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The effect of hot-rolling on chill-cast Al, Al–2 wt % Ni and Al–4 wt % Ni alloys

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The effect of hot-rolling on the mechanical properties and microstructure of directionally-solidified hypoeutectic Al–Al_3Ni alloys has been studied. Chill-cast hypoeutectic alloys were produced by casting into pre-heated mild-steel moulds placed on copper chills. The chill-cast Al–2 wt% Ni and Al–4 wt% Ni hypoeutectic alloys can be hot-rolled at 500° C to reductions of greater than 95%. Deformation is achieved by deforming the aluminium-rich dendrites in the rolling direction, followed by interpenetration of the Al_3Ni fibres into the dendrites resulting in a homogeneous microstructure. The variations of room-temperature tensile properties for the chill-cast hypoeutectic alloys were measured as a function of reduction of thickness during hot-rolling. The ultimate tensile strength and yield strength increase during rolling because of increasing Al_3Ni fibre alignment, homogeneous dispersion of the Al_3Ni fibres throughout the Al matrix, and work hardening in the Al matrix. The as-chill-cast alloys have strengths which agree with the composite law of mixtures for a combination of Al dendrites and Al–Al_3Ni eutectic. After hot-rolling, the alloy strengths can be predicted from discontinuous fibre reinforcement theory.

1. Introduction

The solidification behaviour and room-temperature mechanical properties [1] of chill-cast Al–Al_3Ni eutectic alloys have been reported previously by the present authors. From this work, where the chill-cast Al–Al_3Ni eutectic alloy was produced by casting into pre-heated mild-steel moulds heated to 50 or 150° C above the eutectic temperature of 640° C and placed on either a water-cooled or plain copper chill, it was shown that the different casting conditions had little effect on the resulting microstructure and mechanical properties.

The chill-cast Al–Al_3Ni eutectic can be hot-rolled at 500° C to reductions of greater than 95% [2, 3] with the deformation being achieved by Al_3Ni fibre fracturing followed by separation of the broken pieces in the rolling direction. The as-solidified cellular microstructure disappears during rolling and the Al_3Ni fibres are homogeneously distributed throughout the matrix after reductions greater than 60 to 70%. The ultimate tensile strength of the chill-cast Al–Al_3Ni eutectic remains relatively constant during hot-rolling. It would appear that the effect of the decrease in Al_3Ni fibre length during hot-rolling of the chill-cast eutectic is balanced by the redistribution of the fibres into the cell walls so that the ultimate tensile strength is virtually independent of reduction of thickness. The redistribution of the fibres into the cell walls also leads to an increase in yield strength due to dislocation flow being inhibited and a decrease in fracture strain because plastic flow in the cell walls has been eliminated.

The objective of the present work was to investigate the effects of hot-rolling on the microstructure and room-temperature mechanical properties of chill-cast hypoeutectic Al–Al_3Ni alloys produced

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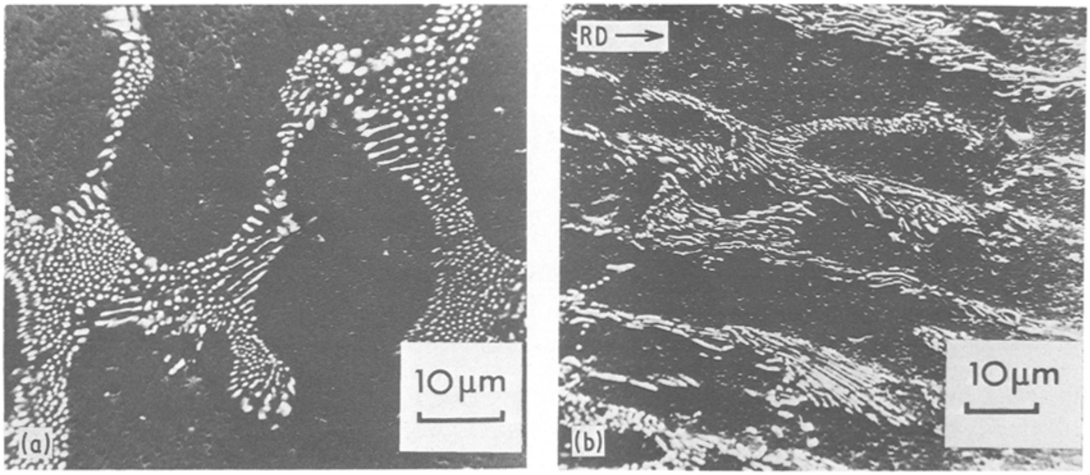

Figure 1 SEM (45° tilt) micrographs of chill-cast Al–2 wt% Ni alloy, hot-rolled at 500° C to a reduction of thickness of 25%. (a) Transverse and (b) longitudinal sections. RD = rolling direction.

using the same chill-casting conditions as the eutectic alloy.

