JOURNAL OF MATERIALS SCIENCE 29 (1994) 4901–4905

Young's modulus of cold- and hot-rolled $(Al_2O_3)_p$–Al composite

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The Young's modulus of hot-rolled Al alloy reinforced with Al_2O_3 particulates, $(Al_2O_3)_p$–Al composite, is measured using the dynamic sonic resonance test method. The variation in the moduli of cold- and hot-rolled composites, as a function of the reduction ratio, is compared. Although both cold and hot rolling result in more uniform distribution of the particulates, hot rolling causes less damage to the reinforcements, resulting in more isotropic composites possessing a higher Young's modulus. These observed variations in the Young's modulus with respect to reduction ratio are analysed on the basis of the microstructural changes due to the rolling and T6 heat-treating operations.

1. Introduction

Metal-matrix composites reinforced with low-cost ceramic particles, with attractive mechanical properties suitable for commercial applications that do not require very high unidirectional strengthening, are being investigated. One of the characteristics of such composites is that they can be mechanically worked during the final shaping process. The forces associated with mechanical working not only cause redistribution of the reinforcements but also cause microscopic damage, such as particulate cracking and interfacial debonding [1, 2], affecting the material properties of the resultant composite. Changes in the material properties, especially the elastic properties, due to the mechanical shaping process are one of the important considerations that have to be taken into account in engineering design.

The variation in the Young's modulus of cold-rolled $(Al_2O_3)_p$–Al composite has already been reported in the literature [2]. The results indicate that the Young's modulus along the longitudinal direction increases with increasing reduction ratio. This property along the transverse direction, however, decreases with increasing amounts of cold rolling. Such behaviour could be explained on the basis of the observed microstructural changes caused by the cold-rolling operation, i.e. redistribution of $(Al_2O_3)_p$ and damage to $(Al_2O_3)_p$. In the case of the transverse specimen, the contribution of microcracks to the Young's modulus is more dominant than that due to the redistribution of $(Al_2O_3)_p$ and the formation of texture. As a result, the transverse Young's modulus of a cold-rolled composite is lower than that of the as-extruded material and the longitudinal specimens. Such experimental results indicate that if the damage to $(Al_2O_3)_p$ could be eliminated efficiently during rolling, the rolling operation would result in an increase in the Young's modulus of the composite. In order to minimize the damage to $(Al_2O_3)_p$, hot rolling was carried out in this study.

The objectives of the present study are to investigate the effects of cold and hot rolling on the redistribution of $(Al_2O_3)_p$ clusters and microcracks in $(Al_2O_3)_p$, and to evaluate their influences on the Young's modulus of the composite.

2. Experimental procedure

2.1. Specimen preparation

Duralcan composite W6A 10A, 6061 aluminium alloy reinforced with 10 % $(Al_2O_3)_p$, obtained in the form of extruded cylindrical bars with an extrusion ratio of 20:1, was used in this study. Unidirectional hot rolling with a reduction ratio of about 10 % per pass was carried out in a direction perpendicular to the extrusion direction. The temperature of the specimen measured before the entrance to the rolls was about 500° C. The rolled composite was reheated at 540° C for 3 min between passes so as to maintain consistent hot-rolling conditions. Thin slices with directions parallel (longitudinal) and perpendicular (transverse) to the extrusion direction were cut for rolled sheets having various percentages of reduction. Similar procedures were also employed in cold rolling without the heating of the specimens. The details regarding the procedures used in cold rolling, specimen preparation and T6 heat-treatment utilized are described elsewhere [2]. The grain sizes of the rolled specimens were measured using the line intercept method.

2.2. Modulus measurement

All Young's modulus measurements were carried out at room temperature in air, using the standard sonic resonance test method designated by ASTM C848-78. The equation used for the calculations of the Young's modulus is that derived for prismatic bars with a rectangular cross-section under free–free suspension [3]:

$$E = 0.946\,42\left(\frac{l^4}{t^2}\right)\rho f^2\,T \tag{1}$$

where E is the Young's modulus, l the length of the specimen, t the thickness of the specimen, ρ the density of the specimen, f the fundamental flexural resonance frequency and T a shape factor which depends on the geometry of the specimen. The approximate shape factor used for the calculation is that obtained by Spiner *et al.* [4].

