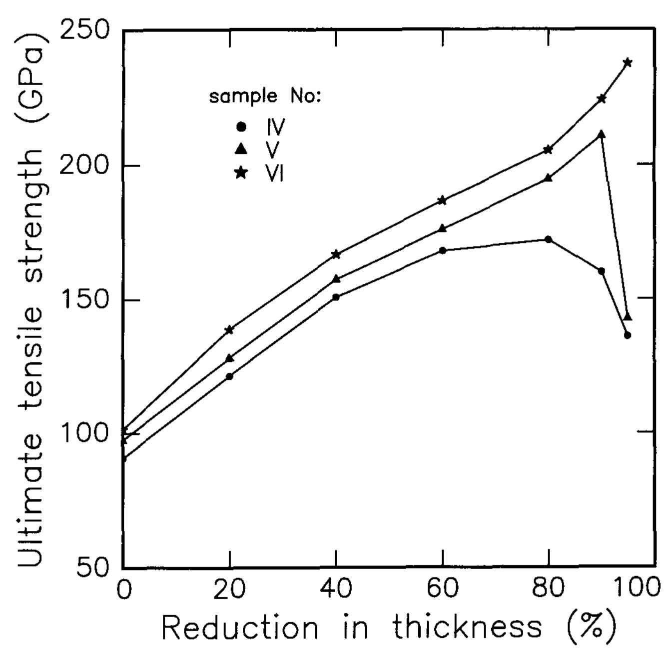

Fig. 4 Ultimate tensile strength versus reduction in thickness of Al-2Fe alloys

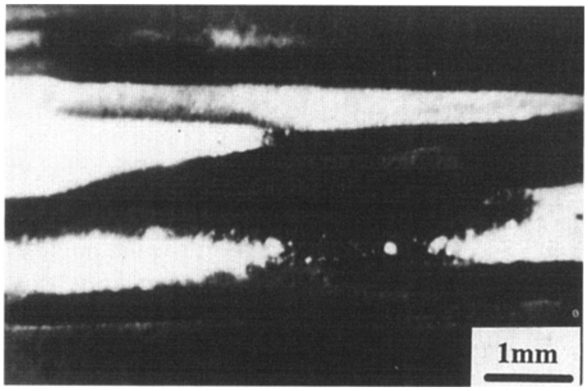

Fig. 5 Optical photograph of the grain structure of sample I rolled at a reduction in thickness of 95%. Grains were elongated along the rolling direction.

