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Factors influencing ductility during cyclic torsional deformation of high purity aluminium

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Cyclic torsion (twisting in a forward clockwise direction followed by twisting in the reverse direction) of high purity Al wires under the simultaneous application of a small tensile load (P) was found to increase the torsional ductility considerably. The number of twists in each direction (N) varied between 5 and 50 and P ranged between 0.1 and 0.78 kg mm^{-2}. The average shear strain ($\bar{\gamma}$) increased considerably as N and/or P decreased. Specimens with a fine grain size showed higher ductility than those with a coarse grain size. By suitable combination of N, P and grain size, $\bar{\gamma}$ exceeding 3000%, indicating superplastic behaviour, was obtained. The accompanying electrical resistivity changes were small and did not exceed 1%. The results are discussed in terms of recovery mechanisms and possible dislocation interactions occurring during this complex mode of deformation.

1. Introduction

The deformation of metals by unidirectional torsion has received much attention because of the large amounts of strain involved compared to that encountered during metal forming [1–3]. The total average shear strain $\bar{\gamma}$ during torsional deformation under tensile stress can be calculated from the equation [4–6]

$$\bar{\gamma} = \tfrac{2}{3}\,\pi ND/L + 3\,\Delta L/L \qquad (1)$$

where N is the number of twists, ΔL the tensile elongation accompanying torsion and L the initial length of the wire of diameter D. Several workers have pointed out the similarity of torsional deformation mechanisms to those of fatigue [7] and creep [8, 9].

The plastic behaviour during cyclic (alternate or bidirectional) torsional deformation, characterised by alternately twisting the specimen in one direction (e.g. clockwise direction) followed by twisting in the reverse direction, has received little attention. The purpose of the present work was to investigate the factors influencing ductility and electrical resistivity changes during this mode of deformation using high purity aluminium at room temperature.

2. Experimental

High purity (99.993%) aluminium wire samples 0.7 mm diameter and 100 mm long were annealed at 300 and 550° C in vacuum for 3 h to produce various grain sizes. The samples were subjected to uniform speed twisting in a conventional twisting machine [10] during unidirectional twisting. In the case of cyclic or alternate torsional deformation, the sample was given N twists in the clockwise direction followed by an equal number of twists in the reverse direction. N varied between 5 and 50. Small tensile stresses not exceeding the yield stress (loads: $P = 30$, 100, 200 and 300 g; equivalent stresses: 0.10, 0.26, 0.52 and 0.78 kg mm^{-2}, respectively) were simultaneously applied during deformation. The tensile strain $\Delta L/L$ and electrical resistivity changes $\Delta\rho/\rho$ during this

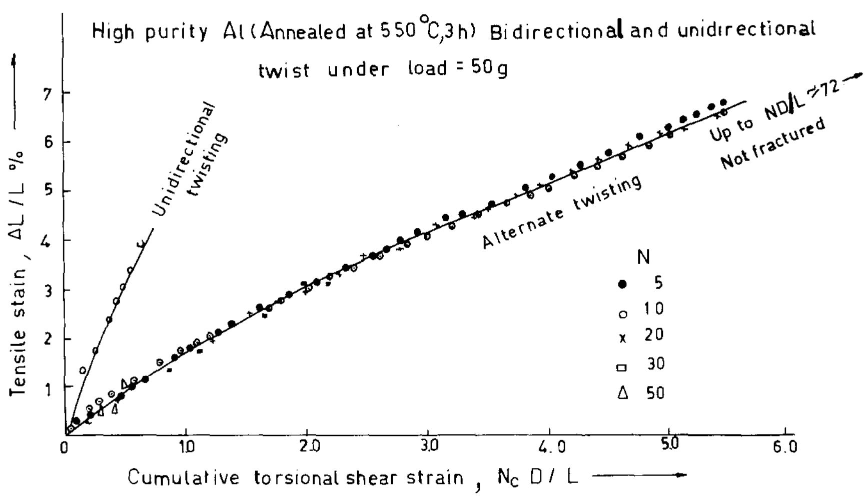

Figure 1 Comparison between unidirectional and bidirectional (alternate) torsional deformation.

mode of deformation were determined as described previously [11, 12]. N_cD/L was used as a measure of cumulative torsional shear strain, where N_c is the total number of twists regardless of the sign of twisting. The total torsional ductility was described by N_fD/L where N_f is the number of twists at fracture regardless of sign. The total tensile elongation was described by $(\Delta L/L)_f$.

