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INFLUENCE OF HIGH-STRAIN RATE AND
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ALUMINIDES

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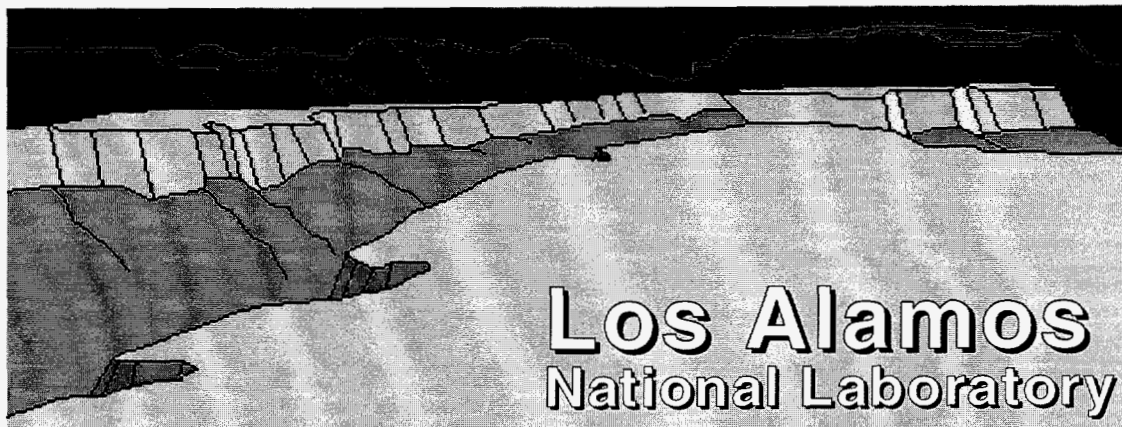
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INFLUENCE OF HIGH-STRAIN RATE AND TEMPERATURE ON THE MECHANICAL BEHAVIOR OF Ni-, Fe-, and Ti-based ALUMINIDES*

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Abstract

The majority of the strength characterization studies on ordered intermetallics have concentrated on the assessment of strength and work-hardening at conventional strain rates. Although the influence of strain rate on the structure / property relationships of pure nickel, iron, and titanium and a variety of their alloys have been extensively studied, the effect of strain rate on the stress-strain response of Ni-, Fe-, and Ti-based aluminides remains poorly understood. Dynamic constitutive behavior is however relevant to high speed impact performance of these materials such as during foreign object damage in aerospace applications, high-rate forging, and localized deformation behavior during machining. The influence of strain rate, varied between 0.001 and 10^4 s^{-1} , and temperatures, between 77 & 800K, on the compressive mechanical behavior of Ni_3Al , NiAl , Fe_3Al , Fe-40Al-0.1B , Ti-24Al-11Nb , and Ti-48Al-2Cr-2Nb will be presented. In this paper the influence of strain rate on the anomalous temperature dependency of the flow stresses in these aluminides will be reviewed and compared between aluminides. The rate sensitivity and work hardening of each aluminide will be discussed as a function of strain rate and temperature and contrasted to each other and to the values typical for their respective disordered base metals.

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Introduction and Background

The structure/property relations of Ni, Fe-, and Ti-aluminides have attracted recent interest as structural materials since these high temperature alloys exhibit promising oxidation and sulfidation resistance at elevated temperatures and retention of good strength to intermediate temperatures[1]. Over the past five years variations in strain rate have been broadly utilized to probe a wide range of kinetic effects in intermetallics including strain rate effects on: 1) defect types activated (slip, twinning, kinking, etc.), 2) specific dislocation mechanisms activated, 3) hydrogen embrittlement phenomena, 4) the rate dependency of yield and work-hardening phenomena, and 5) as "critical experiments" to evaluate the applicability of a wide spectrum of defect models controlling the anomalous temperature dependence in some intermetallic compounds. A survey of the literature on strain-rate effects on aluminides via a computer reference search reveals a reasonably large number of recent citations where "strain-rate" appears within the keyword or title fields, or within the abstract of the paper itself. The recent citations where strain-rate effects are linked to Fe-, Ni-, and/or Ti-aluminides were found to be clustered in several topical categories. Representative citations within these areas are:

- a) superplasticity of aluminides[2-4],
- b) strain rate effects on embrittlement of aluminides[5-19],
- c) creep of aluminides[4, 20],
- d) deformation / mechanical property / mechanism studies[21-33], TiAl[5, 33-50],
- e) modeling deformation response (especially anomalous temperature behavior)[51-54][55, 56], and
- f) impact and shock-loading response[11, 57] [58, 59].