3. Results

3.1. Effect of rolling on microstructural changes

3.1.1. Grain size

The recrystallized grain size of the cold-rolled composites was found to decrease with increasing amounts of prior cold rolling, which is consistent with previous findings [5]. As reported in the literature [5], this is due to the fact that the ratio of nucleation rate to growth rate ($\partial N/\partial G$) at recrystallization temperature increases with increasing amounts of prior cold working. However, the grain size of the hot-rolled composites was observed to increase with increasing reduction. This could probably be explained on the basis that 10 % reduction per pass as used in the present study was not sufficient to promote recrystallization. Under such conditions, gradual extension of the grain boundary with the help of the applied mechanical energy can occur [6]. These observations are presented in Fig. 1.

3.1.2. Redistribution of particulates

The most apparent difference in metallographic features between the as-extruded and the rolled composites is that $(Al_2O_3)_p$, initially present in the form of banded clusters along the extrusion direction, becomes more uniformly distributed with increasing reduction ratio. The microstructural changes due to the redistribution of $(Al_2O_3)_p$ achieved by hot rolling are presented in Fig. 2. Similar redistribution could also be obtained using cold rolling [2].

3.1.3. Particulate damage

Although uniform distribution of $(Al_2O_3)_p$ could be achieved by the rolling operation, the microscopic observations of the cold-rolled composites showed significant damage to the reinforcements, i.e. particulate cracking and interfacial debonding (Fig. 3a). However, hot rolling results in significantly less damage to the reinforcements as shown in Fig. 3b. In addition, there was a strong tendency for these crack planes to be parallel to the direction of compression (i.e. rolling pressure) and perpendicular to the rolling direction, as shown in Fig. 3c. A grid analysis performed on the micrographs taken from the rolled composites showed that the percentage of damaged reinforcements increases linearly with increasing reduction ratio. The results of these studies are presented in Fig. 4.

3.2. Effect of rolling and T6 heat-treating operation on the Young's modulus

The effect of cold rolling on the Young's modulus of this composite has already been reported [2]. This

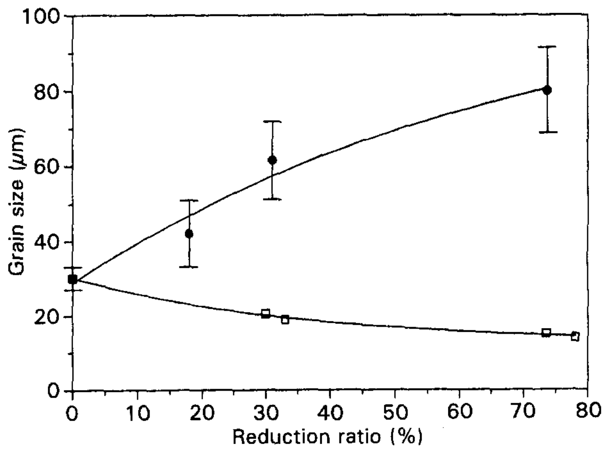

Figure 1 Variation of the grain size of (□) cold-rolled and (●) hot-rolled composites (10 % pass) as a function of the reduction ratio. The error bars indicate one standard deviation.

