Beneficial influence of copper and manganese alloying elements on the mechanical properties of metallic composite materials based on the eutectic Al–5.7% Ni alloy

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We have developed a new type of metallic composite material based on the binary eutectic Al–5.7 wt% Ni alloy. The structure of the initial alloys prepared by simple casting consists of strong, fine fibres of the Al_3Ni phase and a ductile aluminium matrix. These alloys are then transformed into dispersion-hardened materials by isostatic extrusion in which the Al_3Ni fibres are broken and dispersed in the ductile matrix. The materials thus prepared present a mechanical strength of the same order as the unidirectionally solidifed eutectic alloy: the tensile strength is nearly 300 MPa at room temperature. We observed in this work that the mechanical strength is remarkably increased by the addition of a small amount of copper or manganese: it attains about 400 MPa by the addition of 2 to 3 wt% Cu, and more than 500 MPa by the addition of 3 wt% Mn. These alloying elements also produce beneficial effects on the mechanical properties at high temperature.

1. Introduction

We have developed in our previous work [1–3] a new method of preparing metallic composite materials, strengthened by the dispersion of fine intermetallic particles and by severe plastic deformation. It consists in preparing first, by simple casting and non-oriented solidification, a eutectic alloy consisting of a ductile matrix and strong, fine fibres. The material is then severely deformed by isostatic extrusion or swaging. The fibrous intermetallics of the eutectic alloy are aligned in the extrusion direction and they are broken to form fine, dispersed particles in the ductile matrix.

Our first attempts carried out on the eutectic alloy of Al–Al_3Ni (Al–5.7 wt % Ni) show promising results. The tensile strength of as-cast alloys is largely variable from 90 to 180 MPa at room temperature, but it increases remarkably up to 290 MPa by isostatic extrusion in which the ratio of the sectional area of cylindrical test pieces before and after the extrusion is $R = 3.8$. By increasing the plastic deformation by isostatic extrusion, the mechanical strength further increases. The tensile strength at room temperature is 320 MPa with $R = 8.3$.

The above tensile strengths obtained by extrusion are comparable with those which we have obtained previously [1] as well as those reported by Lemkey and co-workers [4, 5] on the unidirectionally solidified eutectic Al–Al_3Ni alloy. The techniques of the unidirectional solidification of eutectic alloys, however, require highly sophisticated production controls to realize good materials, such as the temperature, the solidification velocity or the temperature gradient. On the other hand, our new method is much simpler and consequently expected to have its application on an industrial scale.

As a next step, we have examined the effect of

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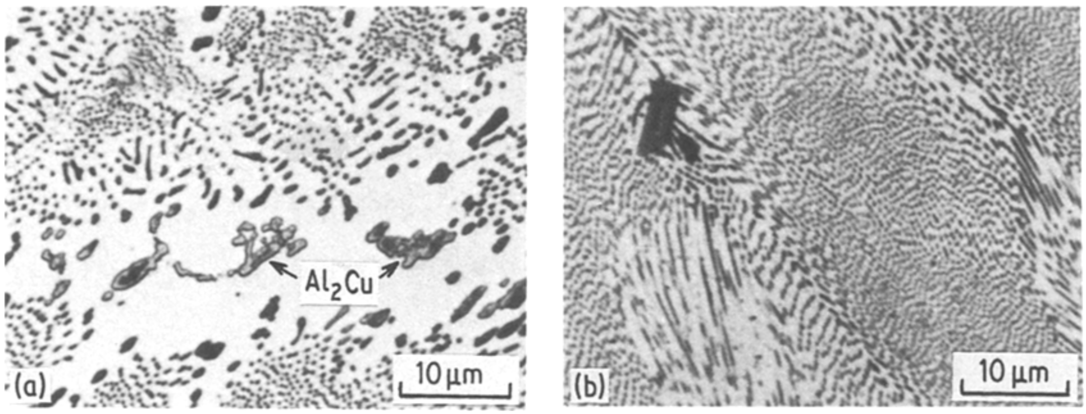


Figure 1 Optical micrographs of cast alloys of (a) Al–5.7% Ni–3% Cu, and (b) Al–5.7% Ni–2% Mn.

an alloying element on the mechanical properties of the binary Al–5 wt % Ni eutectic alloy, and observed that some of the third additional elements show a beneficial influence. We will report in this paper the most promising results obtained by the addition of a small amount of copper or manganese.

