SOLID SOLUTION STRENGTHENING OF Ni_3Al SINGLE CRYSTALS

BY TERNARY ADDITIONS

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Abstract

A systematic approach intended to determine the mechanism by which ternary additions increase the strength of Ni_3Al is presented. Uniaxial tensile and compressive flow stress measurements at constant strain rate were performed on single crystals of Ni_3Al containing additions of Hf, Ta, Zr, and B, and also on binary Ni-rich Ni_3Al. Data were collected over temperatures ranging from liquid nitrogen to 1100 °C, for different orientations within the standard unit triangle, different amounts of ternary additions as well as a function of the sense of the applied uniaxial stress. In agreement with previous studies, the yield strength of binary Ni_3Al presented a positive temperature dependence up to about 800 °C. The critical resolved shear stress (CRSS) for the {111}<110> slip was found to be orientation dependent, mostly over the positive temperature range (200 °C up to 800 °C). Additions of ternary elements are found to enhance the CRSS of octahedral slip with much less effect on the CRSS for cube slip. The temperature of the maximum CRSS as well as the orientation of the stress axis for which the tension-compression asymmetry is zero are both found to be composition dependent. The value of the octahedral CRSS measured at low temperatures exhibits a strong dependence on both composition and orientation of the stress axis. The tension-compression asymmetry, taken as a measurement of the rate of cross slip, is affected by the ternary additions, specially Ta and Hf, and mostly at intermediate temperatures. At low temperatures the asymmetry is almost zero in most cases. For orientations in which the tension-compression asymmetry was found to be zero, the increase of the octahedral CRSS with ternary additions is believed to be a consequence of a lattice parameter/modulus mismatch mechanism. For orientations in which the asymmetry is non zero the effect of ternary additions on dislocation core configuration also needs to be considered.

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Introduction

A positive temperature dependence of the flow stress is well documented, both for polycrystalline and single crystalline Ni_3Al (1). This unusual behavior has been attributed to thermally and stress-activated cross-slip from the (111) to the (010) plane of the leading $1/2(111)[\bar{1}01]$ screw superpartial comprising a $(111)[\bar{1}01]$ superdislocation. This cross-slip can be driven by anisotropy of the antiphase boundary (APB) energy, resolved shear stress on (010), or elastic anisotropy (1,2) . These effects have been combined in a theory which explains the observed dependence of the CRSS for $(111)[\bar{1}01]$ slip on both orientation and sense of the applied uniaxial stress (3-6).

Many ternary elements are soluble in Ni_3Al and some result in remarkable strengthening. Curwick was the first to study their effect in single crystals (7) and recently there has been a great deal of research performed on polycrystalline material (8). The current work was initiated on single crystalline, ternary Ni_3Al-based alloys to separate the effects of Fleischer-type solid solution strengthening from effects arising from cross-slip considerations.

Experimental Procedure

Tension/compression specimens where machined by grinding from single crystal bars of binary nickel rich Ni_3Al and Ni_3Al containing ternary additions of Hf, Ta, Zr and B. We tested two compositions of each, Hf, Ta, and Zr, and three compositions of B. The detailed chemical composition of the single crystal bars is shown in Table I. The orientation of the specimens in the standard [001]-[011]-$[\bar{1}11]$ unit triangle is shown in Fig.1. Schmid Factors for octahedral slip are listed in Table II. Experimental details are described in ref (6).

Table I. Alloy Composition of the Ni_3Al + X Single Crystal Bars

Material (addition)	Composition (at%) at% Ni	at% Al	at% X
Binary	76.60	23.40	none
1Ta	74.30	24.70	1 Ta
2.5 Ta	74.50	23.00	2.5 Ta
1 Hf	75.80	23.00	1.0 HF+0.2 B
3.3 Hf	74.80	21.80	3.28 Hf
0.3 Zr	76.01	23.63	0.26 Zr
1 Zr	76.19	22.80	1.04 Zr
0.2 B	77.15	22.63	0.195 B
0.7 B	76.92	22.56	0.67 B
1 B	76.52	22.08	0.98 B