2. Experimental methods

The Al–Al_3Ni hypoeutectic alloys were prepared by induction melting 99.9% commercial purity Al with 99.99% purity Ni, in recrystalized alumina crucibles under a dynamic argon atmosphere. Chill-cast hypoeutectic ingots, typically 100 mm in length and 10 mm x 10 mm in cross-section, were produced by casting the hypoeutectic alloys into mild-steel moulds pre-heated to 800° C, mounted on a water-cooled chill.

The chill-cast Al–Al_3Ni hypoeutectic alloys were hot-rolled at 500° C. To ensure that the ingots did not crack during rolling, the reduction of thickness per pass had to be very small, particularly for the initial few passes. In addition, the rolling temperature had to be maintained at 500° C by reheating every 3 to 4 passes. The cold rolls (of radius 35.1 mm) operated at a peripheral speed of ~ 0.1 m sec^{-1}.

Transverse and longitudinal sections of each alloy at the various reductions in thickness were prepared metallographically, using Keller's reagent as an etch and examined in a Cambridge Stereoscan 2A scanning electron microscope. Tensile specimens were machined from the rolled hypoeutectic alloy specimens to a gauge width of 4 mm and gauge length of 50 mm. These specimens were then tested using an Instron testing machine with a 4.45 kN load cell and a cross-head speed of 2.1×10^{-5} m sec^{-1}. An Instron 50.8 mm 10% strain gauge extensometer was attached to each specimen to measure extensions. All the tensile tests were carried out at room temperature. The resulting fracture surfaces of the tensile specimens were examined in the stereoscan electron microscope. The microstructure and tensile properties of the alloys were monitored as a function of the reduction of thickness during hot-rolling.

3. Results and discussion

3.1. Microstructure

The chill-cast Al, Al–2 wt% Ni and Al–4 wt% Ni hypoeutectic ingots were initially heated to 500° C for ten minutes and then four passes were made through the rolls with a 0.2 mm reduction in thickness on each successive pass. The rolled ingots were then returned to the furnace for a further reheating period of ten minutes. This was to try to minimize temperature losses to the atmosphere and rolls and was exactly the same procedure using in hot-rolling the Al–Al_3Ni eutectic alloy, previously reported by the authors [3]. As expected from the hot-rolling experiments on the chill-cast eutectic and the increased amount of ductile α-aluminium in the hypoeutectic alloys compared to the eutectic, no difficulty was experienced in hot-rolling. Percentage reductions in thickness of greater than 97% were easily achieved. No edge cracking was experienced during hot-rolling.

On microscopic analysis, it was found that the hypoeutectic morphology of α-aluminium dendrites and inter-dendritic eutectic regions had hardly changed after low reductions of thickness, about 20% except that the alignment of the α-aluminium dendrites had increased in the rolling direction

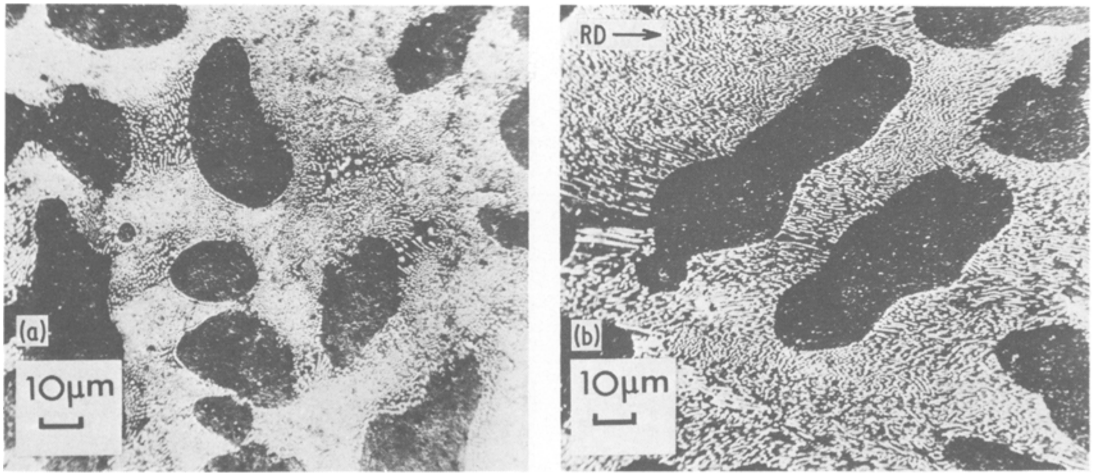

Figure 2 SEM (45° tilt) micrographs of chill-cast Al–4 wt% Ni alloy, hot-rolled at 500° C to a reduction of thickness of 15%. (a) Transverse and (b) longitudinal sections. RD = rolling direction.

