

The Effects of Cr Additions to Binary TiAl-Base Alloys

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The effects of Cr additions to γ -base alloys have been investigated, using bulk materials consolidated from rapid solidification-processed ribbons. The composition ranges studied were 0 to 4 at. pct Cr and 44 to 54 at. pct Al. It was found that Cr additions do not affect the deformation behavior of single-phase γ alloys. However, they significantly enhance the plasticity of Al-lean duplex alloys which contain grains of single-phase γ and grains of lamellar γ/α_2 . Other Cr effects on microstructure, phase stability, site occupancy, and deformation substructures were characterized and correlated to the observed mechanical behavior. It was concluded that the ductilization effect of Cr in duplex alloys is partially due to the tendency of Cr to occupy Al lattice sites. Ductilization is also partially due to the ability of Cr to modify the Al partitioning and, therefore, the thermal stability of transformed α_2 laths.

I. INTRODUCTION

BECAUSE of its attractive high-temperature properties, the lightweight compound γ -TiAl has received a great deal of research attention since early 1950.^[1,2] Much of the attention was devoted to low-temperature deformability, since this is a major hindrance to actual uses. Early work of Marcinkowski *et al.*^[3] and Greenberg^[4,5] suggested that γ aluminide deforms by slip of $1/2[110]$ unit dislocations and $[101]$ and $1/2[112]$ superdislocations. The superdislocations would dissociate into a $1/6[112]$ partial bounded by a $\{111\}$ superlattice stacking fault. However, Shechtman *et al.*^[6] and Hug *et al.*^[7,8] showed that in single-phase γ materials, the $1/6[112]$ partials tend to be pinned, forming sessile faulted dipoles.

Recently, Huang and co-workers^[9,10,11] studied Al-lean binary alloys which contained α_2 -Ti₃Al as a second phase. It was found that superdislocations are inactive in fine-grained duplex alloys; instead, twinning on $\{111\}$ planes, with the $1/6[112]$ partial as the twin dislocation, becomes an important mode of deformation. This change in deformation mechanism is an indication of a reduced stacking fault energy. Correspondingly, duplex alloys are more ductile than single-phase alloys. However, the α_2 phase, typically in the form of lamellar laths transformed from α , has the tendency to resist deformation.^[10]

Also recently, alloying additions of Mn, V, or Cr were reported to enhance the plasticity of duplex alloys, as summarized in References 12 and 13. The effects of Mn and V additions have been characterized extensively. Hanamura *et al.*^[14,15,16] concluded that Mn enhances plasticity by stabilizing thermal twins which provide nucleation sites for twin dislocations. Manganese was measured to lower stacking fault energy.^[17] Huang and Hall^[18] showed that V reduces the stability of transformed α_2 . Both Mn^[19,20] and V^[17] were shown to substitute for Al and, therefore, modify the Ti-Al bond.^[21] All of the above three elements reduced the lattice unit cell volume.^[12]

This study was aimed at understanding the effect of Cr additions to γ -base alloys. Systematic variations in Cr and Al concentrations were carried out, and their ef-

fects on ductility, microstructure, deformation, and lattice substitution were characterized. The results are compared to those obtained from parallel studies on binary^[11] and TiAl-V alloys^[18] in order to correctly assess the Cr effects. All of the materials studied here were processed *via* the rapid solidification route to ensure microstructural homogeneity.

II. EXPERIMENTAL

Several γ -base ternary alloys containing 45 to 54 at. pct Al and 1 to 4 at. pct Cr were prepared by rapid solidification processing for this investigation. Each alloy was melt-spun into ribbon^[22] which was then consolidated by cold compaction, hot isostatic pressing, and extrusion to produce homogeneous bulk material. Samples for heat treatment were cut from the consolidated materials, each wrapped in a tantalum foil, and encapsulated with a piece of yttrium in a quartz tube backfilled with 2 to 3 $\times 10^4$ Pa of argon. The sample capsules were heated for 2 hours between 1250 °C and 1425 °C and cooled to room temperature in air. Chemical analyses indicated that the heat-treated materials had Al contents within 0.5 at. pct of the nominal compositions. The interstitial contents were nitrogen ~ 200 ppm and oxygen ~ 800 ppm by weight.

The microstructures of the heat-treated materials were studied by optical microscopy, using metallographic samples prepared with a procedure described in Reference 23. Some materials were also studied by analytical electron microscopy (AEM). The mechanical behavior was studied by four-point bending and tensile tests at room temperature. After the tests, the deformation substructures were studied by AEM, using a PHILIPS* EM430 operating at 300 kV. Additionally,

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ALCHEMI (atom location by channeling-enhanced microanalysis) experiments were performed on foils prepared from undeformed Ti-48Al-2Cr and Ti-54Al-2Cr alloys. Both axial (on the pole) and planar channeling spectra were obtained, the latter using the 110-type plane. The microscope was operated in nanoprobe mode, with

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the illumination convergence lessened such that an $\sim 0.8\text{-}\mu\text{m}$ -diameter area of the sample was illuminated.

III. RESULTS

A. Microstructural Types

The microstructures of the present alloys were studied in bulk materials consolidated from melt-spun ribbons. They were homogeneous, and showed no prior-ribbon boundaries on an optical scale. They varied significantly, however, depending on composition and heat-treatment temperature. In alloys containing ≤ 2 at. pct Cr, three distinct microstructures were observed, as in binary alloys.^[11] They included a single-phase equiaxed γ structure, a fully transformed lamellar $\gamma + \alpha_2$ structure, and a duplex structure consisting of both constituents above. Examples of the microstructures are shown in Figures 1(a) through (c). They correspond to heat treatments in the phase field of γ , α , and $\gamma + \alpha$, respectively. In addition to the phase volume and distribution differences, they also differed in grain size.