In addition to the utilization of strain rate as a testing variable to probe specific aspects of defect phenomena, the effect of strain rate on overall deformation response is of importance to future applicability of aluminides in engineering systems. This is the case for the interest in the high-rate deformation and impact response of aluminides. Dynamic constitutive behavior is relevant to the high-strain rate deformation response and the impact performance of aluminides encountered in: 1) extreme service conditions such as during foreign object damage encountered in aerospace applications, and 2) for manufacturing environments such as high-rate forging as well as the localized high-rate deformation behavior during metal removal operations such as machining and grinding. While the influence of higher strain rate deformation on the structure / property response of pure Ni, Fe, and Ti and their alloys has been widely investigated, the effect of high-rate deformation and impact phenomena on the mechanical response of aluminides has been less extensively studied. The purpose of this paper is to review results of a number of studies examining the effect of high-strain rate and temperature on the mechanical response of Ni-, Fe-, and Ti-aluminides. Utilization of compression testing, in contrast to tension, allows in-depth study of the work-hardening response of the various aluminides without the premature termination of the stress-strain response due to intersection with the failure envelope.

Experimental Procedures

Materials

The materials summarized in this review were 6 intermetallic aluminides, all polycrystalline with the exception of NiAl, with chemical compositions in at.% as listed in Table I. The Fe-40Al-0.1B and Fe₃Al were supplied by Oak Ridge National Laboratory. The NiAl and Ti48Al-2Cr-2Nb were supplied by GE Aircraft Engines. In-depth details of the chemistry, processing, heat-treatments, and final microstructures have been presented previously for the NiAl[25, 28], Ni₃Al[29, 30], Ti₃Al[32, 33, 37], TiAl[34-36, 42], Fe₃Al[60], and FeAl[40].

Table I - Chemical Composition of Aluminides Studied [at. %]

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Aluminide	Element									
	Ni	Al	Ti	Fe	B	Cr	Nb	O	C	P
Ni ₃ Al	75.9	24.1			0.095			0.03	0.02	0.005
NiAl	50.0	50.0								
Ti-24Al-11Nb		24.6	64.63	0.068			10.5	0.161	0.039	
Ti-48Al-2Cr-2Nb		47.8	48.2			2.0	1.7	0.2	0.1	
Fe ₃ Al		30.0		70.0						
Fe-40Al-0.1B		40.0		59.9	0.1					

Mechanical Testing

The true-stress true-strain responses of the aluminides were measured in compression using solid-cylindrical samples 5.0 mm in dia. by 5.0 mm long, lubricated with molybdenum grease. Quasi-static compression tests were conducted on a screw-driven load frame at strain rates of 0.001 and 0.1 s⁻¹ at 77 and 298K. Dynamic tests, strain rates of 1000-8000 s⁻¹, were conducted as a function of strain rate and temperature utilizing a Split-Hopkinson Pressure Bar[61]. High temperature tests were performed in a vacuum furnace mounted on the Split-Hopkinson Pressure Bar[62]. The high temperature Hopkinson-Bar samples were lubricated with a boron nitride powder / alcohol slurry which was allowed to dry on the sample prior to testing. The samples were heated to temperature and allowed to stabilize prior to testing, based upon thermocouple monitoring of directly adjacent to the sample, with the elapsed time of ~7-10 minutes required from the inception of heating to testing. The inherent oscillations in the dynamic stress-strain curves, due to elastic wave dispersion in the bars[61], and the lack of stress equilibrium in the specimens at low strains make the exact determination of yield inaccurate at high strain rates. Accordingly, values of the flow stress for the high-strain-rate tests are most often plotted in comparisons as flow stresses at low values of plastic strain (< 5%).