2. Preparation of the metallic composite materials

The Al–5.7 wt % Ni alloys were cast with an additional element, copper or manganese, under argon gas in a copper mould. The amount of the additional element was varied from 0 to 3 wt %. The volume of each cast ingot was about 60 cm^3, while the volume of the massive copper mould was 760 cm^3. The mass of the mould was so large in comparison with that of the ingot that a high cooling rate produces a eutectic alloy with fine fibrous structure of the Al_3Ni phase. Electron microscopic observation shows that the diameter of Al_3Ni fibres is in the range of 50 to 150 nm [1].

The addition of copper or manganese of more than 0.5 to 1% content produces a new, third phase: a granular Al_2Cu phase (θ phase) in Al–5.7% Ni–Cu alloys, and a plate-like phase which is probably Al_6Mn in Al–5.7% Ni-Mn alloys, as shown in Fig. 1. The Al_2Cu phase is formed in the boundary zones of the eutectic Al–Al_3Ni regions and it often encloses the coarsened Al_3Ni particles. The Al–5.7% Ni–Mn alloys present a fine compact structure consisting of nearly perfect eutectic regions.

We have observed, in preliminary trials, that the plastic deformation of these as-cast ingots by isostatic extrusion at room temperature produced many microfissures with a so-called "snake-skin" aspect on the ingot surface. Consequently, we placed, in order to avoid these surface defects, the cast ingot in a copper capsule and then extruded them together. The extrusion ratio R was chosen as 3.8 for the Al–5.7% Ni–Cu alloys and 4.8 for the Al–5.7% Ni–Mn alloys.

3. Experimental procedures

We used the tensile test in order to evaluate the mechanical properties of our composite alloys, using test pieces of cylindrical form at room temperature and at high temperatures (200 and 260° C). The dimension of test pieces in the effective region is 5 mm diameter and 30 mm length. The 0.2% offset yield strength σ_E, the ultimate tensile strength σ_R and the fracture elongation A were measured on engineering stress–strain diagrams. We used an extensometer with 25 mm gauge length for tensile tests at room temperature and at 200° C in order to measure the yield strength with a higher precision. The tensile velocity was small (0.01 cm min^{-1} for Al–5.7% Ni–Cu alloys and 0.02 cm min^{-1} for Al–5.7% Ni–Mn alloys) during a first stage of deformation and then it was increased, after the yield strength, to 0.1 cm min^{-1} in both cases until fracture of the composite materials.

In the case of Al–5.7% Ni–Mn alloys, the influence of heat treatments of 500 h at 200, 300, 400 and 500° C on the mechanical properties was also examined.