Typically, the grain size was $\sim 50\ \mu\text{m}$ in the single-phase γ structure, $> 500\ \mu\text{m}$ in the fully transformed structure, and $\sim 15\ \mu\text{m}$ in the duplex structure.

The above three microstructures were also observed in alloys containing > 2 at. pct Cr. However, the formation of a third phase became obvious in these high-Cr alloys. Figure 1(d) shows an essentially duplex structure with particles (arrow) present in grain-boundary areas. The particles were 1 to 2 μm in size.

B. Phase Field Examination

A systematic metallographic examination was done on samples heat treated from $1250\ \text{°C}$ to $1425\ \text{°C}$ at $25\ \text{°C}$ intervals. The results allowed the determination of transitions from one structure or, in effect, from one phase field to another. Two major transitions were observed in the present composition and heat-treatment temperature ranges. One transition was from a single phase to a duplex structure, due to the formation of α from γ phase. The temperature of this transition is the γ solvus. The other transition occurred from a duplex to a fully transformed structure. This temperature is the α transus.

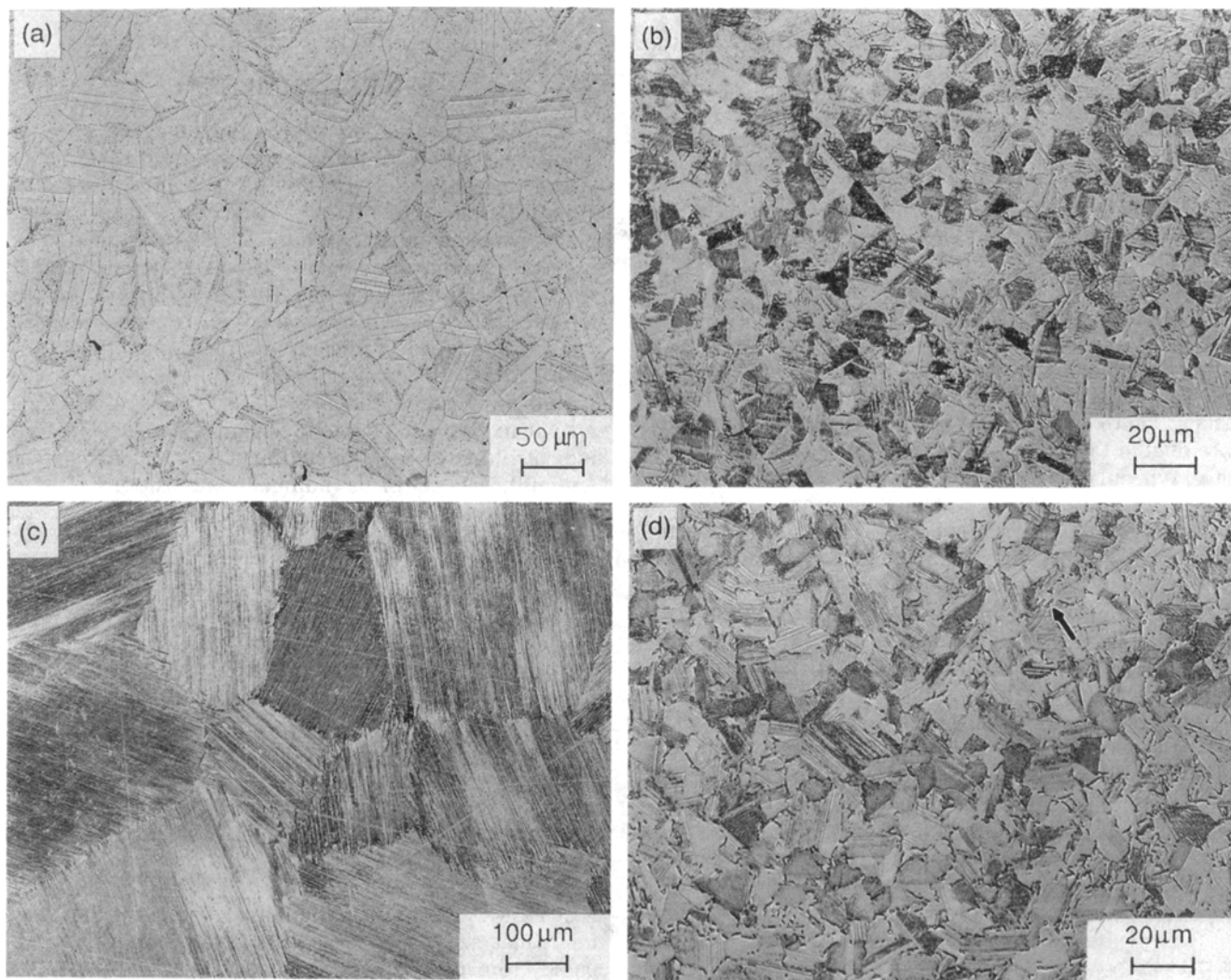


Fig. 1—Optical micrographs of (a) Ti-54Al-2Cr heat treated at $1400\ \text{°C}$, showing a single-phase γ structure; (b) Ti-48Al-2Cr heat treated at $1300\ \text{°C}$, showing a duplex structure; (c) Ti-48Al-2Cr heat treated at $1400\ \text{°C}$, showing a fully transformed α structure; and (d) Ti-48Al-4Cr heat treated at $1300\ \text{°C}$, showing a duplex structure with particles of a Cr-rich phase (arrow).

It was found that the α transus decreased with increasing Cr additions (Figure 2(a)). The rate of decrease was $\sim 15^\circ\text{C}$ for every atomic percent addition. Similar depressions in the transus occurred at all Al concentrations from 45 to 50 at. pct, as shown in Figure 2(b). Thus, Cr had the effect of extending the α -phase field toward higher Al.