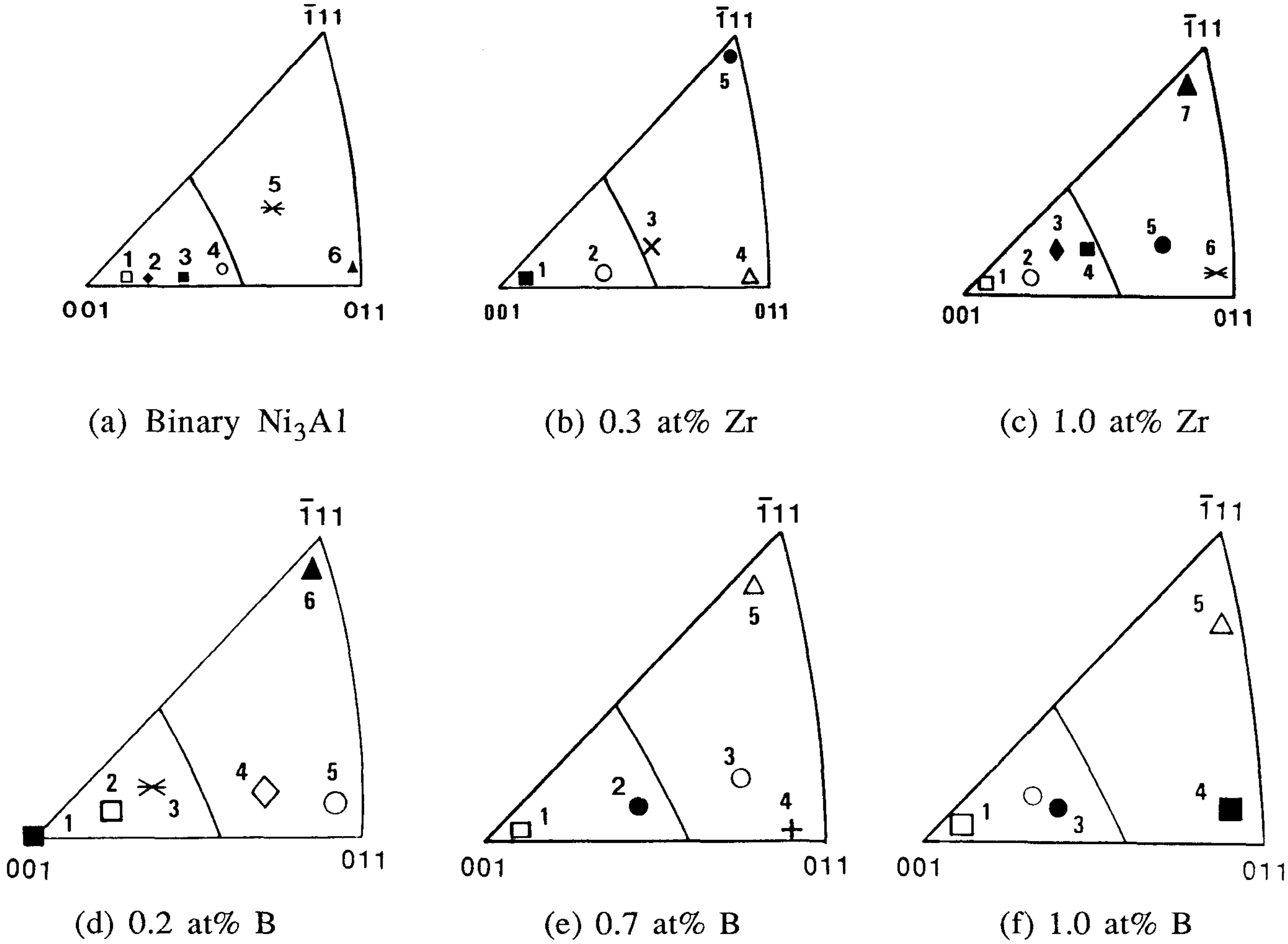

Figure 1 - Orientation of the samples tested in the present study. The numbers refer to the orientation in table II.