4. Results

4.1. Al–5.7% Ni–Cu alloys

The experimental results of tensile test are

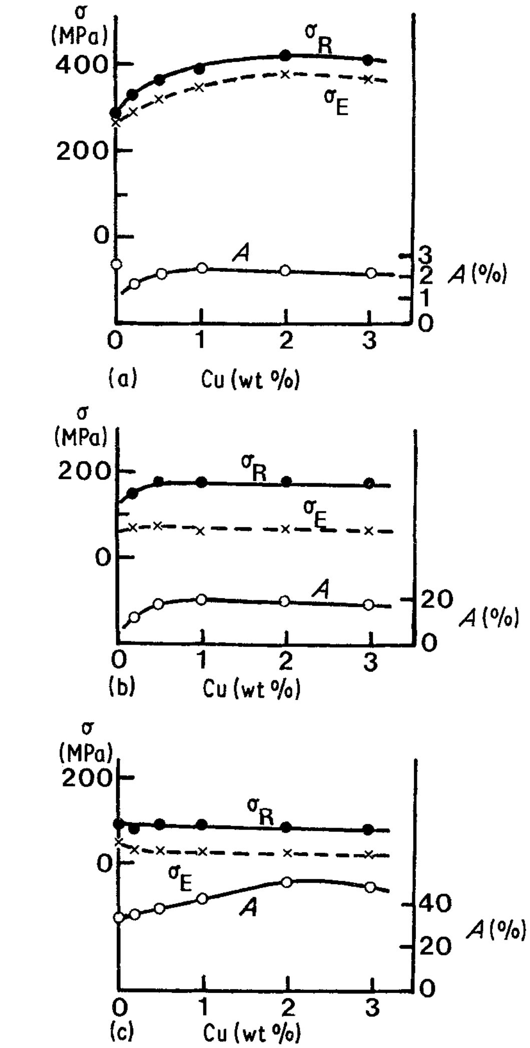


Figure 2 Experimental results on σ_E(0.2% offset yield strength), σ_R(ultimate tensile strength) and A(fracture elongation) of Al–5.7% Ni–Cu alloys, prepared by isostatic extrusion with $R = 3.8$: (a) test temperature $T = 20°$ C, (b) $T = 200°$ C and (c) $T = 260°$ C.

summarized in Fig. 2 as a function of copper content. The tensile strength at room temperature for Al–5.7% Ni–Cu alloys, prepared by isostatic extrusion with $R = 3.8$ attains the maximum value, 410 MPa, at about 2% Cu. The fracture elongation increases with copper additions of small amount but it shows a decreasing tendency at higher copper content.

Fig. 3 shows the variation of mechanical properties as a function of testing temperature, as an example, for the Al–5.7% Ni–2% Cu alloy. The tensile strength decreases almost linearly as the temperature increases, while the

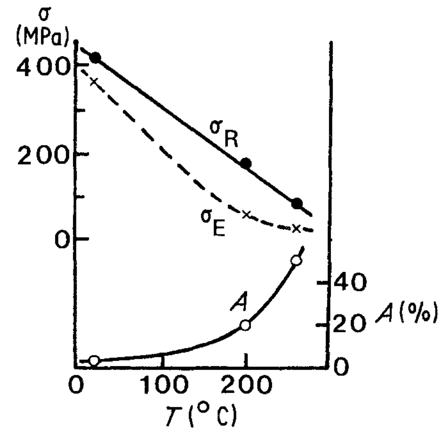


Figure 3 Variation of mechanical properties (σ_E, σ_R and A) of Al–5.7% Ni–2% Cu alloy, prepared by isostatic extrusion with $R = 3.8$, as a function of test temperature T.

composite materials become fairly ductile at temperature above 200° C.

4.2. Al–5.7% Ni–Mn alloys

Fig. 4 shows the results of tensile tests, carried out on Al–5.7 % Ni–Mn alloys prepared by isostatic extrusion with $R = 4.8$. The tensile strength increases with increase of manganese content and it attains 480 MPa for 2% Mn and 510 MPa for 3% Mn at room temperature, but at the same time the alloys become brittle. In some cases the samples are broken during the isostatic extrusion for the 3% Mn alloys.

Fig. 5 shows one of the typical variations of mechanical properties for the Al–5.7% Ni–Mn alloys as a function of testing temperature. In comparison with the case of copper addition alloys, the tensile strength is still conserved fairly well up to 200° C, but it decreases at temperature above 260° C.

Fig. 6 shows the variation of mechanical properties measured at room temperature as a function of annealing temperatures (200, 300, 400 and 500° C, respectively) after 500 h. We have chosen here, as examples, the cases of Al–5.7% Ni, Al–5.7% Ni–1% Mn, Al–5.7% Ni–2% Mn and Al–5.7% Ni–3% Mn alloys. The mechanical strength largely decreases by heating at temperature above about 350° C and the ductility increases. The electron microscopic observation shows that these changes are accompanied by the modification of the alloy structure which is visible by the spheroidization of Al_3Ni fibres.