The γ solvus was determined for Ti-52Al-2Cr and Ti-54Al-2Cr (Figure 3). It should be noted that these measurements were relatively difficult, because the corresponding microstructural changes were quite subtle.^[23] The results are compared to the solvus line recently determined by the present authors for binary alloys. As seen, the Cr additions had relatively little effect on the γ solvus.

In addition to α and γ , a third phase tended to form with a decreasing Al or an increasing Cr concentration. The alloy Ti-48Al-4Cr in Figure 1(d) was apparently heat treated in a three-phase field. The boundary for the third-phase formation was not determined.

C. Transmission Electron Microscopy

The duplex structure in Ti-48Al-2Cr (Figure 1(b)) and Ti-46Al-2Cr was studied by transmission electron microscopy (TEM). Figure 4(a) is an overall micrograph

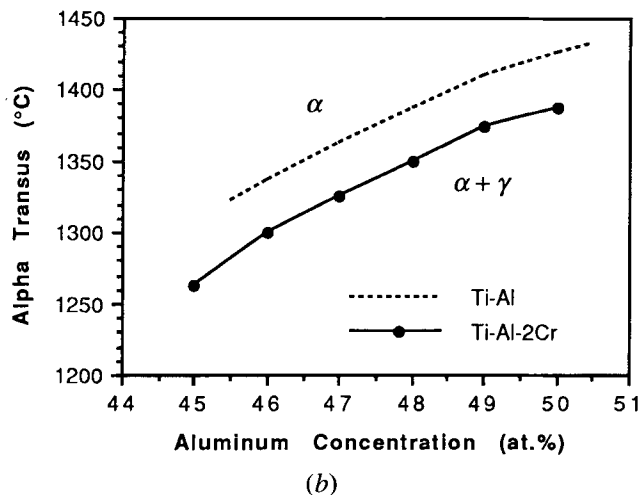
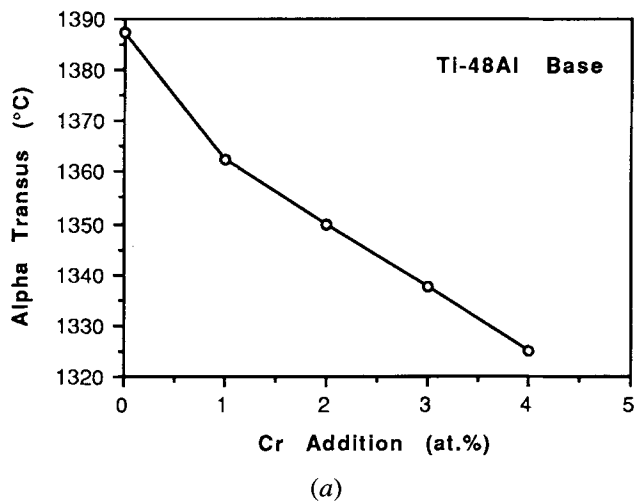


Fig. 2—The effect of Cr additions on α transus: (a) on the 48 at. pct Al basis and (b) at the 2 at. pct Cr addition level.

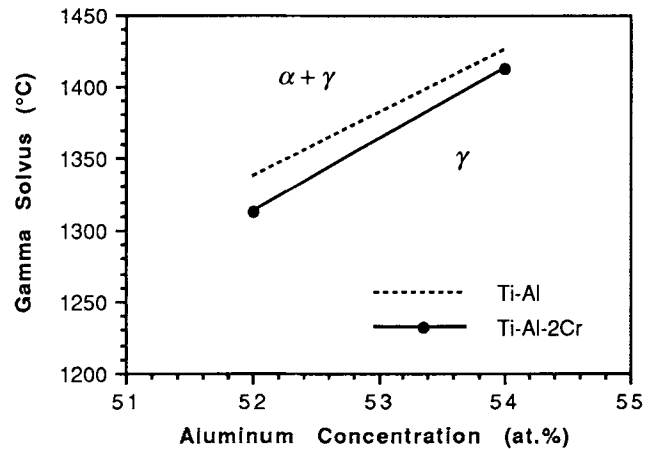


Fig. 3—The effect of 2 at. pct Cr additions on γ solvus loci.

from the latter alloy. In addition to single-phase γ (primary γ) grains, there were a large number of grains which contained γ and α_2 lamellar laths. The lamellar grains were primary α in equilibrium with γ at the annealing temperature. In some lamellar grains, the γ and α_2 laths were quite thick, $\sim 0.3\ \mu\text{m}$, apparently due to continuous coarsening.^[24] In many of the other grains, the laths remained thin, $\sim 0.05\ \mu\text{m}$. However, thin lamellae were only present near grain boundaries, and the grain interiors contained only γ (coarsened γ) with occasional twins. There, α_2 laths appeared to be eliminated by a discontinuous coarsening mechanism.^[25] As a result, the overall γ volume fraction were increased, despite the large number of primary α grains. In comparison with duplex binary alloys,^[11,26] the coarsening-induced redistribution of γ and α_2 appeared to be much more pronounced due to the additions of Cr.

Another Cr-addition effect was the formation of a third phase, as shown in Figure 4(b). This phase was found in both of the two alloys studied by TEM. It was not discernable in the 2 at. pct Cr alloys on the optical scale (Figure 1(b)) but formed in abundance in the 4 at. pct Cr alloys (Figure 1(d)). The electron diffraction patterns from this phase were consistent with an ordered CsCl structure (nominally Ti_2CrAl) with $a = 3.12\text{\AA}$. The Ti_2CrAl phase contained >10 at. pct Cr, as shown in Table I.