Table II. Schmid Factors on the Octahedral System for the Orientations Tested

OCTAHEDRAL SYSTEM (111)[$\bar{1}$01]							
	Orientation						
Material	1	2	3	4	5	6	7
Binary	0.449	0.463	0.491	0.5	0.479	0.429	
1.0% Ta	0.44	0.478	0.489	0.492			
2.5 % Ta	0.435	0.47					
1.0% Hf	0.431	0.474					
3.3% Hf	0.453	0.475	0.489	0.478	0.435	0.412	
0.3% Zr	0.455	0.493	0.499	0.455	0.306		
1.0% Zr	0.428	0.476	0.486	0.49	0.486	0.44	0.33
0.2% B	0.419	0.474	0.489	0.489	0.443	0.307	
0.7% B	0.435	0.498	0.455	0.442	0.496		
1% B	0.442	0.486	0.493	0.451	0.4		

Results and Discussion

Figures 2, 3, and 4 show the temperature and orientation dependence of the CRSS for $(111)[\bar{1}01]$ slip for the binary Ni_3Al alloy and the Ni_3Al with additions of Zr and B for each of the compositions tested. Results are shown for tensile tests as well as for compression tests. The CRSS is resolved in the octahedral system, even though slip is known to occur on (001) planes for temperatures above the peak temperature for orientations other than [001]. The results for Ni_3Al with additions of Hf and Ta are shown in a previous paper (9). However, the results for all the different additions and compositions used in this study, including Zr and B, are shown in Fig. 5 for the orientation in which the tension/compression asymmetry vanishes. In all these figures, each datum point represents the average of at least two tests performed on each orientation. Zr was chosen as an additive because it is a very potent strengthener of Ni_3Al, as is Hf. B on the other hand, is the only additive used in this research which occupies interstitial sites instead substituting for Al in the crystal lattice.

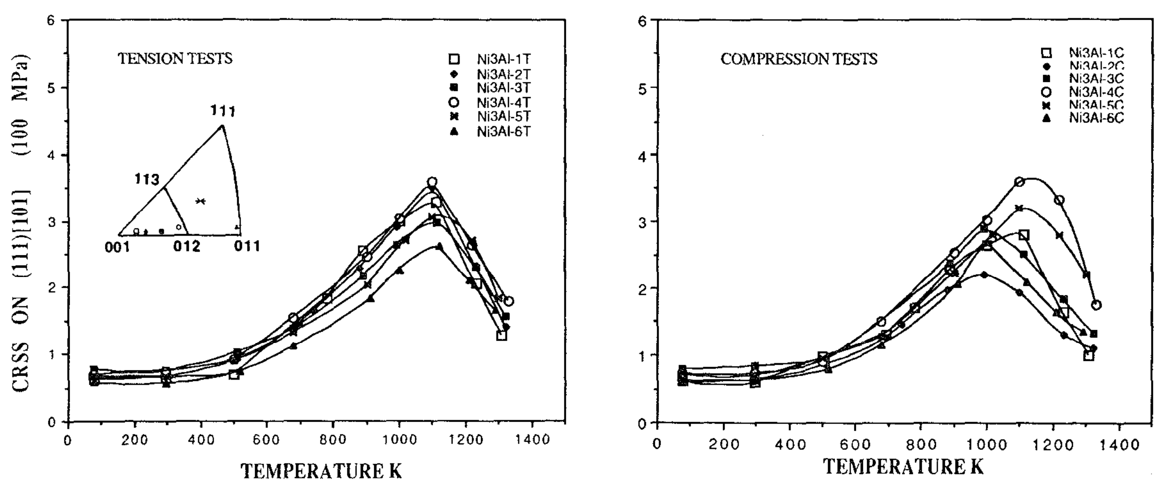

Figure 2 - CRSS for $(111)[\bar{1}01]$ slip of binary Ni_3Al as a function of temperature and orientation of the stress axis.

As pointed out elsewhere (3) the value of the CRSS at temperatures below the peak temperature depends on the orientation of the tension/compression axis, and additions of Zr and B make the dependency more dramatic, as did the additions of Hf and Ta. Note that the CRSS at low temperature for the 0.7 at% B alloys is approximately 75 MPa in tension, about 100 MPa in compression, but the CRSS of the binary Ni_3Al is only about 25 MPa in both tension and compression.