(RD). Figs 1 and 2 show transverse and longitudinal sections of the Al–2 wt% Ni and Al–4 wt% Ni chill-cast alloys after reductions of 25 and 15%, respectively. The hypoeutectic nature of the alloys and the α-aluminium dendrite alignment in the rolling direction is evident. As the reduction of thickness was increased the dendrite alignment became more pronounced, as can be seen in Fig. 3, which shows the Al–4 wt% Ni chill-cast alloy after a reduction of 44%. On greater reduction, the Al_3Ni fibres began to penetrate into the α-aluminium dendrite regions until, after 80% reduction, the dendrite regions were difficult to see. Fig. 4 shows longitudinal sections of the Al–2 wt% Ni chill-cast alloy for reductions of 25 and 80%, in which this interpenetration can be seen. Fig. 5 shows longitudinal sections of the Al–4 wt% Ni chill-cast alloy after a reduction of 84%; the Al_3Ni fibres have completely penetrated the α-aluminium dendrites and the dendritic regions are no longer visible.

Very little evidence of Al_3Ni fibre fracturing was found as the fibres were initially only 2 to 4 μm in length. By comparison, Al_3Ni fibres were initially 30 μm in length in the as-chill-cast eutectic alloy [3] and, after a rolling reduction of 90%, fibre fracturing had caused the fibre length to decrease to 4 μm [3].

3.2. Room-temperature tensile behaviour

Fig. 6 shows the variation of ultimate tensile

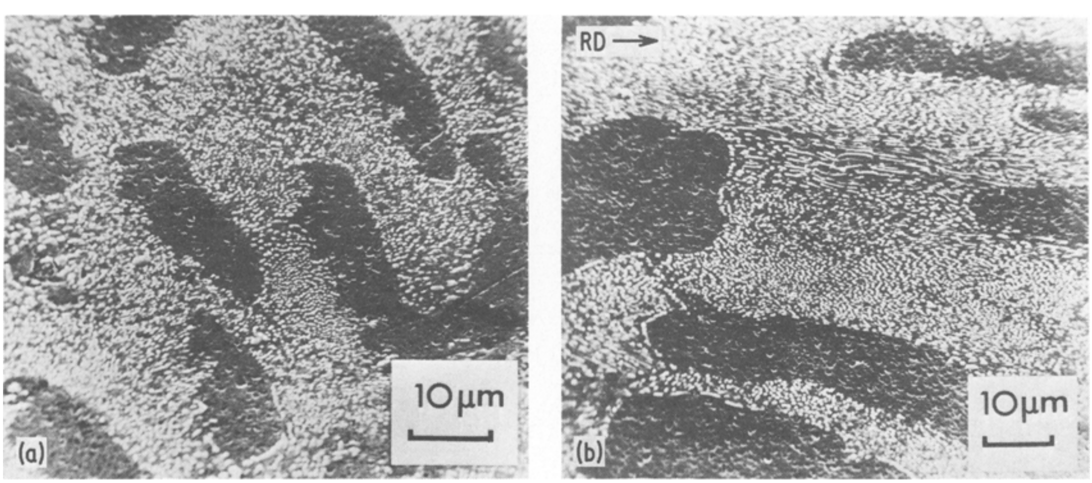

Figure 3 SEM (45° tilt) micrographs of chill-cast Al–4 wt% Ni alloy, hot-rolled at 500° C to a reduction of thickness of 44%. (a) Transverse and (b) longitudinal sections. RD = rolling direction.