D. Mechanical Behavior

A series of alloys based on 48 at. pct Al was studied to evaluate the effect of 1 to 4 at. pct Cr additions on the plasticity of γ -base alloys. The 48 at. pct Al was chosen as the basis, since it produced the duplex structure and yielded the highest ductility among binary alloys.^[11] The ternary alloys studied here also had the duplex structure, using heat-treatment temperatures between 1275°C and 1300°C . Figure 5 shows plastic fracture strain as a function of Cr concentration, measured by bending and tensile tests at room temperature. The tensile tests consistently generated higher strain values than the bending tests, but they revealed the same trend, *viz.* the plasticity increases and then decreases with Cr concentration, showing a maximum at 2 at. pct Cr.

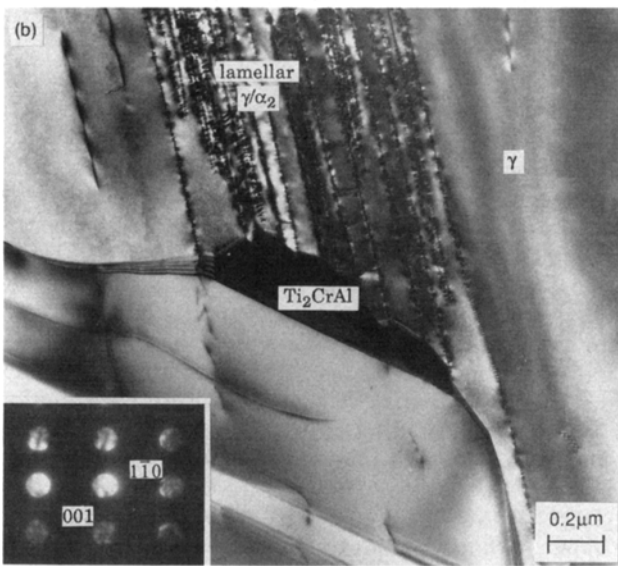
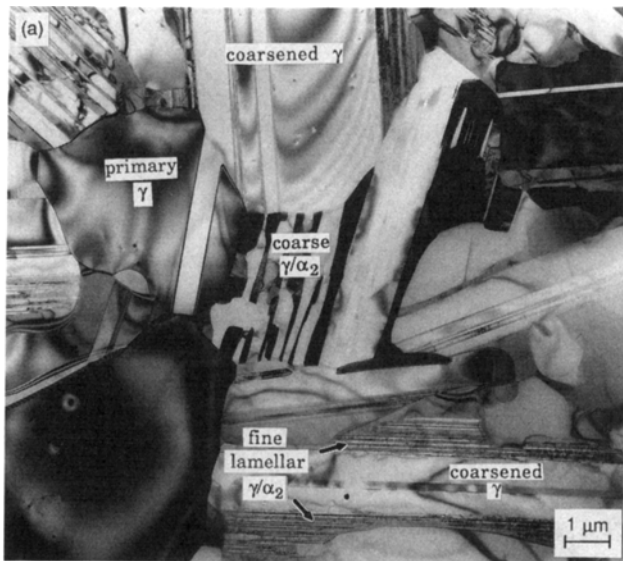


Fig. 4—Transmission electron micrographs of the duplex structure in Ti-46Al-2Cr: (a) the overall microstructure and (b) a Ti_2CrAl particle with inset showing the (110) diffraction pattern.

A second series of alloys based on the addition of 2 at. pct Cr was studied. It was found that even with Cr additions, the type of microstructure had a significant effect on plasticity, as in the case of binary alloys.^[11] Figure 6 shows the plasticity measured as a function of heat-treatment temperature in Ti-46Al-2Cr. The duplex

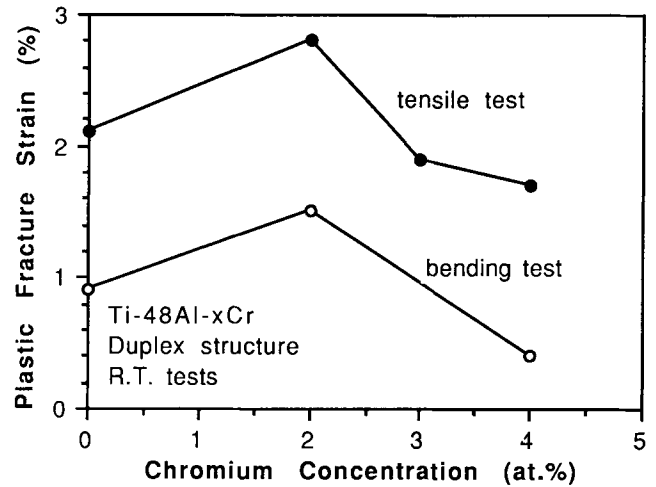


Fig. 5—Plasticity as a function of Cr additions to Ti-48 at. pct Al.

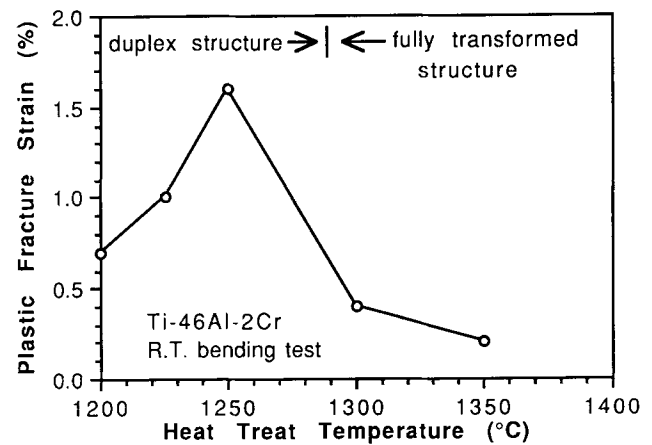


Fig. 6—The effects of heat-treatment temperature on the microstructure and plasticity of Ti-46Al-2Cr.

structure generally showed high plasticities; once the heat-treatment temperature was raised above the α transus to produce the fully transformed structure, a precipitous drop in plasticity was observed. The fully transformed structure was shown to be a relatively brittle structure,^[11] and Cr additions did not appear to be beneficial to its deformability.