Results and Discussion

The compressive true-stress true-strain responses of Ni₃Al, NiAl, Fe₃Al, Fe-40Al-0.1B, Ti-24Al-11Nb, and Ti-48Al-2Cr-2Nb were all found to depend on both the applied strain rate, which ranged from 0.001 to 7500 s⁻¹, and the test temperature at high rate, which was varied between 77 and 1273K (Figures 1-12). The stress-strain responses at quasi-static and high-strain rate for all the different aluminides at 298K are compared in Figures 13 and 14, respectively. Examination of the individual stress-strain responses of the aluminides as a function of strain rate and temperature as well as the cross-plots reveals some striking similarities and some distinct differences. The yield stresses of all the various polycrystalline aluminides at both strain rates are seen to span a reasonably narrow range from 250 to 600 MPa while being bounded by the soft <110> and hard <100> NiAl single-crystal behavior. The work-hardening behaviors of the Ni-, Fe-, and Ti-aluminides are all seen to exhibit: 1) considerably higher hardening rates than that typical for their disordered polycrystalline base metals, and 2) remarkable linear sustained hardening behavior, in particular for the Fe-40Al-0.1B, NiAl, Ni₃Al, and Ti-48Al-2Cr-2Nb, over a wide range of temperatures. The average work-hardening rates for the aluminides are summarized in Table II.

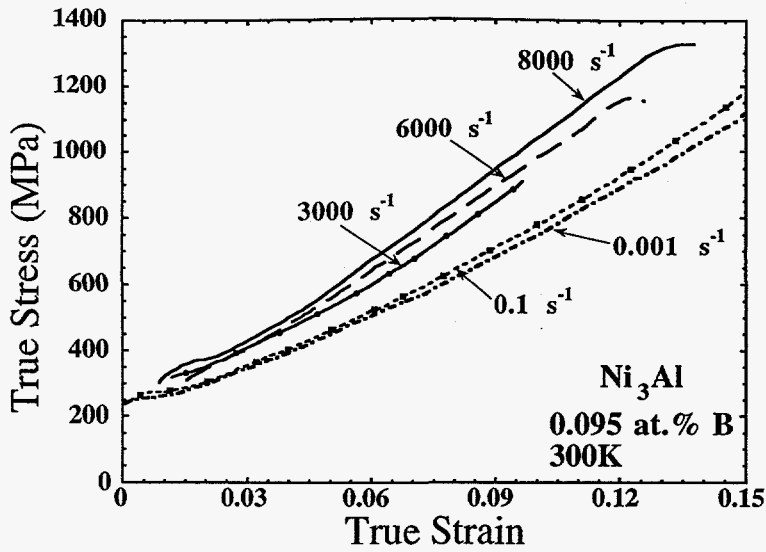


Figure 1 - Stress-Strain response of Ni₃Al as a function of strain rate at 300K[30].

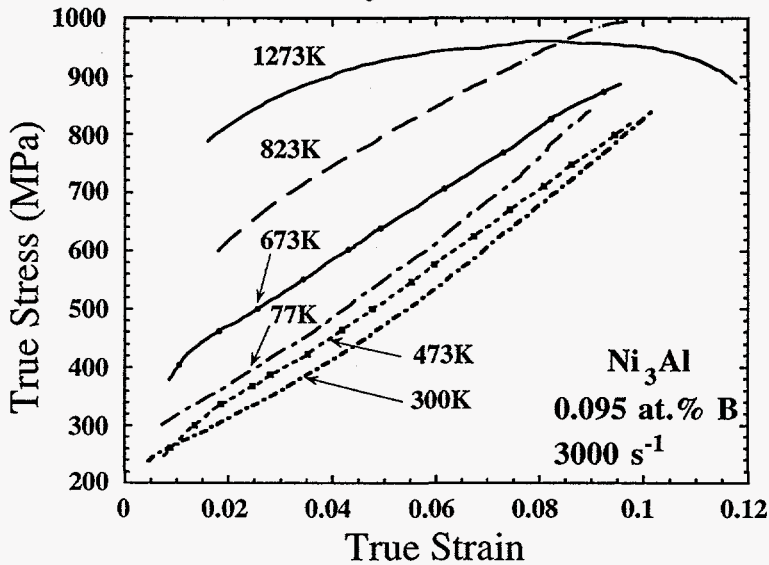


Figure 2 - High-rate response of Ni₃Al as a function of temperature[30].