3. Results

3.1. Torsional deformation

Fig. 1 shows that very large amounts of cumulative torsional shear strain are produced in alternate or bidirectional torsion tests compared to that produced in unidirectional twisting experiments using aluminium wires annealed at 550° C for 3 h. It is also shown that $(\Delta L/L)_f$ accompanying bidirectional torsion is higher than that produced during unidirectional twisting, although, $\Delta L/L$ per unit torsion is higher in undirectional twisting than in cyclic twisting.

Fig. 2 and Table I illustrate that N is a very important parameter influencing N_fD/L during cyclic torsion. As N decreases both N_fD/L and $(\Delta L/L)_f$ increase; consequently $\bar{\gamma}_f$ increases markedly. This increase becomes significant at

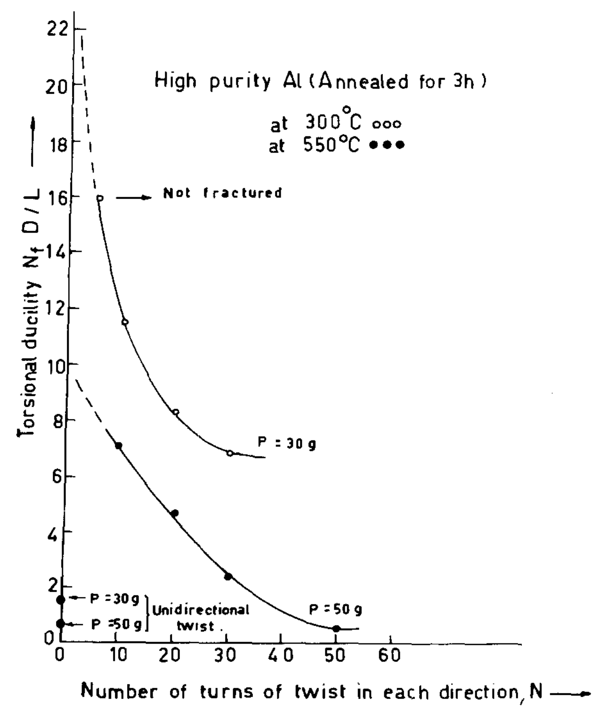

Figure 2 Effect of number of twists in each direction on torsional ductility during cyclic torsion.

TABLE I Effect of N on ductility of Al wires (annealed at 550° C, 3 h) deformed by cyclic twisting ($P = 50$ g)

N	ND_f/L	$(\Delta L/L)_f$	$\bar{\gamma}_f$
5	7.2*	0.085*	14.25*
10	7.03	0.070	14.21
20	5.45	0.065	10.27
30	2.47	0.045	5.17
50	0.56	0.0095	1.20
Unidirectional twisting	0.70	0.037	11.58

*Specimen not yet broken.

TABLE II Effect of N on ductility on Al wires (annealed at 300° C, 3 h) deformed by cyclic twisting ($P = 30$ g)

N	N_fD/L	$(\Delta L/L)_f$	γ_f
5	15.9*	0.08*	33.6*
10	11.6	0.06	24.5
20	8.4	0.05	17.8
30	7.0	0.04	14.8
Unidirectional twisting	1.45	0.02	3.0

*Specimen not broken.

small values of N; e.g. at $N = 5$ $\bar{\gamma}_f$ reached 14.25 (and the specimen is not yet broken). In case of $N = 10$, $\bar{\gamma}_f$ reached 14.2 compared to 1.6 in unidirectional twisting. This represents about 1000% increase in ductility over undirectional twisting.