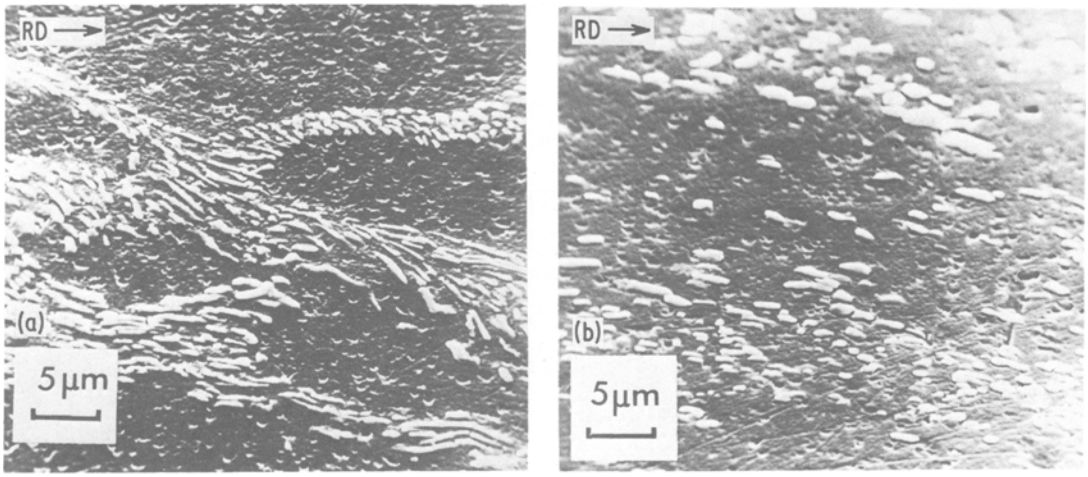

Figure 4 SEM (45° tilt) micrographs of chill-cast Al–2 wt% Ni alloy, hot-rolled at 500° C to a reduction of thickness of (a) 25% and (b) 80%. Longitudinal sections. RD = rolling direction.

strength, 0.2% off-set yield strength, and fracture strain as a function of Ni-content for as-chill-cast Al, Al–2 wt% Ni, and Al–4 wt% Ni alloys. Also included are previous data for the as-chill-cast Al–6.1 wt% Ni eutectic alloy [1]. Both the ultimate tensile strength and 0.2% off-set yield strength increased approximately linearly with increasing Ni-content, the ultimate tensile strength from 53 MPa (pure Al) to 219 MPa (6.1 wt% Ni), and the 0.2% off-set yield strength from 27 MPa (pure Al) to 112 MPa (6.1 wt% Ni). This increase in strength was associated with a rapid decrease in fracture strain with increasing Ni-content, from 24.7% (pure Al) to 3.1% (6.1 wt% Ni). These variations can also be seen on the typical stress–strain curves in Fig. 7 for the chill-cast alloys as a function of Ni-content.

Figs 8, 9 and 10 show the variation of ultimate tensile strength, 0.2% off-set yield strength and fracture strain, respectively, as a function of reduction in thickness during hot rolling for chill-cast Al, Al–2 wt% Ni, and Al–4 wt% Ni alloys. Also included are previous data for chill-cast Al–6.1 wt% Ni eutectic alloys [1]. Typical stress–strain curves are shown in Figs 11, 12 and 13.

For pure Al, the ultimate tensile strength and 0.2% off-set yield strength increased from 53 and 28 MPa in the as-chill-cast condition to 121 and 81 MPa after a reduction of 95%. Similarly, for both the Al–2 wt% Ni and Al–4 wt% Ni hypo-

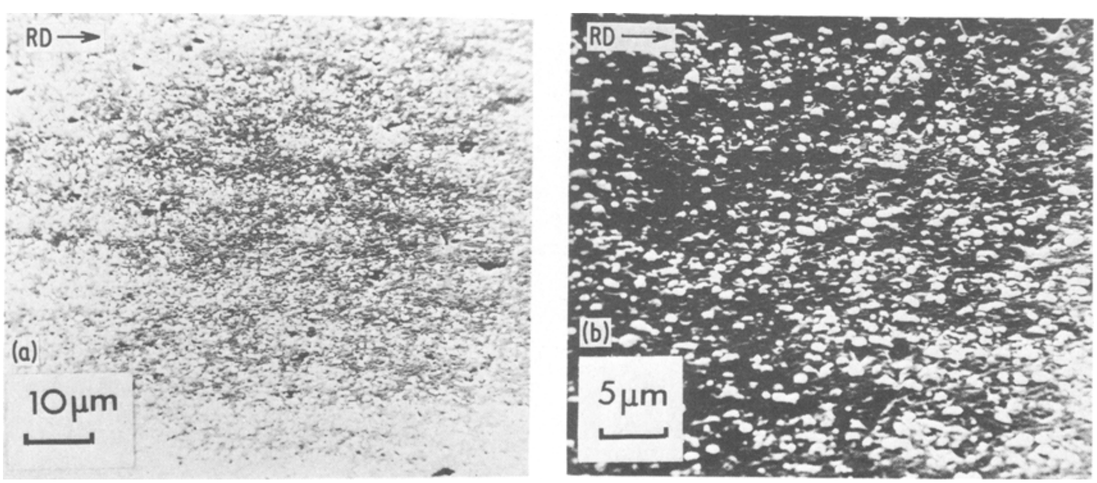

Figure 5 SEM (45° tilt) micrographs of chill-cast Al–4 wt% Ni alloy, hot-rolled at 500° C to a reduction of thickness of 85%. Longitudinal sections. RD = rolling direction.