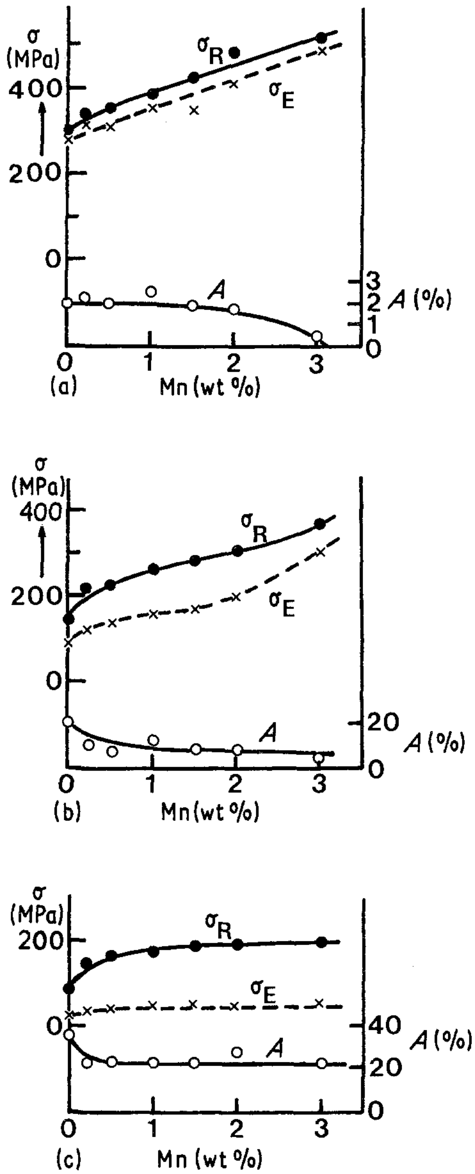


Figure 4 Results of tensile tests on Al–5.7% Ni–Mn alloys, prepared by isostatic extrusion with R = 4.8: (a) test temperature T = 20° C, (b) T = 200° C and (c) T = 260° C.

5. Electron microscopic observation of structure and plastic deformation

Fig. 7a shows the fracture surface and lateral polished surface of the Al–5.7% Ni–3% Cu alloy, prepared by isostatic extrusion with R = 3.8 and tested at room temperature. The Al_3Ni fibres are broken and finely dispersed in the matrix by extrusion, but large grains of the Al_3Ni and the Al_2Cu phases remain in the boundary zones of the Al–Al_3Ni eutectic

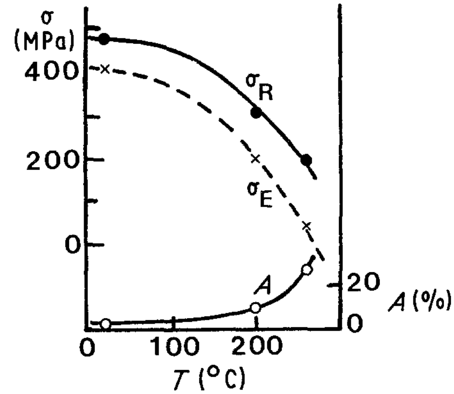


Figure 5 Variation of mechanical properties of Al–5.7% Ni–2% Mn alloy, prepared by isostatic extrusion with R = 4.8, as a function of testing temperature T.

regions. The fractures often initiate from these large grains and matrix interfaces. The fractured surfaces show that they are formed by large plastic deformation.

Fig. 7b is obtained from the region near the fracture surface of Al–5.7% Ni–1% Mn alloy, prepared by isostatic extrusion with R = 4.8 and tested at 260° C. The Al_3Ni fibres are still fine and the alloy structure is highly compact. It is frequently observed that decohesion starts from the large plate-like precipitate and matrix interfaces. Fig. 7c shows the microstructure of the fractured surface of the same Al–5.7% Ni–1% Mn alloy. Large cusps, a characteristic aspect of ductile fracture, are often formed around large particles by plastic deformation.

6. Concluding remarks

The addition of a small amount of copper or manganese conserves the fine fibrous structure of the Al_3Ni phase and increases the tensile strength remarkably. Our experimental results show that these beneficial effects of alloying elements are first of all due to the solid-solution hardening of the Al-matrix phase.