A similar set of experiments was performed on aluminium wires annealed at 300° C for 3 h; these wires are expected to have a finer grain size than those annealed at 550° C for 3 h. The results given in Fig. 2 and Table II confirm the trend noted previously for coarse grain size Al. However, it is shown clearly that N_fD/L, $(\Delta L/L)_f$, and consequently $\bar{\gamma}_f$ are considerably higher in the fine grain size than in the coarse grain size specimens at comparable deformation conditions. At $N = 5$, $\bar{\gamma}_f$ reached 33.6 without fracture. This is an increase of about 1000% over $\bar{\gamma}_f$ obtained during unidirectional twisting.

The tensile strain accompanying deformation was measured subsequent to twisting in the forward and reverse direction. Fig. 3 shows that tensile strain is produced mainly during twisting in the forward twisting and not during the reversed twisting.

The effect of applied tensile stress on ductility and tensile strain produced during cyclic twisting, ($N = 10$), in comparison to unidirectional twisting is illustrated in Fig. 4 for specimens annealed at 300° C for 3 h. It is shown that as the stress or load increases, the tensile strain per unit torsion increases either in bidirectional (cyclic) or unidirectional twisting. It is also shown that N_fD/L decreases markedly as P increases during alternate twisting, while in unidirectional torsion P does not influence torsional ductility, as illustrated in Fig. 5 and Table III. At an applied stress of 0.8 kg mm^{-2} the torsional ductility obtained by bidirectional twisting approaches that produced in unidirectional twisting.

Table III also shows that $(\Delta L/L)_f$ increases with P in unidirectional twisting, but does not depend on P in cyclic twisting. In general, $\bar{\gamma}_f$ decreases significantly as P is increased since the contribution to

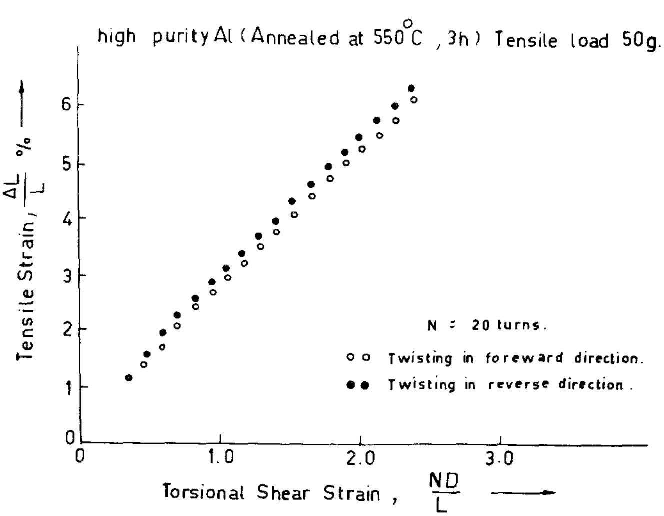

Figure 3 Effect of twisting in the forward and reverse direction on tensile strain accompanying torsion.

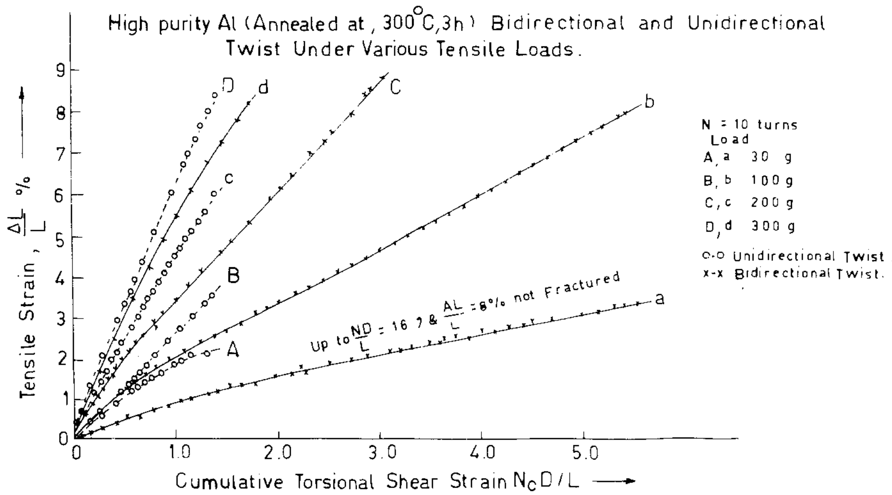

Figure 4 Effect of applied tensile load on tensile elongation and torsional ductility in unidirectional and cyclic torsion.