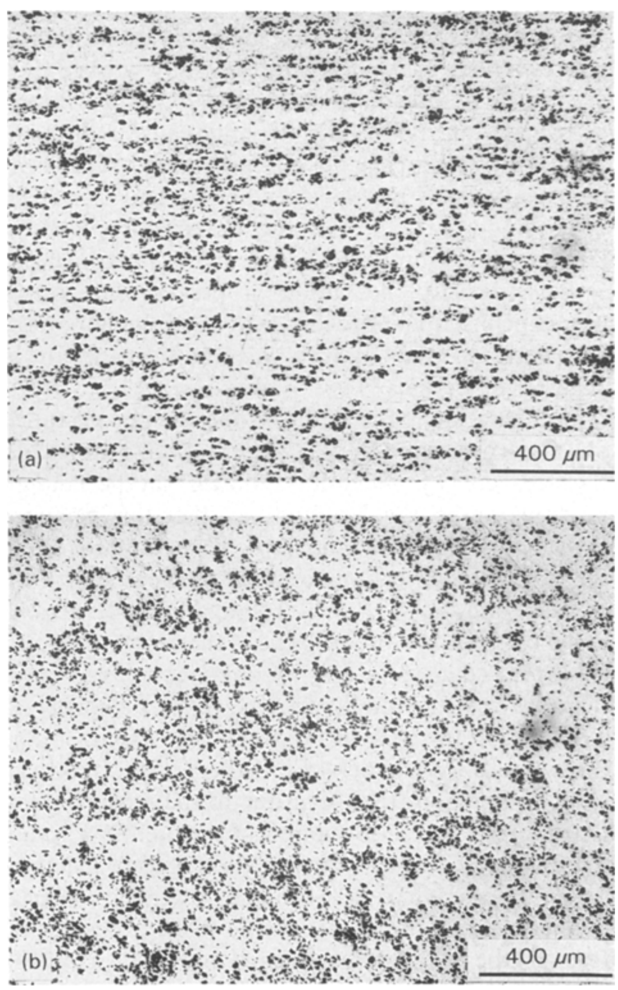

Figure 2 Optical micrographs showing the distribution of $(Al_2O_3)_p$ in (a) as-extruded composite and (b) 70 % hot-rolled composite.

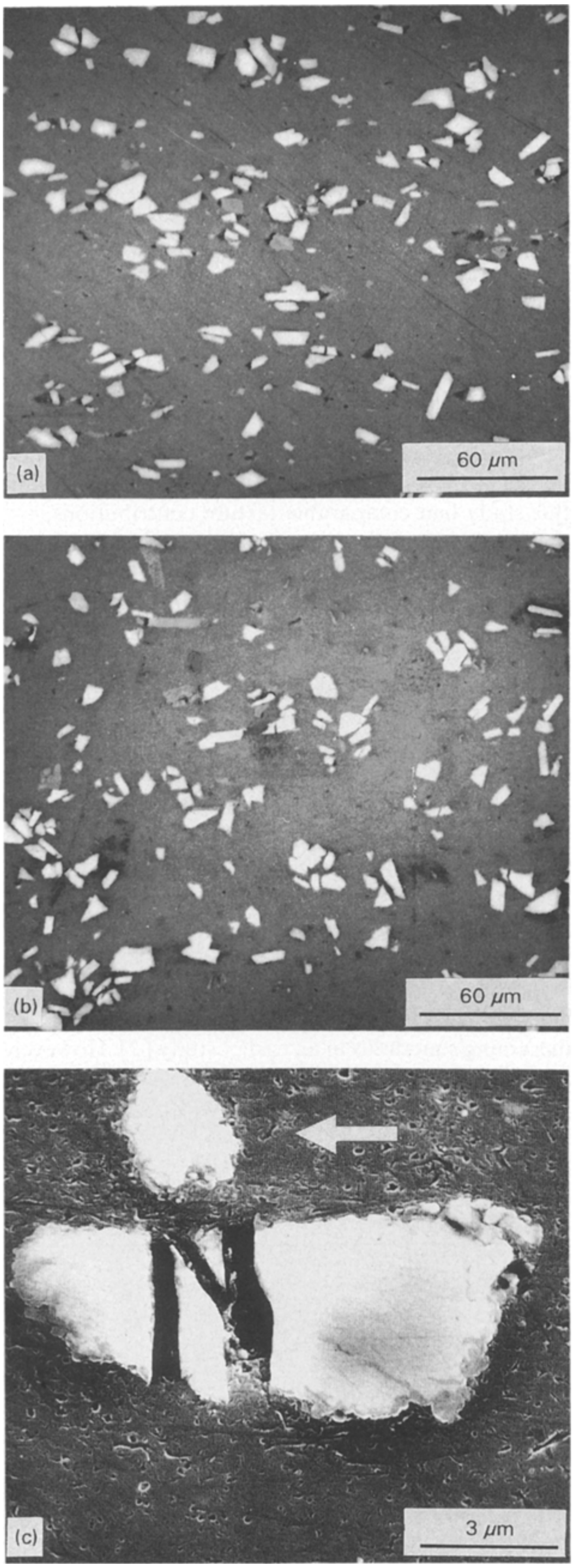

Figure 3 Scanning electron micrographs showing the particulate damage in (a) 70 % cold-rolled composite , (b) 70 % hot-rolled composite and (c) a magnified view of a cracked particle in which the crack planes are perpendicular to the direction of rolling (indicated by an arrow).