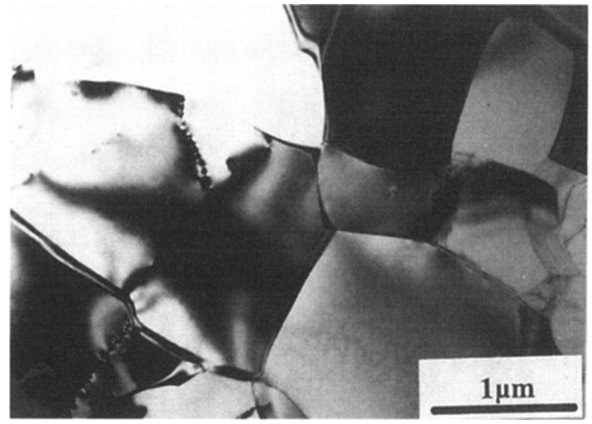

Fig. 6 TEM image of sample I rolled at a reduction in thickness of 95%

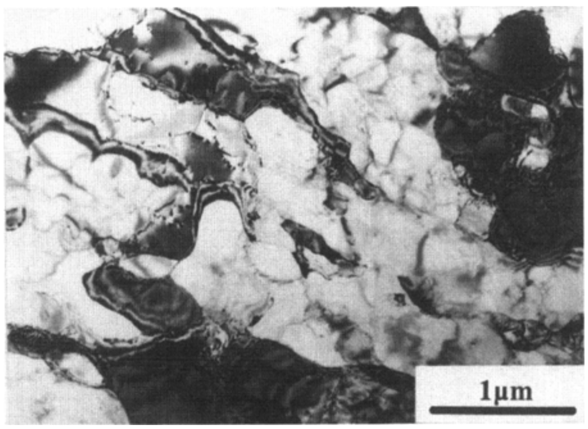

Fig. 7 TEM image of sample II rolled at a reduction in thickness of 95%

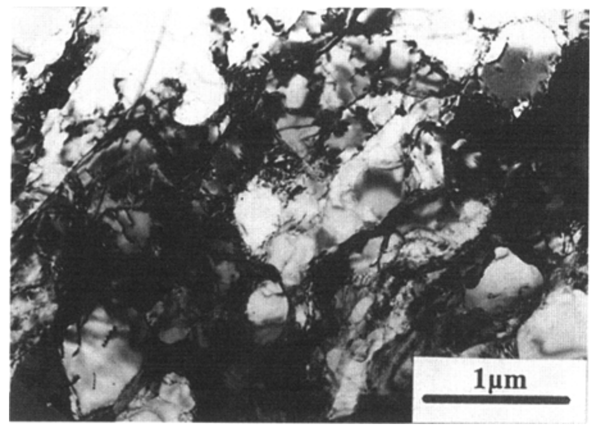

Fig. 8 TEM image of sample III rolled at a reduction in thickness of 95%

For sample V, worked at the same reduction in thickness as sample IV, large equiaxed subgrains are still apparent (Fig. 10). The second phases in the matrix and the grain boundaries are mainly $FeAl_3$, determined from the Al-Fe phase diagram (Ref 12) combined with an EPMA analysis (Fig. 11). Impurities such as copper and silicon may accumulate in the $FeAl_3$ phases.

For sample VI rolled at a reduction in thickness of 95%, no work softening occurs. Subgrains show an unequiaxed shape and orient along some direction. The dislocations can be resolved in the grains, as shown in Fig. 12.

Aluminum, with a face-centered cubic lattice, contains high stacking fault energy, which could increase with reduced impurities (Ref 13). The amount of impurities is low in sample I, indicating a high stacking fault energy. The relatively high impurity content in samples II and III leads to comparatively low stacking fault energy. The second phases formed due to the addition of iron to aluminum (samples IV to VI) improve the purity of the aluminum matrix. For the samples with lower impurity levels, the purification effect of iron is more significant.

The dislocations in crystals with high stacking fault energy are not easily decomposed. They are able to move by cross-slip, overcoming the barriers. The origin, multiplication, and movement of dislocations due to plastic deformation result in the formation of a cell-like substructure. When the distortion energy increases to some extent, the dislocations are able to perform polygonization recovery by slip or cross-slip in the elastic field, releasing the distortion energy and internal stresses and decreasing the resistance to further deformation. For sample I, the recovery is put into effect as the reduction in thickness increases above 80%. Meanwhile, the softening rate is greater than the hardening rate, which leads to work softening.

The dislocations in samples II and III, multiplied during continuous deformation, randomly distribute in the crystals and form complicated networks due to reduced mobility. Even in extensive plastic deformation, it is difficult to form the cell-like substructure. The distortion energy cannot be relaxed by polygonization recovery. Resistance to deformation is further increased due to the internal stresses. Work hardening is predominant for samples II and III.

The content of impurities in sample IV is very low, and the addition of iron further purifies the aluminum matrix. When the reduction in thickness is greater than 60%, work softening occurs. Compared to sample I, the effect of iron is clear.

The level of impurities in sample V is greater than that in sample IV. The addition of iron can purify the aluminum ma-