The effect of heat-treatment temperature on the plasticity of Ti-52Al-2Cr is shown in Figure 7. The 1250 °C and 1300 °C heat treatments produced an essentially single-phase γ structure, and the measured fracture strains

Table I. Compositions of Phases by X-Ray Spectroscopy (Atomic Percent)

| Alloy | Heat-Treatment Temperature (°C) | Measurement Area | Composition (Atomic Percent) | | |
|-------------|---------------------------------|------------------------------|------------------------------|----|----|
| | | | Ti | Al | Cr |
| Ti-46Al-2Cr | 1250 | primary γ | 50 | 49 | 1 |
| | | lamellar $\gamma + \alpha_2$ | 56 | 42 | 2 |
| | | Ti (Cr, Al) | 56 | 31 | 13 |
| Ti-48Al-2Cr | 1300 | primary γ | 48 | 50 | 2 |
| | | lamellar $\gamma + \alpha_2$ | 52 | 45 | 3 |
| | | Ti (Cr, Al) | 54 | 30 | 16 |

were ~0.8 pct. At the 1325 °C and 1400 °C heat treatments, the microstructures became duplex, due to the appearance of transformed α . Correspondingly, the ductilities were significantly increased to levels of ~1.5 pct.

In addition to the above two alloys, alloys of compositions Ti-45Al-2Cr, Ti-47Al-2Cr, Ti-48Al-2Cr, and Ti-54Al-2Cr were studied after various heat treatments between 1200 °C and 1400 °C. It was reaffirmed that the duplex structure was more deformable than either the single-phase or the fully transformed structure. The highest strain values measured for each alloy are plotted in Figure 8. As seen, the addition of 2 at. pct Cr widened the ductile ($\epsilon_p > 2$ pct) range of Al concentration from about 48 to 50 at. pct in binary alloys to about 46 to 50 at. pct in ternary alloys. On the same Al concentration basis, relatively large ductility increases (about 1 to 2 pct) were observed in 46 to 48 at. pct Al range. The maximum plasticity occurred at 48 at. pct Al, consistent with the binary alloy result. It should be noted that Cr additions enhanced the plasticity of duplex alloys only. The Ti-54Al-2Cr alloy remained essentially single-phase γ , even after heat treatment at 1400 °C. No increase in plasticity was measured in that alloy over the corresponding binary single-phase alloy Ti-54Al.

E. Fracture Mode

The fractured surfaces of the bending and tensile samples studied showed a mixture of transgranular and grain-boundary failure. The ratio of the two failure modes varied with the type of microstructure, as in binary alloys.^[11] The ductile duplex structure tended to show cleavage or lamellar interface failure, although secondary cracking along grain boundaries was still visible. By comparison with the fracture surface of Ti-48 at. pct Al,^[11] it may be concluded that Cr additions slightly increased the tendency for intragranular failure in the duplex structure.

F. Deformation Substructures

The substructures in fractured samples of Ti-46Al-2Cr, Ti-52Al-2Cr, and Ti-54Al-2Cr were studied by TEM. In the Ti-46Al-2Cr sample ($\epsilon_p = 2.4$ pct as plotted in Figures 6 and 8), grains of primary γ and grains con-

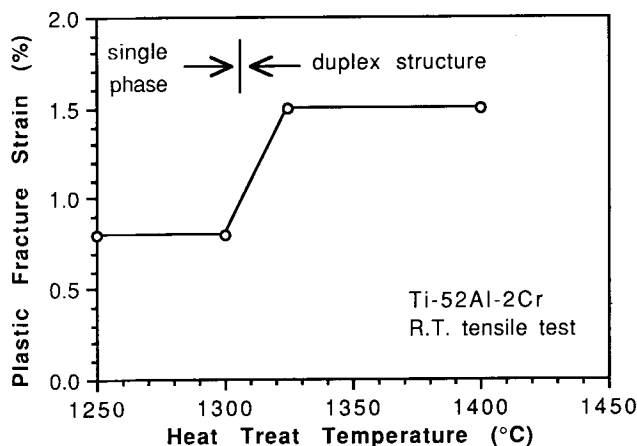


Fig. 7—The effects of heat-treatment temperature on the microstructure and plasticity of Ti-52Al-2Cr.

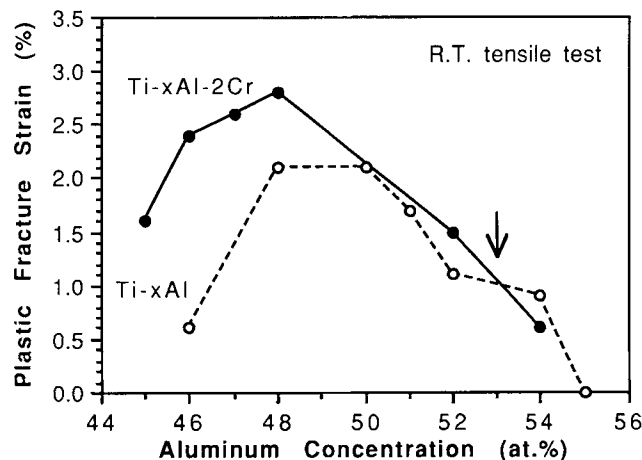


Fig. 8—Plasticity as a function of Al concentration with and without an addition of 2 at. pct Cr. Arrow shows the transition from a single-phase structure to a duplex structure, with decreasing Al concentration.