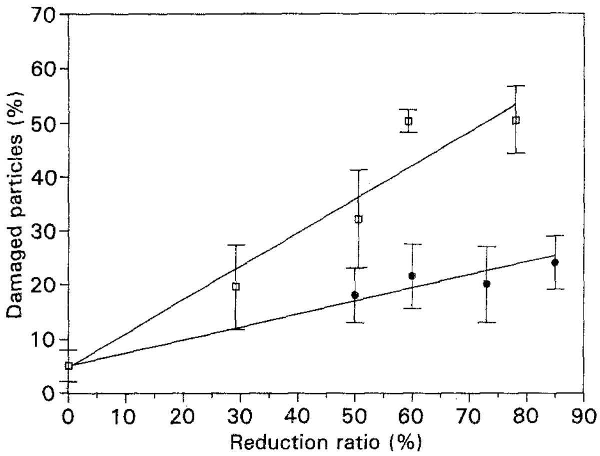

Figure 4 Plots of the percentage of damaged particulates in (□) cold-rolled and (●) hot-rolled composites as a function of the reduction ratio. The error bars indicate one standard deviation.

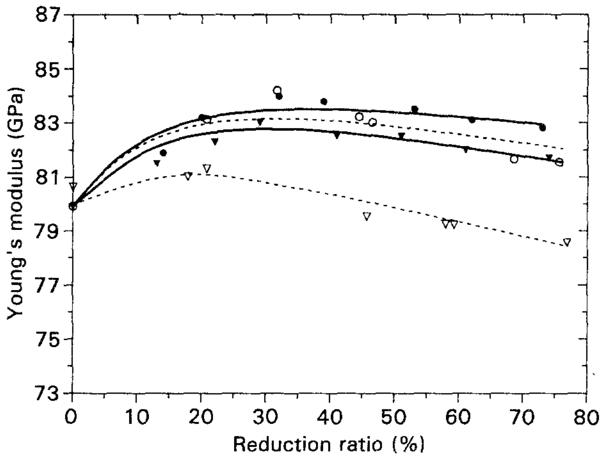

Figure 5 Plots of the experimentally measured Young's modulus of (- - -) cold-rolled and (——) hot-rolled composites along the longitudinal (L) and the transverse (T) directions: (▽) cold-rolled (T), (○) cold-rolled (L), (▼) hot-rolled (T), (●) hot-rolled (L).

study showed that the longitudinal Young's modulus increases substantially in the early stages of cold rolling and decreases slightly afterwards; on the other hand, the transverse Young's modulus increases slightly in the early stages of rolling and decreases substantially afterwards (Fig. 5). The deviation between the longitudinal and transverse moduli of the cold-rolled composites increases as the reduction ratio increases. In the case of the hot-rolled composites, a similar trend has been observed in the variation of the Young's modulus along the longitudinal direction. However, the transverse moduli of the hot-rolled composite, unlike the case of the cold-rolled ones, increase substantially and approach the longitudinal values. These features are presented in Fig. 5.

4. Discussion

Although the Young's modulus has been known as one of the microstructure-insensitive material properties, variation (usually less than 30 %) in the modulus of a polycrystalline material can occur due to the changes in the microstructure. For a given material, such a variation in the modulus due to the microstructural changes can be related to changes in the resonance frequency of the material (or propagating speed of resonant waves), as suggested by Equation 1. As a result, the presence of microstructural defects such as pores, microcracks, grain boundaries, dislocations etc. lower the Young's modulus, since they impede the travelling sonic waves, resulting in a lower resonant frequency. The effects of such microstructural changes on the variations of the Young's modulus (due to the rolling and T6 heat-treating operations) are discussed in this section.

4.1. Effect of grain size and microcracks on Young's modulus

Sugihara [7] and Koster [8] have reported that the Young's modulus of an aluminium alloy is relatively unaffected (or increases slightly if at all) with increasing grain size. Since the average grain size observed in this investigation is within the range considered in their studies, grain size is not believed to be an important contributor to the observed variations in Young's modulus.