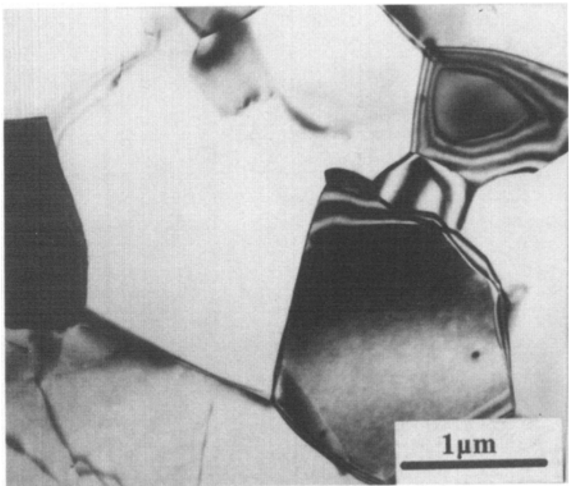

Fig. 9 TEM image of sample IV rolled at a reduction in thickness of 95%

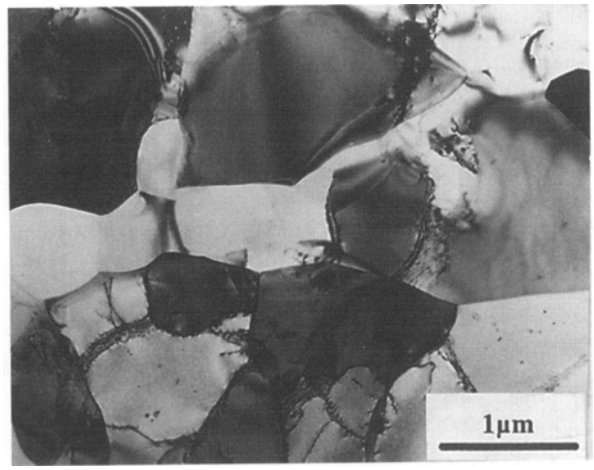

Fig. 10 TEM image of sample V rolled at a reduction in thickness of 95%

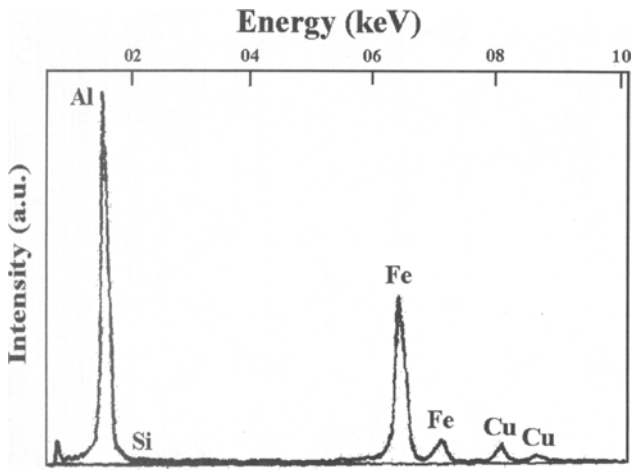

Fig. 11 EPMA analysis on the second phases of sample V

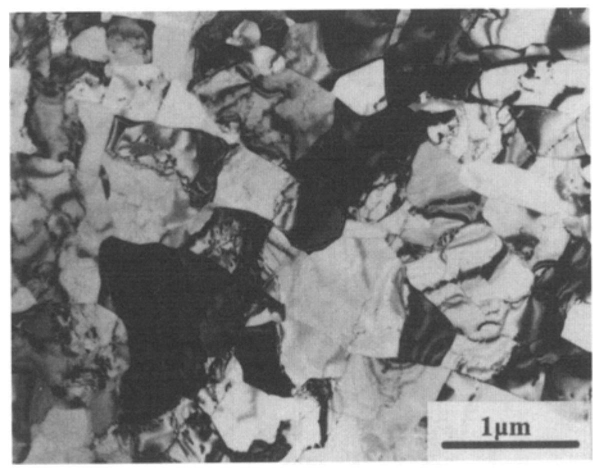

Fig. 12 TEM image of sample VI rolled at a reduction in thickness of 95%

trix, but the effect of iron is not as significant as for sample IV. Work softening of sample V requires a relatively higher reduction in thickness (e.g., >90%).

Sample VI contains even more impurities. The interactions between the dislocations and between the dislocations and the impurities or the second phases may induce very high internal stresses, which cannot be relaxed by the polygonization recovery. This further increases resistance to subsequent deformation and prevents work softening from occurring.

4. Conclusions

Work softening occurred for aluminum with a purity of 99.996% at a reduction in thickness above 80%, but no evidence of work softening was found for 99.96% Al and 99.6% Al.

For Al-2Fe alloys, work softening was observed for an aluminum matrix with a purity of 99.996% at a reduction in thickness above 60% and for an aluminum matrix with a purity of 99.96% at a reduction in thickness above 90%. No work softening was noticed for an aluminum matrix with a purity of 99.6%.

Work softening was mainly related to the polygonization recovery at room temperature. The impurities in aluminum decreased the stacking fault energy, preventing recovery. The addition of iron to the aluminum matrix purified the matrix; impurities such as silicon and copper tended to accumulate in the $FeAl_3$ second phases.

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