taining $\gamma + \alpha_2$ were seen, confirming the duplex structure. Some of the α_2 laths have disappeared due to coarsening, as described in conjunction with Figure 4(a). In all of the primary and coarsened γ regions, a large amount of twinning was evident after fracture (Figure 9(a)). Numerous dislocations were visible between twins, but no fault dipoles were found. Burgers vector analysis indicated that virtually all of the intertwin matrix dislocations were $1/2[110]$ unit dislocations. These deformation characteristics are the same as those of the duplex binary Ti-48 at. pct Al.^[11]

The Ti-52Al-2Cr sample ($\epsilon_p = 1.5$ pct as plotted in Figures 7 and 8) showed a duplex structure due to the 1400 °C heat treatment. Pockets of α_2 were primarily seen at grain boundaries, some containing γ laths. Few oxide or nitride particles were visible, as in the Ti-46Al-2Cr sample. In γ regions, profuse twinning was seen, as shown in Figure 9(b). The dislocations between twins were predominantly $1/2[110]$ unit dislocations. Faulted dipoles which resulted from local dissociation of superdislocations were visible in some regions of the specimen (inset); however, their density was much lower than the single-phase binary Ti-52 at. pct Al.^[11] This sample thus showed features similar to those of Ti-48 at. pct Al, although some of the Ti-52 at. pct Al deformation features, such as faulted dipoles, were also found.

Another Ti-52Al-2Cr sample heat treated at 1250 °C ($\epsilon_p = 0.8$ pct as plotted in Figure 7) showed no α_2 formation. The sample of Ti-54Al-2Cr heat treated at 1400 °C ($\epsilon_p = 0.6$ pct as plotted in Figure 8) also showed no evidence of α_2 . Both samples were essentially single-phase γ containing some Al_2O_3 and Ti_2AlN particles. These two samples exhibited a large number of faulted dipoles, as shown in Figures 9(c) and (d). Only a small amount of twinning was visible. Burgers vector analysis indicated a mixture of superdislocations and $1/2[110]$ unit dislocations. Thus, in every way, the deformation of these two samples resembles that of single-phase binary alloys deformed at room temperature.^[11]

G. ALCHEMI Measurements

In order to shed light on the mechanism by which Cr affects the mechanical properties of Ti-Al alloys,

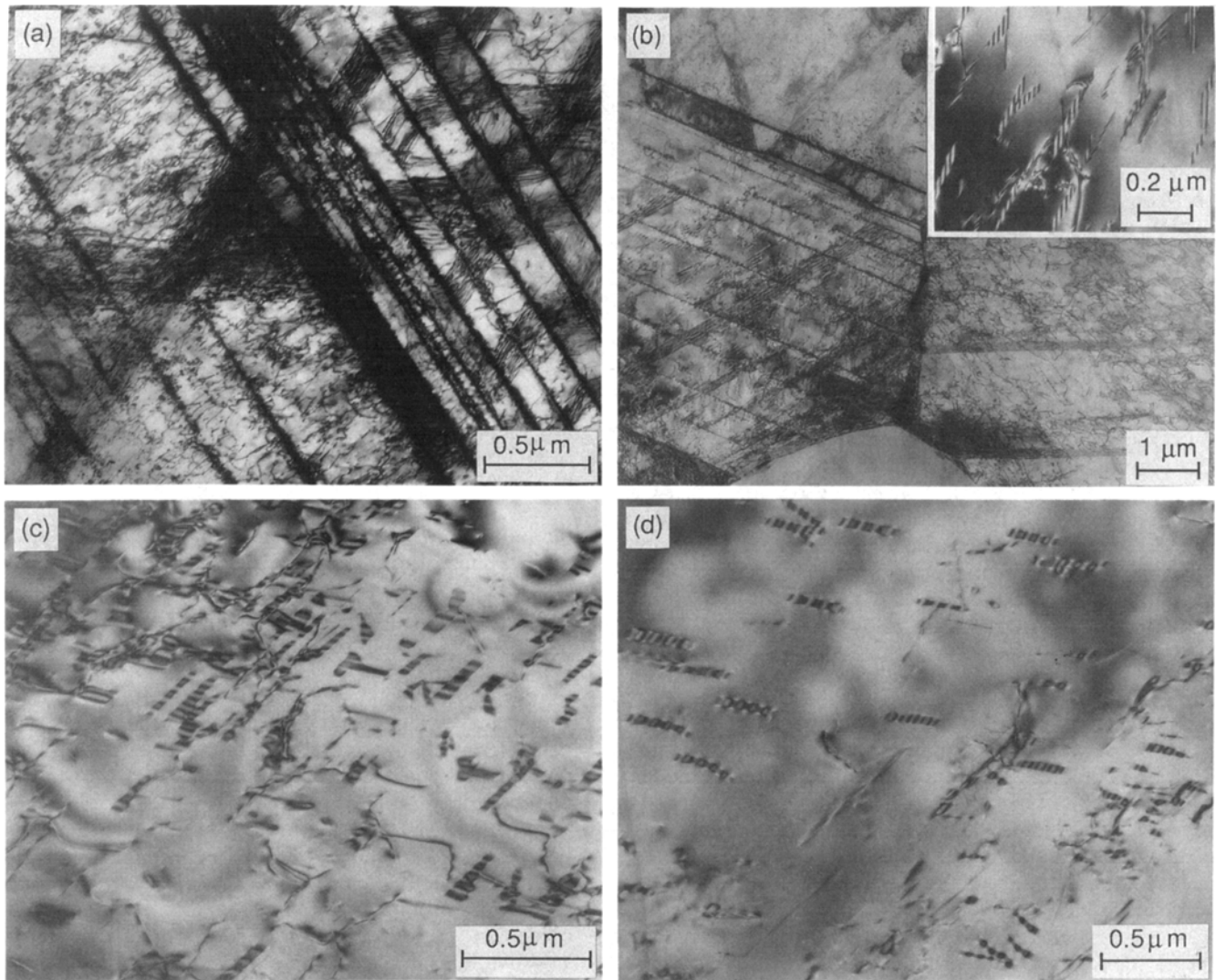


Fig. 9—Transmission electron micrographs from the fractured tensile samples of (a) Ti-46Al-2Cr heat treated at 1275 °C, (b) Ti-52Al-2Cr heat treated at 1400 °C, (c) Ti-52Al-2Cr heat treated at 1250 °C, and (d) Ti-54Al-2Cr heat treated at 1400 °C.