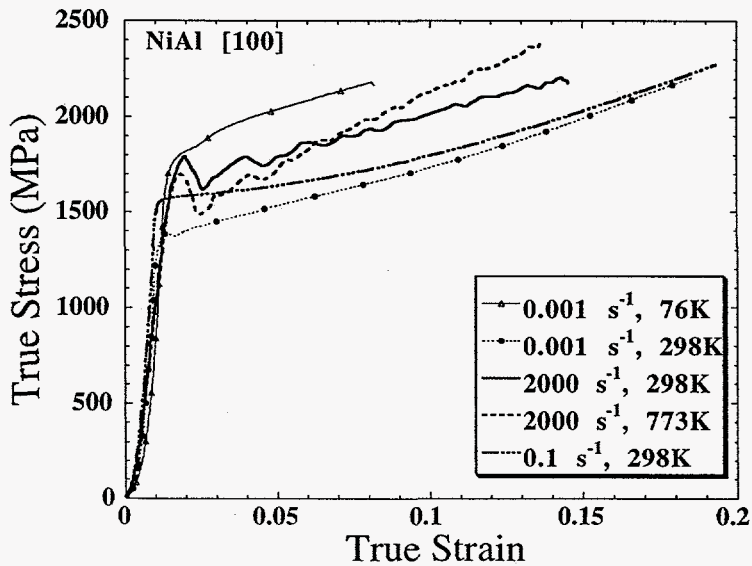


Figure 3 - Stress-Strain response of NiAl [100] as a function of temperature and strain rate[25].

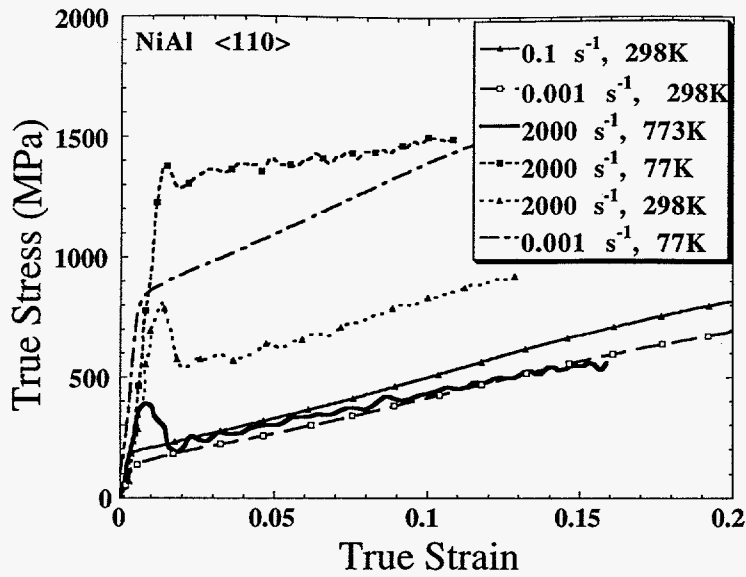


Figure 4 - Stress-Strain response of NiAl <110> as a function of temperature and rate[28].

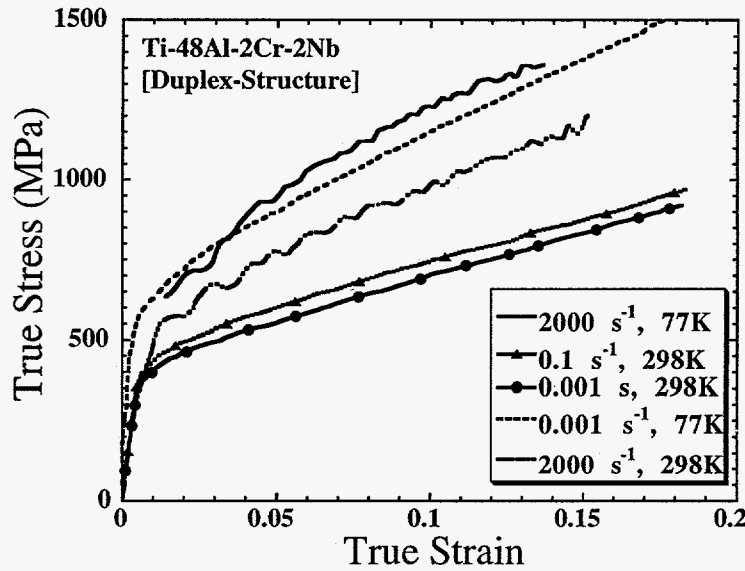


Figure 5 - Response of Ti-48Al-2Cr-2Nb as a function of strain rate and temperature[36].