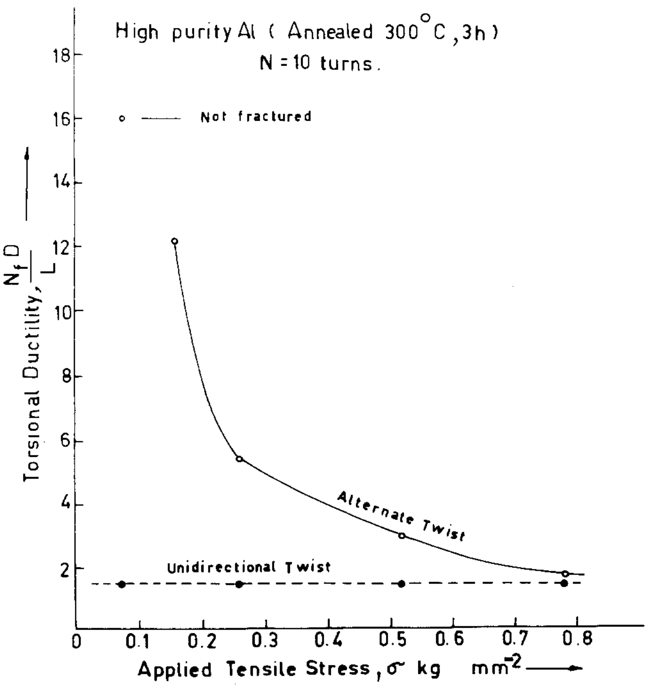

Figure 5 Relation between applied tensile stress and torsional ductility during cyclic twisting.

TABLE III Effect of applied tensile load (*P*) on ductility during unidirectional and bidirectional twisting of Al

Bidirectional twisting ($N = 10$)				Unidirectional twisting		
P(g)	(N_fD/L)	$(\Delta L/L)_f$	γ_f	(N_fD/L)	$(\Delta L/L)_f$	γ_f
30	15.9*	0.082*	33.6*	1.45	0.021	3.10
100	5.4	0.081	11.6	1.45	0.045	3.18
200	3.0	0.087	6.6	1.50	0.060	3.30
300	1.7	0.083	3.8	1.40	0.083	3.18

*Specimen not yet broken.

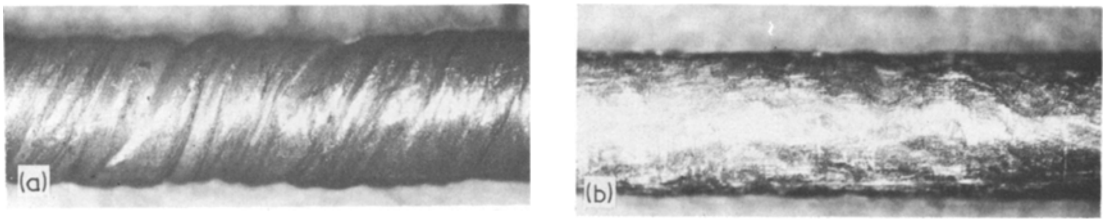

Figure 6 Surface features of Al wire (annealed at 550° C, 3 h) after (a) unidirectional twisting, (b) cyclic twisting ($N = 20, P = 50$ g) x 35.

$\bar{\gamma}_f$ arises mainly from torsional ductility. At the smallest load used ($P = 30$ g) very large $\bar{\gamma}_f$ about 3300% was obtained (while the specimen was not yet broken) which is about 1000% higher than in unidirectional torsion.