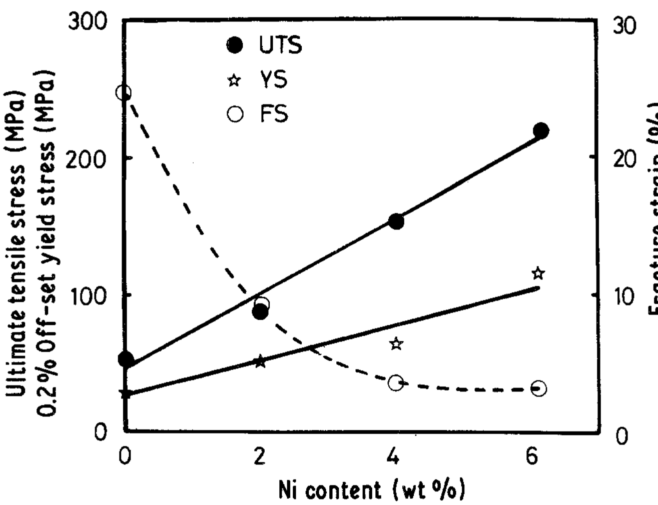

Figure 6 Variation of ultimate tensile stress, 0.2% off-set yield stress and fracture strain with increasing weight per cent Ni for chill-cast Al–Al_3Ni alloys.

eutectic alloys the ultimate tensile strength increased approximately linearly as the reduction of thickness increased, i.e., 88 MPa as-chill-cast to 156 MPa after a reduction of 91% for the Al–2 wt% Ni chill-cast alloy, and 154 MPa as-chill-cast to 167 MPa after a reduction of 97% for the Al–4 wt% Ni chill-cast alloy. This was in contrast to the ultimate tensile strength of the chill-cast eutectic alloy which remained approximately constant at 216 MPa during hot-rolling. As the reduction of thickness increased, the 0.2% yield strength also increased approximately linearly for each of the hypoeutectic alloys, from 52 MPa as-chill-cast to 132 MPa after a reduction of 91% for the Al–2 wt% Ni chill-cast alloy, and from 65 MPa as-chill-cast to 174 MPa after a reduction of 95% for the Al–4 wt% Ni chill-cast alloy. The fracture strain decreased from 9.3% as-chill-cast to 2.6% after a reduction of 91% for the Al–2 wt% Ni chill-cast alloy and from 3.6% as-chill-cast to 1.4% after a reduction of thickness of 97% for the Al–4 wt% Ni chill-cast alloy.

4. Discussion

The hypoeutectic Al–Al_3Ni alloys can be considered from two points of view. Firstly, they can be considered to be composites of α-aluminium dendrites and interdendritic eutectic regions. This applied to the as-cast and slightly deformed alloys where the Al–2 wt% Ni and Al–4 wt% Ni alloys contain 31 and 64 vol% dendrites, respectively [4]. Secondly, they can be considered to be composites of aluminium and Al_3Ni fibres. This applies to the highly deformed alloys in which the Al_3Ni fibres have been homogeneously dispersed throughout the matrix. In this case, the Al–2 wt% Ni and

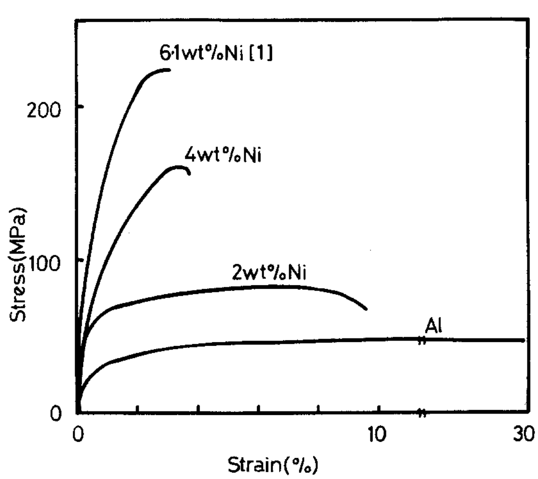

Figure 7 Stress–strain curves for chill-cast Al–Al_3Ni alloys.