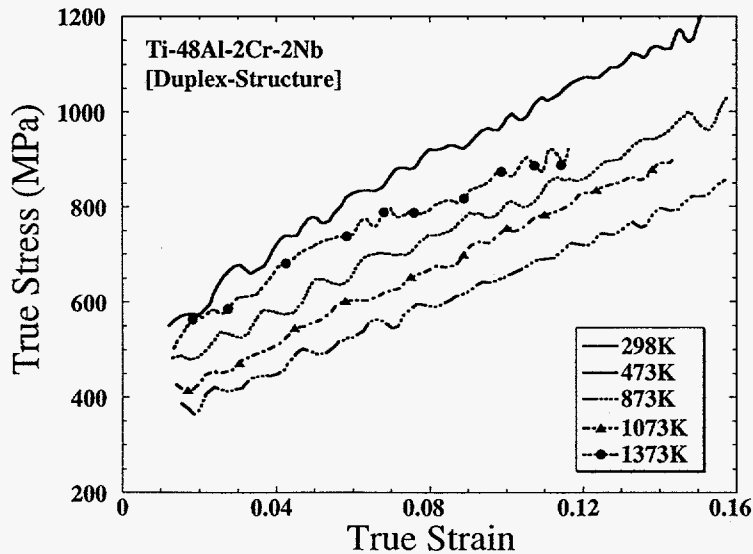


Figure 6 - High-rate response of Ti-48Al-2Cr-2Nb as a function of temperature[36].

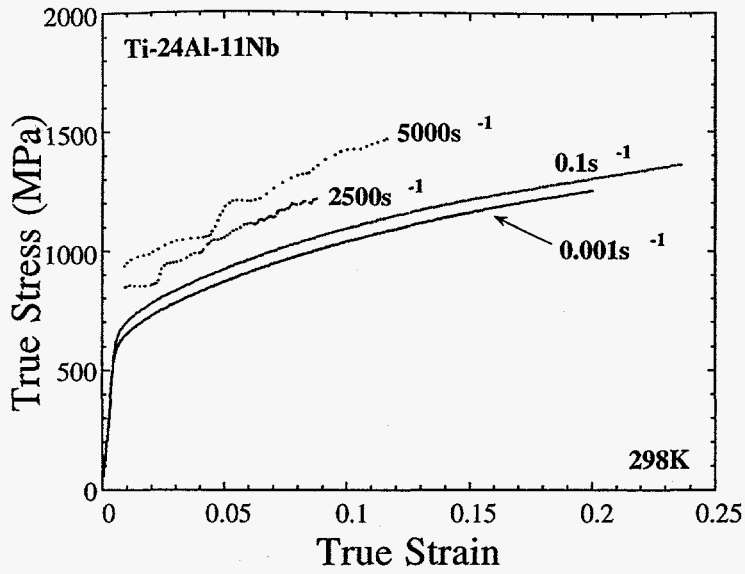


Figure 7 - Stress-Strain response of Ti-24Al-11Nb as a function of strain rate and temperature[33].

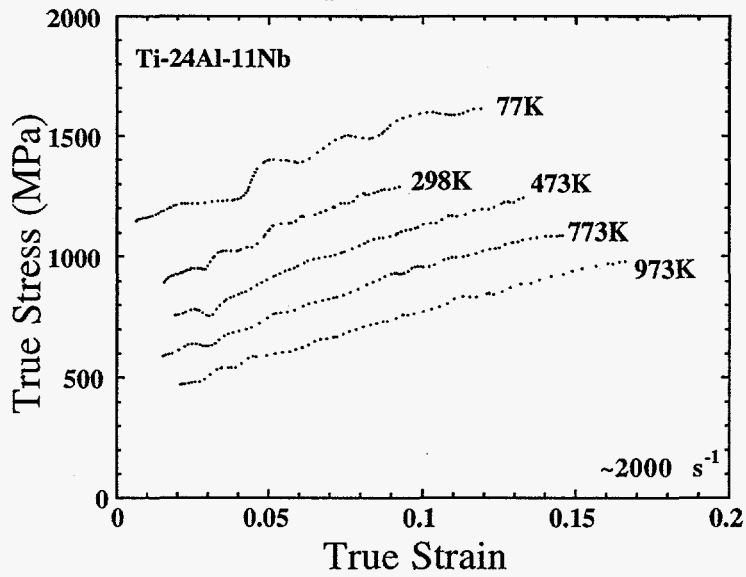


Figure 8 - High-rate response of Ti-24Al-11Nb as a function of temperature[33].