The magnitude of the CRSS is increased in the range of positive temperature dependence by additions of 1 at% Zr and 0.7 at% B, but it is increased by additions of 1 at% B by approximately 150 MPa over the entire range of temperatures studied. In contrast, the value of the CRSS was not seriously affected by additions of 0.3 at% Zr and 0.2 at% B, and only at 77 K do these two additions change the magnitude of the CRSS: 0.3 at% Zr has a "softening effect" lowering the value of the CRSS by an average of about 18 MPa, and 0.2 at% B increases the CRSS at 77 K by approximately 15 MPa on average, depending on the orientation tested.

Comparing these results with those previously obtained for additions of 1 and 3.3 at% Hf and 1 and 2.5 at% Ta, it is noticed that the effect of 0.7 and 1 at% B on the octahedral CRSS are the strongest

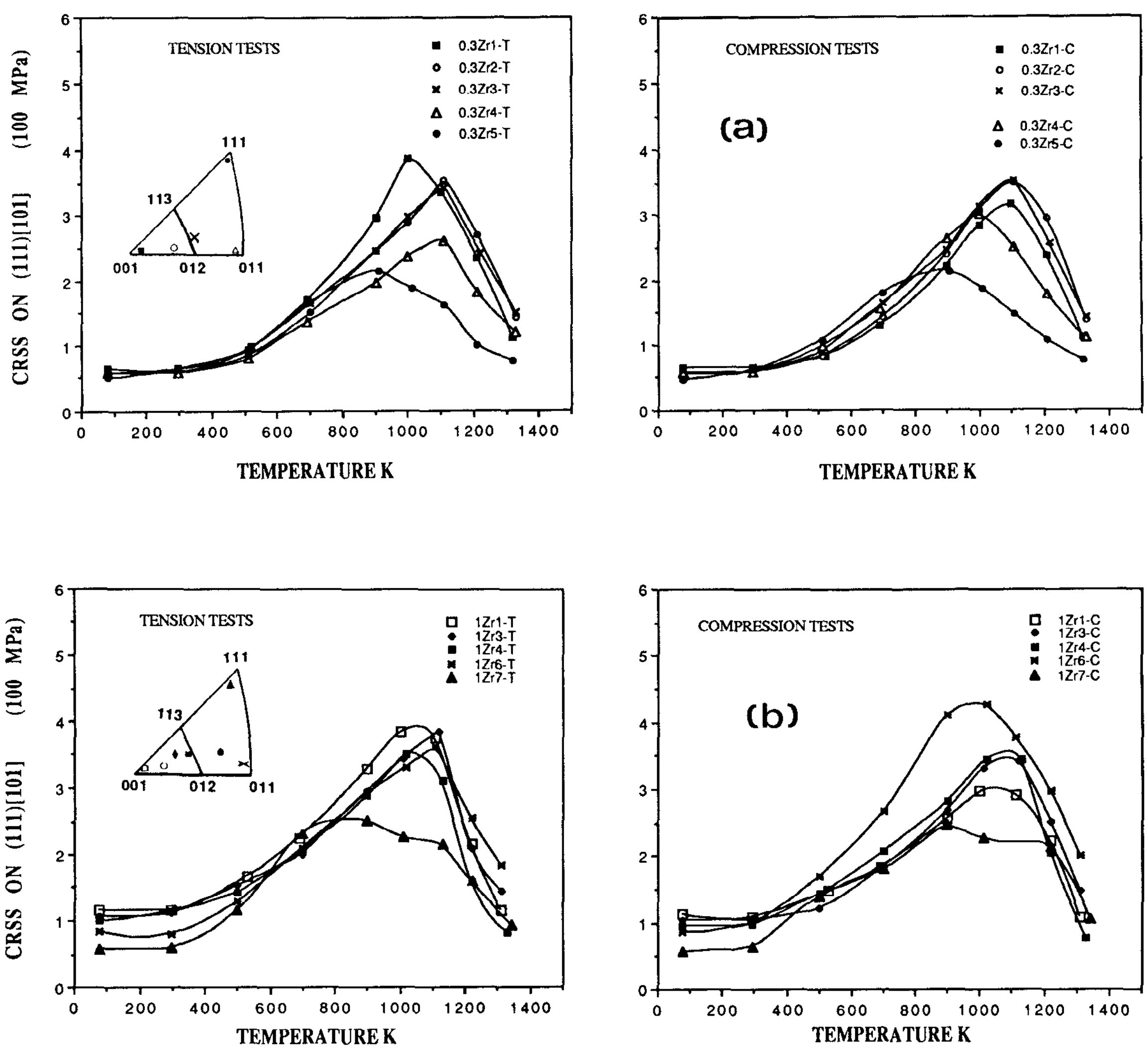

Figure 3 - CRSS for (111)[$\bar{1}$01] slip as a function of temperature and orientation of the stress axis for Ni_3(Al, Zr) with additions of (a) 0.3 at% Zr, and (b) 1.0 at% Zr.