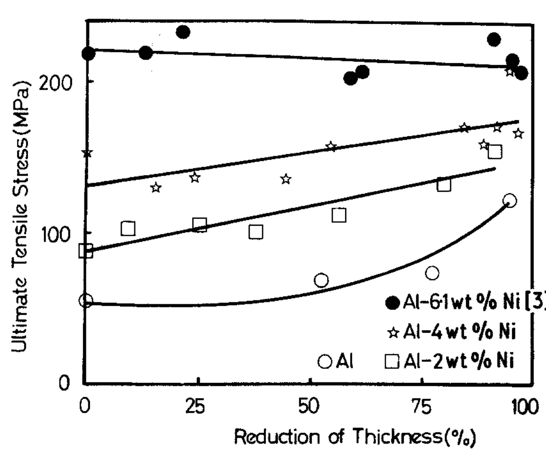

Figure 8 Variation of ultimate tensile stress with increasing reduction of thickness for chill-cast hypoeutectic and eutectic [3] Al–Al_3Ni alloys.

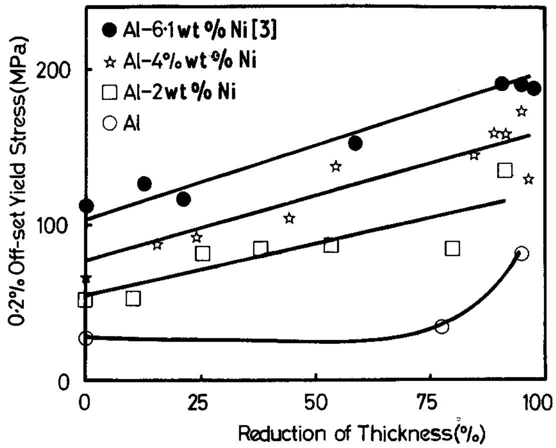

Figure 9 Variation of 0.2% off-set yield stress with increasing reduction of thickness for chill-cast hypoeutectic and eutectic [3] $Al–Al_3Ni$ alloys.

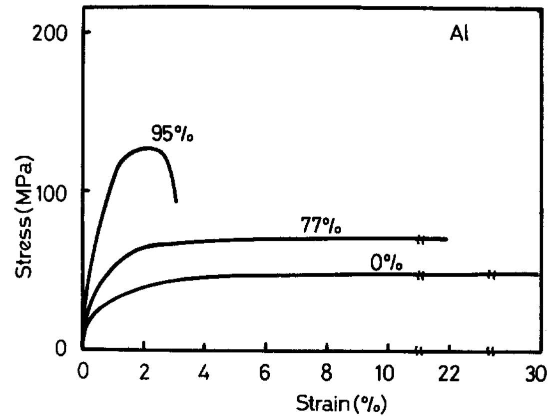

Figure 11 Stress–strain curves for chill-cast Al as a function of reduction of thickness.

Al–4 wt% Ni alloys contain 2.5 and 6.6 vol% Al_3Ni fibres [4], respectively.

For the as-chill-cast alloys of pure Al, Al–2 wt% Ni and Al–4 wt% Ni, and the eutectic, the ultimate tensile strength increases approximately linearly with increasing Ni-content (see Fig. 6). This suggests that the increasing volume-fraction of the strong, brittle Al_3Ni fibres is the factor responsible for this increase. As the $Al–Al_3Ni$ alloys consist of α-aluminium dendrites with interdendritic eutectic regions, the increase in volume-fraction of Al_3Ni is seen as an increase in the volume-fraction of the interdendritic eutectic regions. To interpret the increase in ultimate tensile strength in terms of eutectic present, the law of mixtures can be applied to give:

$$\sigma_c = V_e\sigma_e + V_d\sigma'_d, \tag{1}$$

where σ_c and σ_e are the ultimate tensile strengths of the hypoeutectic chill-cast composite, and the chill-cast eutectic, respectively, σ'_d is the stress borne by the dendrites, assumed to be pure Al, at the composite fracture strain, and V_e and V_d are the volume-fractions of eutectic and dendrites, respectively. Taking $\sigma_e = 219.2$ MPa [1], $\sigma'_d =$ 48.1 and 45.1 MPa from Fig. 7, $V_e = 0.31$ and 0.64 [4] and $V'_d = 0.69$ and 0.36 [4] for chill-cast Al–2 wt% Ni and Al–4 wt% Ni alloys, leads to predicted composite lengths of 101.1 and 156.3 MPa, respectively. These values compare well with the measured values of 88.4 and 153.8 MPa. Thus, the ultimate tensile strength of the hypoeutectic