In the case of manganese addition, the alloy structure is very fine and compact and its strengthening effect is larger than that of copper addition, but the addition of copper is more advantageous to maintain the ductility, especially at high temperature. The tensile strength at room temperature is more than 400 MPa for Al–5.7% Ni–2 to 3% Cu alloys, prepared by isostatic extrusion with R = 3.8 and nearly 500 MPa for Al–5.7% Ni–2 to 3% Mn

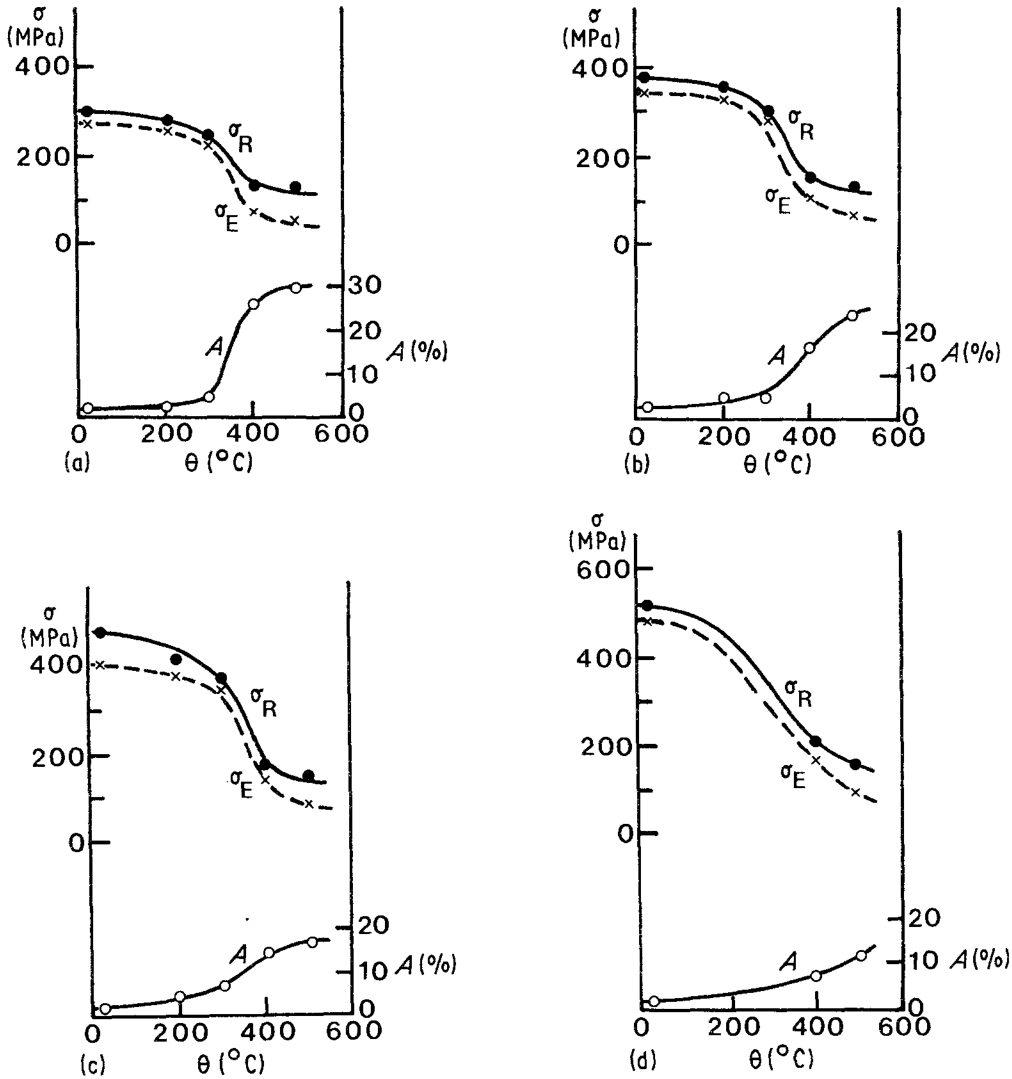


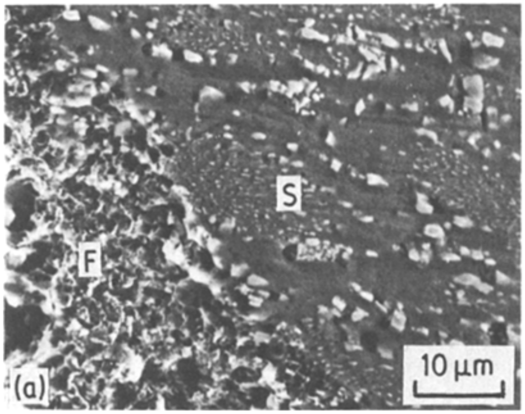
Figure 6 Mechanical properties of Al–5.7% Ni–Mn alloys, prepared by isostatic extrusion with R = 4.8 followed by annealing of 500 h at temperature θ and tested at room temperature: (a) Al–5.7% Ni, (b) Al–5.7% Ni–1% Mn, (c) Al–5.7% Ni–2% Mn and (d) Al–5.7% Ni–3% Mn.

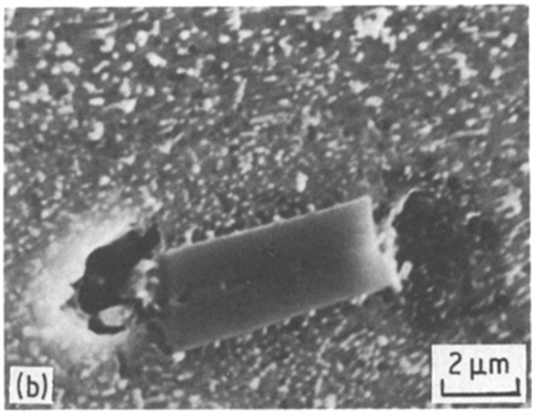
alloys, prepared by isostatic extrusion with R = 4.8.

Large precipitates such as Al_2Cu or Al_6Mn induce premature decohesion at the precipitate–matrix interfaces. Consequently, the presence of these large precipitates is not favourable for maintaining the ductility of our composite materials. In the case of copper or manganese addition, however, the Al–5.7% Ni alloys show an increase of their tensile strength without a significant loss of their ductility, as long as the content of additional elements is less than 2 wt %.