ALCHEMI experiments were performed in the analytical electron microscope. The basis of ALCHEMI was described by Tafto and Spence.^[27] In the present study, two alloys were examined—Ti-48Al-2Cr and Ti-54Al-2Cr—both in the undeformed condition. The sample was oriented with the 110 pole parallel to the electron beam. In this orientation, both the (001) and (1 $\bar{1}$ 0) planes consist of alternating planes of Ti and Al atoms parallel to the electron beam. The (1 $\bar{1}$ 0) planes were used, since the reciprocal lattice spacings of these planes are greater than the (001) planes, making it easier to adjust the precise diffracting condition. X-ray spectra were recorded with the sample positioned at positive and negative deviations (deviation parameter $s > 0$ and $s < 0$) from the Bragg angle. In order to rule out other effects associated with sample tilting, such as increases in thickness and hence in X-ray absorption, the sample was also tilted so that the same experiment could be performed for (1 $\bar{1}$ 0). Spectra were also recorded for random orientations (no strongly diffracting planes) close to the 110 pole.

The results of the ALCHEMI experiments are given in Table II for the two alloys of interest, as well as for

a Ti-52 at. pct Al standard. The results are presented as ratios of integrated peak intensities after background subtraction. The results from the binary alloy show that the electron wave was localized on the Al sites for $s > 0$ and on the Ti sites for $s < 0$. In the Ti-48Al-2Cr alloy, the Cr/Al ratio did not change with diffracting condition, implying that Cr atoms are mainly present on the Al sites. In the Ti-54Al-2Cr sample, a somewhat different result was seen. Both the Cr/Al and Cr/Ti ratios changed significantly with diffracting condition, implying that Cr atoms are located on both the Ti and Al sites. For both samples, the random values lie between the two channeling conditions, as expected.

IV. DISCUSSION

Chromium additions substantially increased the ductility in the 46 to 50 at. pct Al range. These alloys had the duplex structure. At 54 at. pct Al, the structure became single-phase γ and no ductility improvement was achieved by Cr additions. This Cr effect may be related to both microstructural and intrinsic factors, as discussed

Table II. Results of ALCHEMI Experiments

| Sample | Condition | Al/Ti | Cr/Ti | Cr/Al | Conclusions |
|-------------|-----------------------------|-------|-------|-------|---|
| Ti-52Al | $s > 0$; $\bar{1}\bar{1}0$ | 0.646 | — | — | electron wave localized on the Al sites for $s > 0$; on the Ti sites for $s < 0$ |
| | $s < 0$; $\bar{1}\bar{1}0$ | 0.491 | — | — | |
| | $s > 0$; $\bar{1}10$ | 0.661 | — | — | |
| | $s < 0$; $\bar{1}10$ | 0.492 | — | — | |
| | random | 0.598 | — | — | |
| | random | 0.608 | — | — | |
| | random | 0.606 | — | — | |
| Ti-48Al-2Cr | $s > 0$; $\bar{1}\bar{1}0$ | 0.482 | 0.055 | 0.114 | Cr is present exclusively on the Al site |
| | $s < 0$; $\bar{1}\bar{1}0$ | 0.297 | 0.034 | 0.114 | |
| | $s > 0$; $\bar{1}10$ | 0.468 | 0.052 | 0.112 | |
| | $s < 0$; $\bar{1}10$ | 0.302 | 0.037 | 0.122 | |
| | random | 0.390 | 0.041 | 0.106 | |
| | random | 0.375 | 0.049 | 0.131 | |
| Ti-54Al-2Cr | $s > 0$; $\bar{1}\bar{1}0$ | 0.803 | 0.051 | 0.064 | Cr is present on the Ti and Al sites |
| | $s < 0$; $\bar{1}\bar{1}0$ | 0.359 | 0.040 | 0.112 | |
| | $s > 0$; $\bar{1}10$ | 0.806 | 0.048 | 0.059 | |
| | $s < 0$; $\bar{1}10$ | 0.318 | 0.039 | 0.122 | |
| | random | 0.504 | 0.043 | 0.086 | |
| | random | 0.529 | 0.043 | 0.081 | |

in Sections A and B. Obviously, the responsible factors will need to explain why Cr additions only improve the ductility of duplex structure and not single-phase structure.

A. The Microstructural Effects of Cr Additions

Several microstructural factors have been suggested for the ductile behavior of duplex binary alloys,^[11] including the fine grain size. Also, the α_2 phase was postulated to scavenge oxygen and nitrogen and, therefore, reduce the interstitial content in γ .^[9,28-30] In Cr-modified duplex alloys, the grain size remained small and oxide and nitride particles were absent, similar to duplex binary alloys. No evidence was found that Cr additions further refined the grain size or reduced the interstitial contents.

In binary duplex alloys, transformed $\gamma + \alpha_2$ lamellar grains tended not to deform as much as single-phase γ grains.^[10] Some twinning and dislocations were seen in γ laths and along the γ/α_2 interfaces but not in α_2 laths. Further, α_2 laths were found to hinder deformation across the lamellar structure.^[31,32] In "single crystals" of fully transformed structure, deformation transfer across the γ/α_2 interfaces only occurred at stresses significantly higher than the flow stress of γ .^[33] Thus, the role of α_2 in regard to the deformability of duplex structure is ambiguous. While α_2 may benefit deformability by absorbing interstitials, refining grain size, and creating dislocation-emitting interfaces, it forms fine ($\sim 0.1 \mu\text{m}$) and closely spaced ($\sim 0.2 \mu\text{m}$) hard laths which are undesirable for homogeneous deformation.