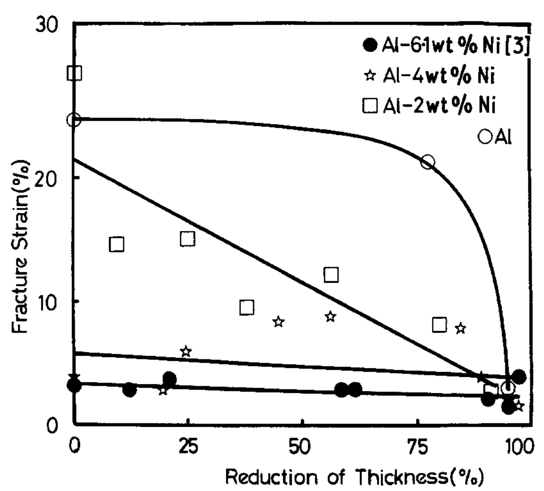

Figure 10 Variation of fracture strain with increasing reduction of thickness for chill-cast hypoeutectic and eutectic [3] $Al–Al_3Ni$ alloys.

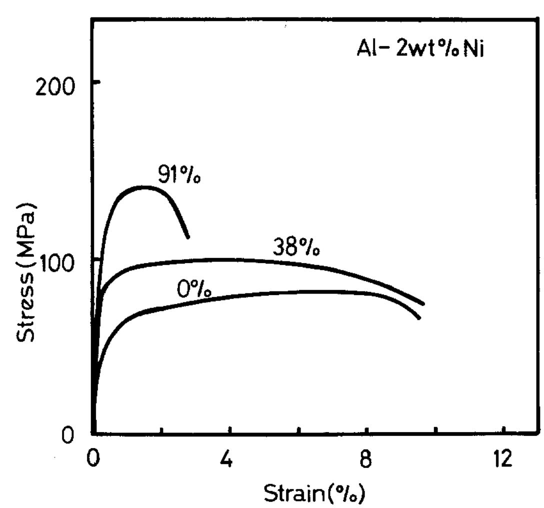

Figure 12 Stress–strain curves for chill-cast Al–2 wt% Ni as a function of reduction of thickness.

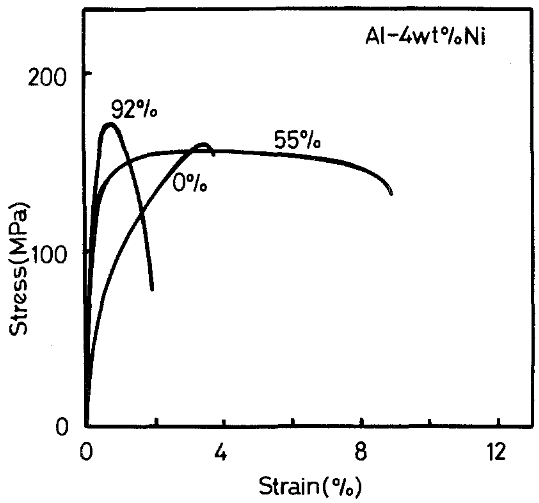

Figure 13 Stress–strain curves for chill-cast Al–4 wt% Ni as a function of reduction of thickness.

chill-cast alloys varies approximately linearly with volume-fraction of eutectic present and can be calculated using Equation 1. On hot-rolling the hypoeutectic Al–Al_3Ni chill-cast alloys the deformation behaviour is very similar to the chill-cast eutectic. Deformation is achieved by deforming the aluminium-rich dendrites in the rolling direction followed by interpenetration of the Al_3Ni fibres into the dendrites resulting in a homogeneous microstructure. This is similar to the interpenetration of the Al_3Ni fibres into the cell walls in the eutectic alloy [3]. However, unlike the eutectic, no fibre fracturing is experienced as the Al_3Ni fibres are initially only 2 to 4 μm in length. Thus, the hypoeutectic alloys on extensive deformation (reductions greater than 80%) can be considered as composites of Al_3Ni fibres in an aluminium-rich matrix.

The ultimate tensile strengths for the hot-rolled chill-cast Al, Al–2 wt% Ni and Al–4 wt% Ni alloys increase with increasing reduction of thickness (see Fig. 8). The increase in the hot-rolled pure Al is presumably caused by work hardening and increased alignment of the aluminium grains in the rolling direction. The increase for the Al–2 wt% Ni and Al–4 wt% Ni hypoeutectic alloys is presumably due to a combination of Al_3Ni fibre alignment and homogeneous dispersion through the matrix, and work hardening of the matrix.