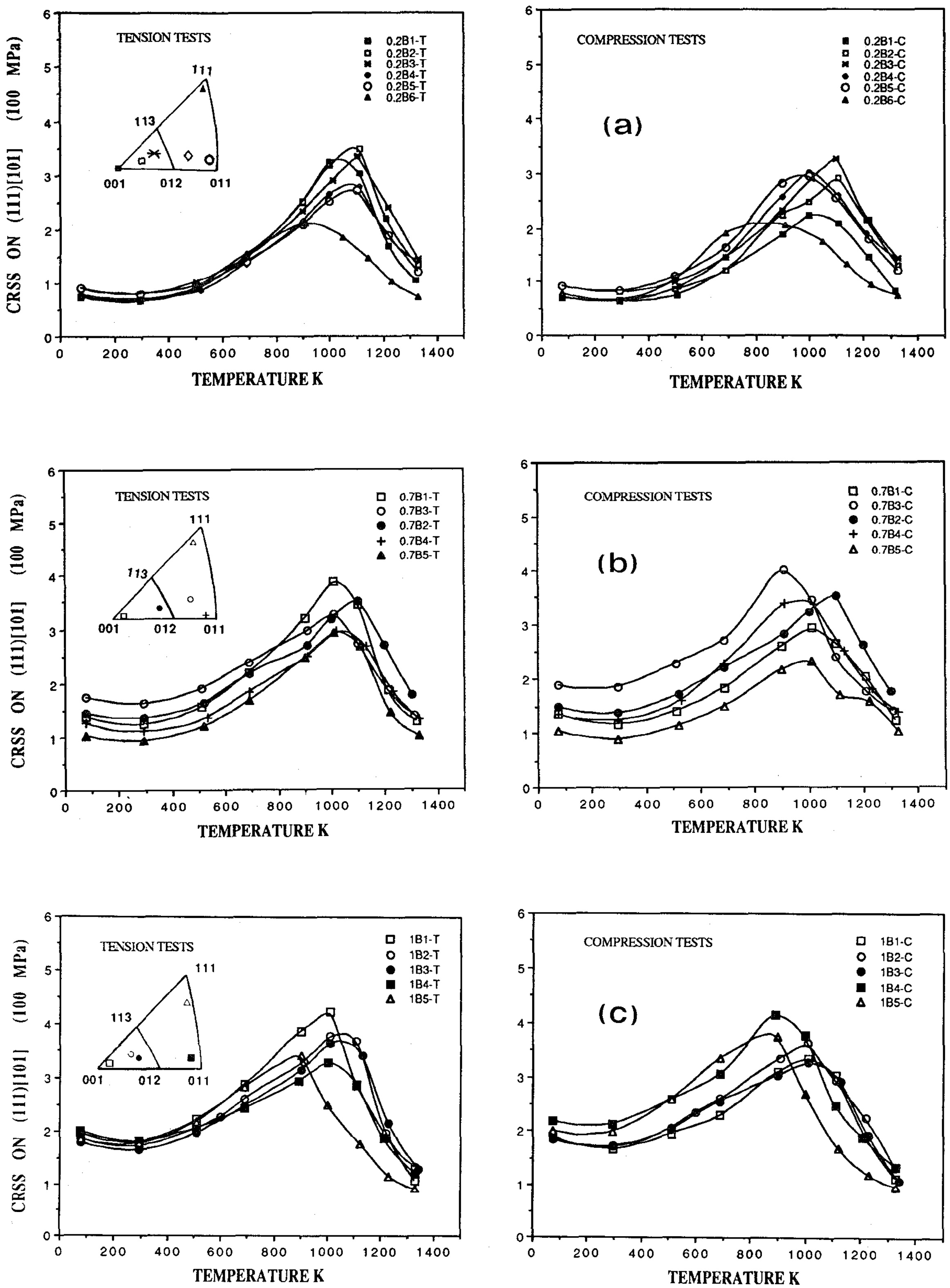

Figure 4 - CRSS for (111)[$\bar{1}$01] slip as a function of temperature and orientation of the stress axis for Ni_3Al + B: (a) 0.2 at% B; (b) 0.7 at% B; (c) 1.0 at% B

at low temperatures but addition of 3.3 at% Hf has the most effect at the peak temperature, especially for orientations near [001]. The effect of the ternary additions on the tension/compression asymmetry follows the same trends discussed for the increase of the CRSS. The additions of 0.3 at% Zr and 0.2 at% B slightly increase the asymmetry over that of binary Ni_3Al. The remaining additions all increase the asymmetry but the increase is similar for each case. The sense of the asymmetry follows the same trends as predicted by the Paidar *et al.* model (3) and verified later by Ezz (4) and Umakoshi (5) on single phase single crystals and by Heredia and Pope in a two phase single crystalline alloy (6).

It is important to note at this point that Zr as well as Hf, Ta and Nb (4) occupy the Al sites in the ternary alloy Ni_3Al + X, but B occupies interstitial sites and therefore the effect of lattice friction plays an important role on the strengthening mechanism of the alloys. Among the compositions tested, 0.7 at% B produces the most accentuated effect. 1 at% B raises the magnitude of the CRSS qualitatively similar to the effect of the substitutional type elements.