In Cr-modified duplex alloys, α_2 laths were present, but their shape and distribution were significantly different from those in binary alloys. Some of them became thick ($\sim 0.3 \mu\text{m}$) and widely spaced ($\sim 0.5 \mu\text{m}$); others appeared to be removed, producing large single-phase γ regions similar to primary γ . This tendency of lamellar coarsening can be related to the effect of Cr on the α transus. Chromium additions depress the α transus. Thus,

for a given Al concentration and heat-treatment temperature, Cr additions raise the Al content of primary α . This leads to a reduced volume fraction of α_2 laths which can be as thin as $\sim 0.05 \mu\text{m}$. Both the small volume and fine size would promote coarsening, as observed. Chromium would have the same effect on α_2 stability if it reduces the Al solubility limit in γ .^[34]

The Cr-induced coarsening of the transformed lamellar structure is believed to have significant effects on the deformation of duplex structure. First, it eliminates α_2 laths and produces single-phase γ regions in primary α . The coarsened γ should deform similarly to primary γ without the hindrance of α_2 plates. Second, the γ coarsened from α should be lean in Al and low in stacking fault energy.^[35] Finally, the coarsened γ contains thermal twins which may be nucleation sources of mechanical twins.^[14] These factors all favor plastic deformation.

Chromium additions also promoted the formation of a CsCl Ti_2CrAl -type phase. Excessive formation of that phase reduced ductility.

B. The Intrinsic Effect of Cr Additions

The deformation mechanisms in binary alloys were found to vary with microstructure.^[11] The single-phase γ structure tended to deform by slip of unit dislocations and superdislocations, but the latter were frequently pinned, producing stacking fault dipoles. In contrast, the duplex structure tended to deform by unit dislocation slip and $1/6[112]$ twinning. It has been suggested that twin and superdislocation nucleation are competing mechanisms in γ alloys, depending on stacking fault energy.^[11] The duplex structure favors twin deformation, because its fault energy is lower, due to a lower Al concentration^[34] or the presence of α_2 which absorbs and lowers the interstitial content in γ .^[9,28-30]

In the present Cr-modified alloys, deformation mechanisms were still found to vary with microstructure. Even with Cr additions, the deformation of a single-phase alloy

was dominated by $1/2[110]$ unit dislocations and partially pinned superdislocations while a duplex structure was dominated by $1/2[110]$ slip and $\{111\}$ twinning. Thus, no evidence of changes in a stacking fault energy was found in the deformation mode study. However, a dramatic contrast in the preferred location of Cr atoms was found, depending on alloy composition and microstructure. Some Cr atoms were present on the Ti sites in single-phase Ti-54Al-2Cr, as expected from atom size and valency considerations. On the other hand, Cr atoms were exclusively present on the Al sites in the duplex Ti-48Al-2Cr. This occupancy behavior is believed to bear directly on the observed Cr ductilization effect. When Cr atoms occupy the Al sites in a duplex alloy, they reduce the overall covalency of Ti-Al bond and thus favor plastic deformation.^[21] This bond modification generally leads to changes in dislocation core structure and energetics. In contrast, Cr atoms partially occupy Ti sites in a single-phase γ alloy, resulting in little bond modification and plasticity enhancement.

C. Comparison with Other Results

Several Cr-modified duplex alloys studied here were also studied in thermomechanically processed ingots.^[36] Those wrought ingots generally showed the same Cr effects on microstructure and properties as the present rapid solidification-processed materials. On a same composition and heat-treatment basis, the wrought ingots were more ductile, perhaps because of higher purity.^[28] For example, plastic elongations of ~ 4 pct were measured in wrought Ti-46Al-2Cr.^[36] The Cr ductilization of a duplex structure was also observed by Kawabata *et al.*^[37] and Wunderlich *et al.*^[32] The former authors further reported that Cr reduced the ductility of single-phase γ alloys. Additionally, Mn^[20] and V^[18] showed similar effects as Cr. Compared to V, which has been characterized in a parallel study,^[18] Cr is a more potent element to depress α transus, substitute for Al, and enhance plasticity. However, Cr has a more limited solubility in γ .

Based on current understanding of binary and ternary alloys containing Mn, V, and Cr, the following factors appear to be important to the ductility of γ alloys:

- (1) formation of primary α in Al-lean alloys to refine grain size and absorb interstitial impurities;
- (2) coarsening of α_2 laths in transformed α to minimize inhomogeneous deformation; and
- (3) modification of Ti-Al bond to reduce stacking fault energy and promote twin deformation.^[38]

V. SUMMARY

1. Chromium additions enhance the plasticity of Al-lean duplex γ -base alloys. However, they exert no ductilization to a fully transformed α structure or a single-phase γ structure.
2. Maximum ductilities occur at ~ 2 at. pct Cr with 46 to 48 at. pct Al. Higher Cr levels form excessive Ti_2CrAl particles and reduce ductility.
3. Chromium additions tend to depress the α transus and increase its Al concentration. This leads to decreases in the volume fraction and thermal stability of trans-

formed α_2 laths. As a result, coarsened γ regions form in primary α grains which can deform without the hindrance of α_2 laths.

4. Chromium atoms occupy Al sites in duplex alloys; they occupy both Ti and Al sites in single-phase alloys.
5. The Cr-induced α_2 instability and Ti-Al bond modification are thought to be responsible for the Cr ductilization observed in duplex alloys.

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