3.2. Surface topography

The topographic features of Al samples twisted by unidirectional and alternate twisting are shown in Fig. 6. Helical coarse deformation bands appeared on the surfaces of unidirectionally twisted samples. Thes helical bands were not observed on the surface of specimens deformed by alternate twisting in opposite directions; instead fine slip bands were observed, particularly at high applied tensile loads.

3.3. Electrical resistivity changes

Fig. 7 shows that $\Delta\rho/\rho$ increases continuously during unidirectional twisting reaching up to 4% at $ND/L \simeq 1$. During cyclic torsional deformation however, $\Delta\rho/\rho$ increases slightly initially, reaching only 1% at $N_cD/L = 1$, and then tends to decrease slightly and becomes more or less constant with increasing amount of deformation.

4. Discussion

Superplasticity or excessively large average shear strain, $\bar{\gamma}$ exceeding 3000%, can be produced in Al by cyclic torsional deformation (in the forward and reverse directions alternately) at certain conditions of applied tensile stress, number of twists in each direction and grain size. As N and/or P decreases, $\bar{\gamma}$ in cyclic twisting increases considerably. Fine grain size specimens show higher torsional ductilities than coarse grain size specimens. It is interesting to note that the highest amount of $\bar{\gamma}$ reported previously for unidirectional twisting of f c c metals was about 500% [6].

The results of alternate or bidirectional twisting reported here are similar in some respects to the torsional fatigue experiments of Packer and Wood [13] on copper. The life of the specimens decreased with increasing applied load and/or the amplitude of the torsion cycles.

The mode of cyclic twisting under applied tensile stress is characterized by extensive recovery in comparison to undirectional twisting. Electrical resistivity changes accompanying the large deformation noted here did not exceed 1%; this slight increase occurred only during the initial stage of deformation and up to $N_cD/L = 1$ measurements (Fig. 7). Similarly, for copper fatigued by cyclic twisting, Wood and Segall [14] showed that after initial hardening, plastic deformation occurs without causing any further hardening. Part of the original strain introduced upon twising in the forward direction seems to be uncoiled upon

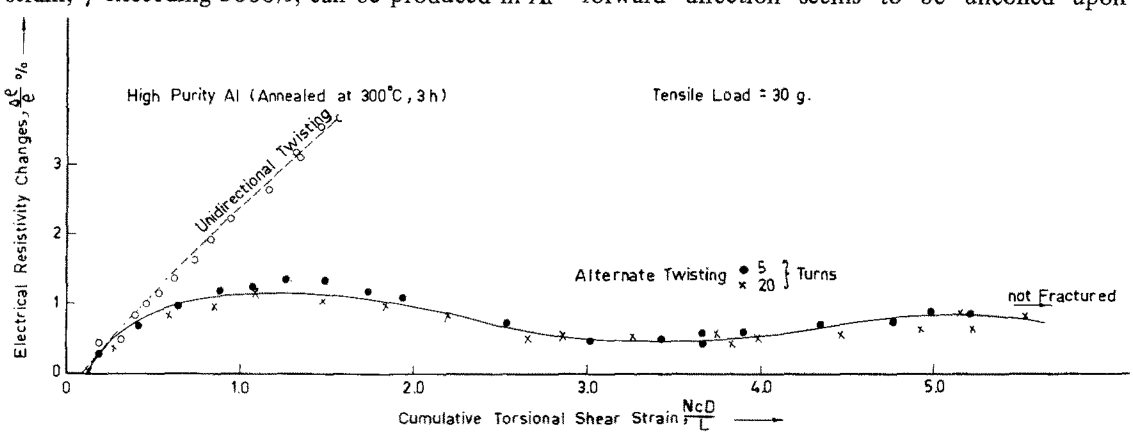

Figure 7 Electrical resistivity changes during unidirectional and cyclic twisting.

reversal of the twist. This is obvious from the absence of coarse torsional deformation bands on the surface of specimens deformed by alternate torsion (Fig. 6). Furthermore, there is detectable strain accompanying twist in the reverse direction (Fig. 3).