In Figure 5 the CRSS for octahedral slip as a function of temperature and composition for the orientations showing zero tension/compression asymmetry is presented. Data for 5 at% Ta and 4.3 at% Nb are from Umakoshi *et al.* (5) and S. Ezz *at al* (4) respectively. Data for the other Ta and Hf alloys have been reported by the present authors earlier (9). It is clearly seen that ternary additions do strengthen Ni_3Al at temperatures as low as 77 K with only one exception, 0.3 at% Zr. The 2.5 and 5 at% Ta alloys show the highest CRSS at the peak temperature, and the highest strengthening rate over the range of positive temperature dependence. The peak temperature, the temperature where the maximum CRSS occurs, decreases as the amount of ternary addition increases, with the exception of Ta. Boron, even though it increases the value of the CRSS at low temperatures, as mentioned previously, does not increase its magnitude at the peak temperature. The high temperature value of the RSS (above the peak temperature) is much less dependent on the composition, because slip actually occurs on the cube system in this temperature range (10).

The orientation for which the tension/compression asymmetry vanishes also shows a compositional dependency: as the amount of ternary element is increased, the orientation for T=C moves toward [001] from the [$\bar{1}$13]-[012] great circle. The T=C orientation of the binary Ni_3Al is the closest to this circle.

Finding the orientation for zero asymmetry is important because for these orientations the rate of cross-slip does not depend on the