At high temperature (200 and 260° C) both alloys, Al–5.7% Ni–Cu and Al–5.7% Ni–Mn, become more ductile but they still retain a fairly high strength. The Al–5.7% Ni–1 to 3% Mn alloys present good mechanical properties at 260° C, namely high tensile strength of nearly 200 MPa with 20% fracture elongation. We obtained a tensile strength of about 100 MPa with more than 40% fracture elongation for Al–5.7% Ni–1 to 3% Cu at 260° C.

The change of alloy structure occurs by heat treatment of long duration at high temperature. Optical and electron microscopic observations show that the spheroidization of Al_3Ni fibres occurs in Al–5.7% Ni alloy after annealing of





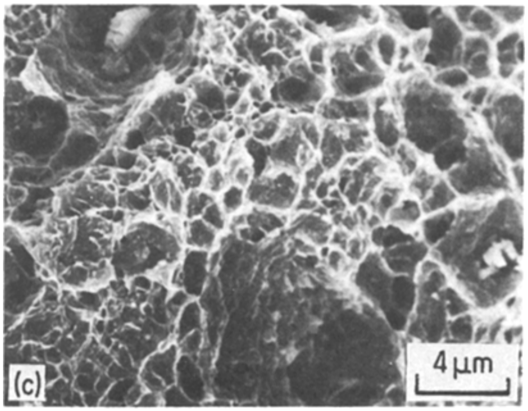


Figure 7 Scanning electron micrographs of alloys, prepared by isostatic extrusion and fractured by tensile test. (a) Al–5.7% Ni–3% Cu alloys, tested at room temperature. F is a fracture surface and S a lateral polished surface. (b) Al–5.7% Ni–1% Mn alloy, tested at 260° C. The examined specimen, with lateral surface near the fracture surface, was polished mechanically and etched by a dilute hydrofluoric acid solution. (c) The fracture surface of the Al–5.7% Ni–1% Mn alloy, tested at 260° C.

1000 h at temperatures above 260° C, and tensile strength decreases significantly while the fracture elongation increases, as reported previously [3]. The experiments carried out on the Al–5.7% Ni–Mn alloys by heat treatment of 500 h at various temperatures show that manganese addition delays the spheroidization of Al_3Ni fibres until above 350° C, and so it contributes to the strengthening of our composite materials at high temperatures.

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