Swift [15] suggested that the reversal of the direction of strain may cause a repair of the damage caused by the initial strain. He suggested that the internal stress system due to differential strains produced by the initial twist may be relieved by the removal of those strains in the reverse twist. Thus the deformation during uncoiling can be considered to cause recovery.

Segall and Finney [16] suggested that the reversed strain relaxes dislocation configurations of high energy and creates rearrangements, such as close dislocation pairs, which are favourable for increased annihilation. Owing to the high stacking fault energy of Al [17], considerable mutual annihilation by cross-slip mechanism should take place during the reverse motion of dislocation. This will cause considerable recovery effects.

The considerable recovery concomitant to bidirectional (cyclic) torsional deformation is the reason behind the large γ and the high torsional ductility obtained during this mode of deformation. As N and/or P is reduced, the probability of recovery is greatly increased because the dislocation configurations introduced under these conditions are not expected to be complex. Thus the dislocation density and internal stresses decrease drastically with decrease in N and P, and the probability of crack formation is considerably reduced.

On the other hand, as the deformation conditions become severe by increasing N and P, dislocation tangles are introduced and recovery during uncoiling becomes incomplete. Thus the accumulation of damage leads to an increased probability of crack nucleation and hence reduced total torsional ductility. The limiting case having minimum total torsional ductility is the unidirectional twisting, since recovery is minimum and accumulation of damage is maximum as can be seen from electrical resistivity measurements (Fig. 7).

5. Conclusions

High purity Al wires exhibited superplastic behaviour when deformed by cyclic or alternate torsion under the effect of small applied tensile stresses not exceeding the yield stress of Al. The torsional ductility and average shear strains increased considerably with decrease in the number of twists in each direction, applied tensile load and/or the grain size. This superplastic behaviour was attributed to extensive recovery accompanying this complex mode of deformation, particularly during reversing the twist. This was supported by measurements of electrical resistivity changes which did not exceed 1% at large amounts of deformation. The extent of recovery was related to the number of twists in each direction and the applied load.

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References

1. C. ROSSARD and P. BLAIN, *Rev. Met.* **61** (1964) 949.
2. H. J. McQUEEN and J. J. JONAS, "Metal Forming" edited by A. L. Hoffmanner (Plenum Press, New York, 1971) p. 393.
3. Deformation under hot working conditions, Iron and Steel Institute Publication No. 108 London (1968).
4. I. KOVACS and E. NAGY, *Phys. Stat. Sol.* **3** (1963) 726.
5. I. KOVACS, E. NAGY and P. FELTHAM, *Phil. Mag.* **9** (1964) 979.
6. I. KOVACS and E. NAGY, *Phys. Stat. Sol.* **8** (1965) 795.
7. S. CERSEARA *Phil. Mag.* **1** (1969) 99.
8. W. A. WONG and J. J. JONAS, *Trans. Met. Soc. AIME* **242** (1968) 2271.
9. H. J. McQUEEN, W. A. WONG and J. J. JONAS, *Canad. J. Phys.* **45** (1967) 1225.
10. M. R. SOLIMAN, F. H. HAMMAD and G. A. HASSAN, *Acta Phys. Acad. Sci. Hung.* **30** (1971) 399.
11. M. R. SOLIMAN, G. A. HASSAN and F. H. HAMMAD, *J. Inst. Metals* **99** (1971) 134.
12. F. H. HAMMAD, G. A. HASSAN and M. R. SOLIMAN, *Aluminium* **4** (1973) 275.
13. M. E. PACKER, and W. A. WOOD, *J. Inst. Metals* **92** (1963–64) 413.
14. W. A. WOOD and R. L. SEGALL, *Proc. Roy. Soc.* **A242** (1952) 180.
15. H. W. SWIFT, *J. Iron Steel, 140* (1939) 181.
16. R. L. SEGALL and J. M. FINNEY *Acta Met.* **11** (1963) 685.
17. I. L. DILLAMORE and R. E. SMALLMAN, *Phil. Mag.* **12** (1962) 191.

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