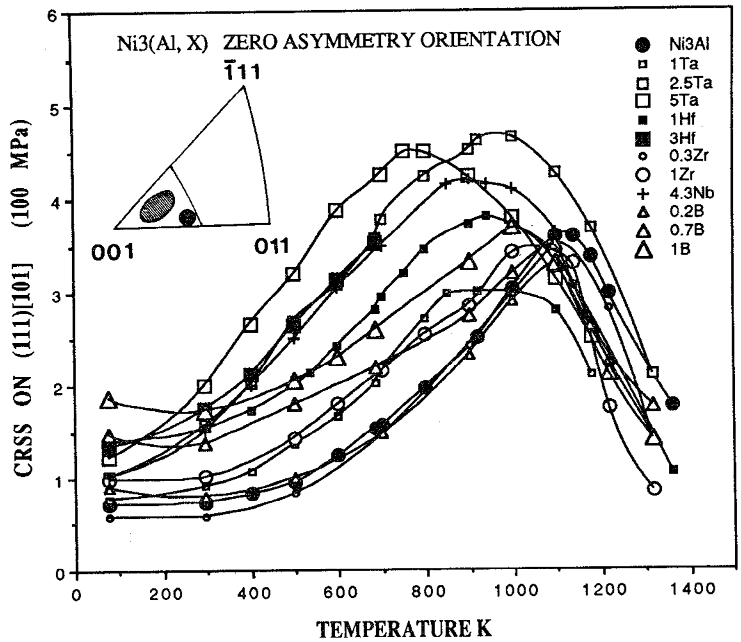

Figure 5 - The CRSS for octahedral slip as a function of temperature and composition for orientations which show zero tension/compression asymmetry.

dislocation core width. For such a condition the expression for the activation enthalpy of cross-slip is greatly simplified (3). For this particular case, assuming that the difference in APB energy on the (111) and (001) planes is small compared with the resolved shear stress (RSS) on the (001) plane, equation [23] in Paidar *et al.* (3) has been shown previously (9) to reduce to:

$$T \ln \Delta \tau_i = A - B\,(\tau_{i,\,pb})^{1/2}, \qquad (1)$$

where $\Delta \tau_i$ is the difference between the RSS at a given temperature with respect to the RSS at 77 K for the same ith ternary addition; $\tau_{i,\,pb}$ is the RSS on the primary (111) plane in the direction of the [$\bar{1}$01] Burgers vector, also for the same ith ternary addition, and A and B are constants.

In Fig. 6, $T\ln\Delta \tau_i$ is plotted against $(\tau_{i,pb})^{1/2}$. A fairly narrow band is obtained in which twelve different compositions and four different temperatures are represented. A slight deviation from the band is found for the boron-containing material which as mentioned earlier has different alloying characteristics. The fact that all the different compositions follow this pattern indicates that the difference in the APB energies between (111) and (001) planes do not depend on temperature or composition. Thus, for the particular case of zero asymmetry orientations, ordinary solid solution strengthening effects seems to be most important in determining the CRSS for (111)[$\bar{1}$01] slip.

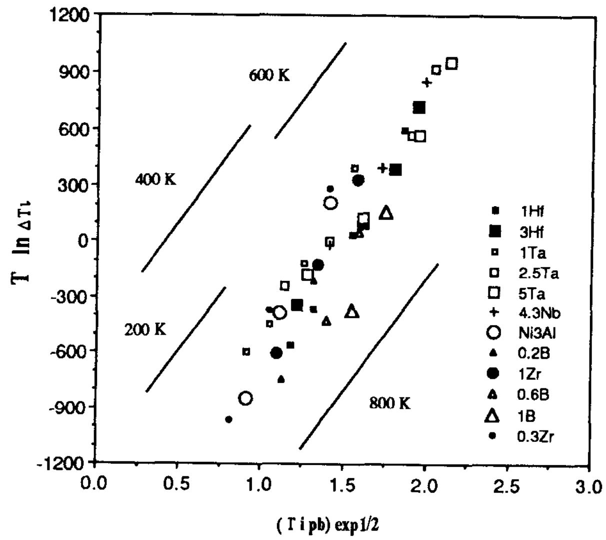

Figure 6 - T lnΔT_i as a function of composition and RSS.The straight lines indicate the ranges over which data are presented for each temperature

Conclusions

1. Additions of ternary elements to Ni_3Al increase the CRSS for octahedral slip but have little effect on the RSS for cube slip.

2. In the present study, Hf and Ta are the elements that show the strongest effects on the CRSS for the (111)[$\bar{1}$01] slip.

3. Additions of more than 0.7 at% Boron markedly increase the value of the octahedral CRSS at low temperatures.

4. The orientation for which the tension/compression asymmetry vanishes is composition dependent.

5. The core dissociation effect is an important mechanism for the tension/compression asymmetry but where it disappears, solid solution strengthening effects are the dominant ones.

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