The ultimate composite strength for discontinuous fibre reinforcement depends upon the critical fibre lengths, l_c, given by [5]

$$l_c = \sigma_f d/2\tau, \quad (2)$$

where σ_f is the ultimate tensile strength of the fibres, d is the fibre diameter and τ is the matrix shear strength given by

$$\tau = \sigma_u \cos^2 45°, \quad (3)$$

where σ_u is the ultimate tensile strength of the matrix. For a discontinuous fibre composite with a fibre length $l > l_c$, the composite ultimate tensile strength is given by [5]

$$\sigma_c = \sigma_f V_f \left(1 - \frac{l_c}{2l}\right) + \sigma'_m (1 - V_f) \quad (4)$$

and for $l < l_c$, the composite ultimate tensile strength is given by

$$\sigma_c = \sigma_u (1 - V_f) + \frac{\tau l V_f}{d}, \quad (5)$$

where V_f is the volume-fraction of fibres, and σ'_m is the strength of the matrix at the fracture strain of the composites.

Hertzberg *et al.* [6] have quoted σ_f for Al_3Ni as 2.7×10^3 MPa, d is about 0.4 μm [3], and σ_u for the chill-cast Al after about 90% reduction is 121 MPa from Fig. 8, so $\tau = 60.4$ MPa. With these values, Equation 2 gives $l_c \simeq 9$ μm, larger than the measured values of 2 to 4 μm for fibre lengths in chill-cast Al–2 wt% Ni and Al–4 wt% Ni alloys after 90% reduction. Thus, both rolled hypoeutectic alloys should fail by shear in the Al matrix at a composite failure stress given by Equation 5. With $l = 4$ μm, $d = 0.4$ μm, $\sigma_u = 121$ MPa and $\tau = 60.4$ MPa, Equation 5 predicts a strength of 133 MPa for $V_f = 0.025$ in Al–2 wt% Ni, and a strength of 153 MPa for $V_f = 0.066$ in Al–4 wt% Ni. These values compare reasonably well with the measured values of 156 and 165 MPa for the hot-rolled Al–2 wt% Ni and Al–4 wt% Ni hypoeutectic alloys, respectively (Fig. 6).

The redistribution of the Al_3Ni fibres into the dendrites leads to an increase in the yield strength (Fig. 9) due to dislocation flow being inhibited and a decrease in fracture strain (Fig. 10), as plastic flow due to the dendrites has been eliminated.

5. Conclusions

(a) For the chill-cast Al–Al_3Ni alloys, i.e., pure Al, Al–2 wt% Ni and Al–4 wt% Ni, and the eutectic, the ultimate tensile and 0.2% off-set yield strengths increase approximately linearly with increasing Ni-content.

(b) The chill-cast Al–2 wt% Ni and Al–4 wt% Ni hypoeutectic alloys can be hot-rolled at 500° C to reductions of greater than 95%. Deformation is achieved by deforming the α-aluminium dendrites in the rolling direction, followed by interpretation of the Al_3Ni fibres into the dendrites resulting in a homogeneous microstructure.

(c) The ultimate tensile strengths of the hot-rolled chill-cast Al, Al–2 wt% Ni and Al–4 wt% Ni alloys increase with greater reductions of thickness. The increase in the hot-rolled pure Al is presumably caused by work hardening and increased alignment of the aluminium grains in the rolling direction. The increase for the Al–2 wt% Ni and Al–4 wt% Ni hypoeutectic alloys is due to a combination of Al_3Ni fibre alignment and homogeneous dispersion through the matrix, and work hardening of the matrix. The redistribution of the Al_3Ni fibres into the dendrites leads to an increase in the yield strength due to dislocation flow being inhibited and a decrease in fracture strain as plastic flow due to dendrites has been eliminated.

(d) The experimentally-determined ultimate tensile strengths of the chill-cast hypoeutectic Al–Al_3Ni alloys are in good agreement with those predicted by a composite law of mixtures which considers the relative strength combinations of the volume-fractions of eutectic and primary dendrites.

(e) The experimentally-determined ultimate tensile strengths of the hot-rolled chill-cast Al–Al_3Ni hypoeutectic alloys, after large reductions of thickness are in good agreement with those predicted by the discontinuous fibre-reinforcement theory for composites containing fibres shorter than their critical length.

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References
1. F. S. J. JABCZYNSKI and B. CANTOR, *J. Mater. Sci.* **16** (1981) 2269.
2. *Idem*, Proceedings of the Conference on *In-situ* Composites III, Sheraton-Baston Hotel, USA, November 1978, edited by J. L. Walter, M. F. Gigliotti, B. F. Oliver and H. Bibriag (Ginn Custom, Lexington, MA, 1979) p. 303.
3. *Idem, Met. Trans.*, to be published.
4. F. S. J. JABCZYNSKI, DPhil thesis, Sussex University (1979).
5. A. KELLY and G. J. DAVIES, *Met. Rev.* **10** (1965) 37.
6. R. W. HERTZBERG, F. D. LEMKEY and J. A. FORD, *TMS-AIME* **233** (1965) 342.

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