The effect of microcracks on the Young's modulus has already been reported in the literature [9, 10]. This indicates that the modulus of a material decreases linearly due to the presence of microcracks when the crack planes of such microcracks within the material are oriented perpendicular to the tensile direction (or the direction of the travelling sonic waves). However, the effect of microcracks on the Young's modulus will be less significant when the crack planes are oriented parallel to the tensile direction. As a result, the effect of microcracks on the transverse and the longitudinal modulus can be expressed as [2]

$$E_t = E_0(1 - \gamma X) \qquad (2)$$

$$E_l \simeq E_0 \qquad (3)$$

where E_t and E_l are the Young's moduli of the rolled and T6-treated composites along the transverse and the longitudinal directions, respectively, E_0 is the Young's modulus of the as-extruded composite, X is the reduction ratio which has a linear relationship with microcrack density, and γ is a constant.

4.2. Effect of particulate redistribution and texture on Young's modulus

Since the formation of microcracks due to the rolling operations should result in a decrease in the modulus, it cannot explain the observed increase in the modulus of the longitudinal specimens. However, two microstructural changes due to rolling, i.e. redistribution of the reinforcements and texture formation, can provide the basis for the measured increment in the modulus of such specimens.

Theoretical treatments dealing with the Young's modulus of metal-matrix composites reinforced with ceramic particulates have considered the role of the volume fraction of the reinforcements [11, 12]. The effects due to the size and the shape of the particulate reinforcements are not taken into account in these treatments. However, experimental studies have shown that for a given volume fraction of the reinforcements, the modulus increases as the particulate size decreases [13, 14]. Such experimental observations are explained on the basis of more efficient load transfer achieved by increased interfacial area in composites with particulates [15]. From this point of view, the separation of particulates present in clusters and their redistribution due to the rolling operation can contribute to an increase in the modulus along both longitudinal and transverse directions. Annealing texture in cold-rolled and T6-treated material can also contribute to an increase in the Young's modulus along both directions, due to the preferred crystallographic orientations with respect to the tensile direction [13]. However, the observed differences in the modulus along different directions as a function of reduction ratio in cold- and hot-rolled (T6-treated) composites, as shown in Fig. 5, cannot be explained on the basis of texture, since all the specimens used in this study had comparable texture contributions.

Based on the experimental observations, changes in the Young's modulus due to microstructural changes can be approximated by the curve-fitting method:

$$E = E_0(1 + \alpha e^{\beta X}) \qquad (4)$$

where α and β are constants that can be determined from the y intercept and the slope of the $\ln(E - E_0)$ versus reduction ratio plot.

4.3. Combined effects of the various parameters on the modulus

An analytical expression of the form

$$E = E_0(1 + \alpha X^{\beta})(1 - \gamma X) \qquad (5)$$

has been used to account for various contributions to the Young's modulus in an earlier study [2]. However, an expression of the form

$$E = E_0(1 + \alpha e^{\beta X} - \gamma X) \qquad (6)$$

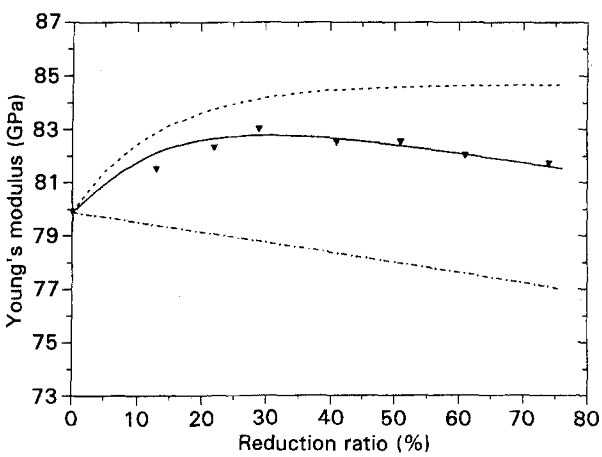

Figure 6 Schematic diagram illustrating the effect of the redistribution of $(Al_2O_3)_p$, texture formation and microcracks on the resultant Young's modulus of hot-rolled transverse composites. (- - -) $E_1 = E_0(1 + \alpha e^{\beta X})$ Young's modulus due to the redistribution of $(Al_2O_3)_p$ and texture formation: (—·—) $E_2 = E_0(1 - \gamma X)$, Young's modulus due to the formation of microcracks; (▼, —) $E = E_0(1 + \alpha e^{\beta X} - \gamma X)$, Young's modulus due to the combined effects of E_1 and E_2.

has been found to provide a better fit with experimental measurements than the above expression. In this equation the term $\alpha E_0 e^{\beta X}$ is due to the texture formation and the redistribution of $(Al_2O_3)_p$, and $-\gamma E_0 X$ corresponds to the effect due to the presence of microcracks. The effects of these two oppositely contributing factors are schematically illustrated in Fig. 6.

5. Conclusion

5.1. Effect of rolling on microstructural features

$(Al_2O_3)_p$ clusters, initially present in the form of banded clusters along the extrusion direction in the as-extruded composite, become more uniformly distributed with increased reduction in cold and hot rolling. However, this uniform distribution of $(Al_2O_3)_p$ due to rolling is always associated with particulate cracking and interfacial debonding. Such crack damage, formed during rolling, was more significant in case of cold rolling than in hot rolling. The extent of damage in $(Al_2O_3)_p$ increases linearly with increasing reduction ratio in both cases. In addition, there is a strong tendency for the crack planes to be formed perpendicular to the rolling direction.

5.2. Effect of rolling on Young's modulus

The Young's moduli of the hot-rolled composites were found to be generally higher than those of the as-extruded material and the cold-rolled composites. The variation of Young's modulus as a function of the reduction ratio had the form $E = E_0(1 + \alpha e^{\beta X} - \gamma X)$. Such a variation in the Young's modulus of the composites is believed to be due to the combined effects of the redistribution of $(Al_2O_3)_p$, texture formation, and microcracks. The analytical expressions which account for their contributions to the Young's modulus were obtained by using a curve-fitting method; the effect of microcracks on the Young's modulus was found to be of the form $E = E_0(1 - \gamma X)$, indicating that the modulus decreases linearly with increasing reduction ratio. However, the effect of the redistribution of $(Al_2O_3)_p$ and texture formation on the Young's modulus has the form $E = E_0(1 + \alpha e^{\beta X})$, indicating that the modulus increases with increasing reduction ratio. Hot rolling minimizes the extent of damage to the reinforcements, resulting in a significant increase in the transverse modulus so that it approaches the longitudinal values.

References

1. J. C. LEE and K. N. SUBRAMANIAN, *Mater. Sci. Eng.* **A 159** (1992) 43.
2. *Idem, J. Mater. Sci.* **28** (1993) 1578.
3. G. PICKETT, *Amer. Soc. Testing Mater. Proc.* **45** (1945) 846.
4. S. SPINER, T. W. REICHARD and W. E. TEFFT, *J. Res. Nat. Bur. Stand.* **16A** (1960) 147.
5. W. A. ANDERSON and R. F. MEHL, *AIME Trans.* **161** (1945) 140.
6. J. D. VERHOEVEN, "Fundamentals of Physical Metallurgy" (Wiley, New York, 1975) p. 352.
7. M. SUGIHARA, *Mem. Coll. Sci. Kyoto Imp. Univ.* **A17** (1934) 392.
8. V. W. KOSTER, *Z. Metallkde* **32** (1940) 282.
9. B. BUDIANSKY and R. J. O'CONNELL, *Int. J. Solids* **12** (1976) 81.
10. D. P. F. HASSELMAN and J. P. SINGH, *Amer. Ceram. Soc. Bull.* (1979) 856.
11. S. AHMED and F. R. JONES, *J. Mater. Sci.* **25** (1990) 4933.
12. F. A. GIROT, J. M. QUENISSET and R. NASLAIN, *Compos. Sci. Technol.* **30** (1987) 155.
13. T. B. LEWIS and L. E. NIELSEN, *J. Appl. Polym. Sci.* **14** (1970) 1449.
14. J. SPANOUDAKIS and R. J. YOUNG, *J. Mater. Sci.* **19** (1984) 473.
15. D. J. MACK, *Trans. AIME* **166** (1946) 68.

Received 30 October 1992
and accepted 21 March 1994