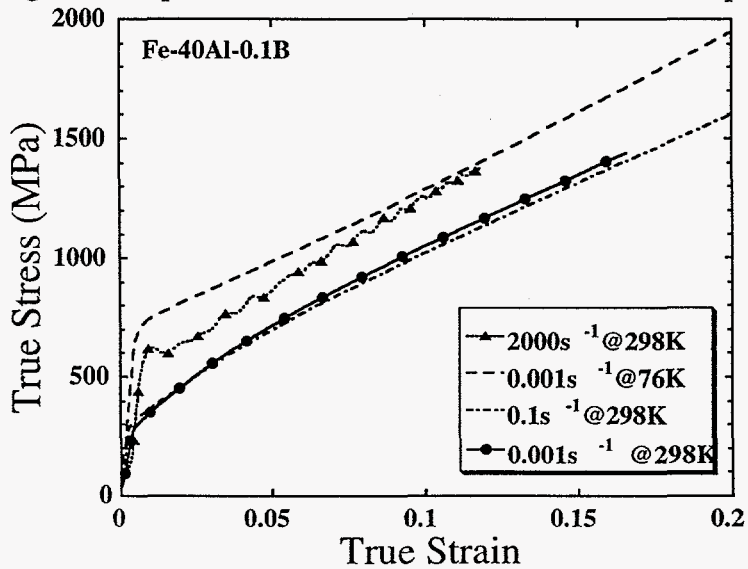


Figure 9 - Stress-Strain response of Fe-40Al as a function of strain rate and temperature[40].

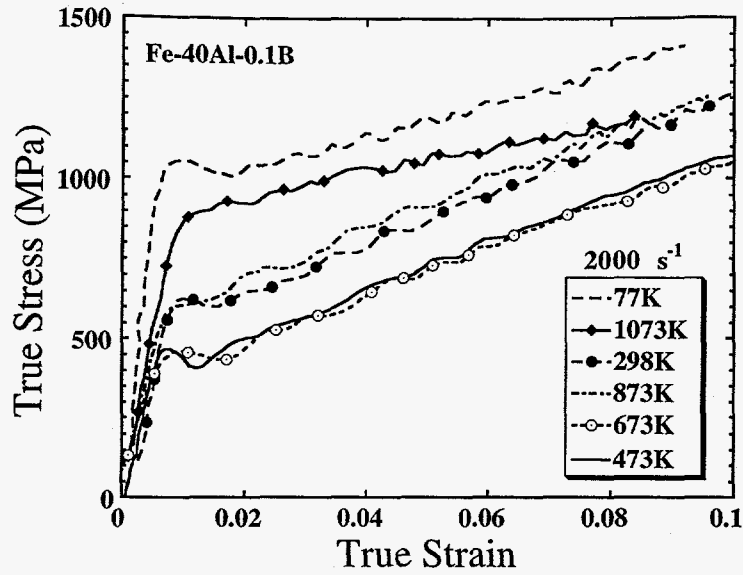


Figure 10 - High-rate response of Fe-40Al as a function of temperature[40].

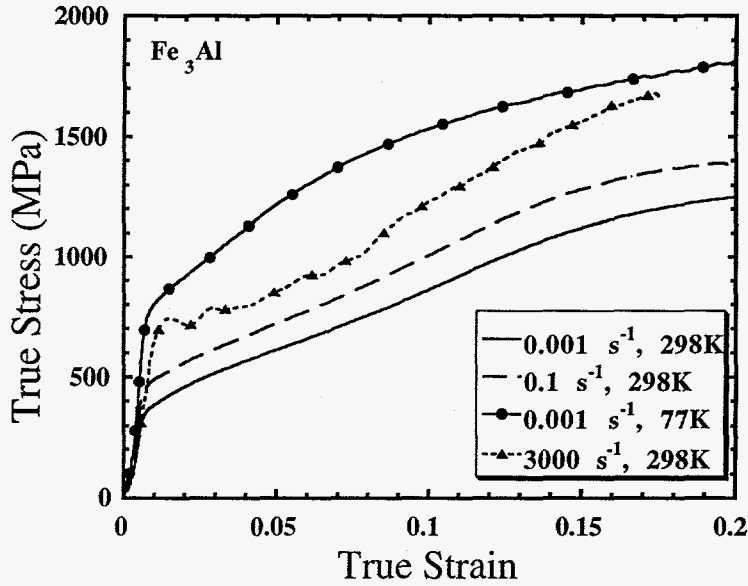


Figure 11 - Stress-Strain response of Fe₃Al as a function of temperature and strain rate.

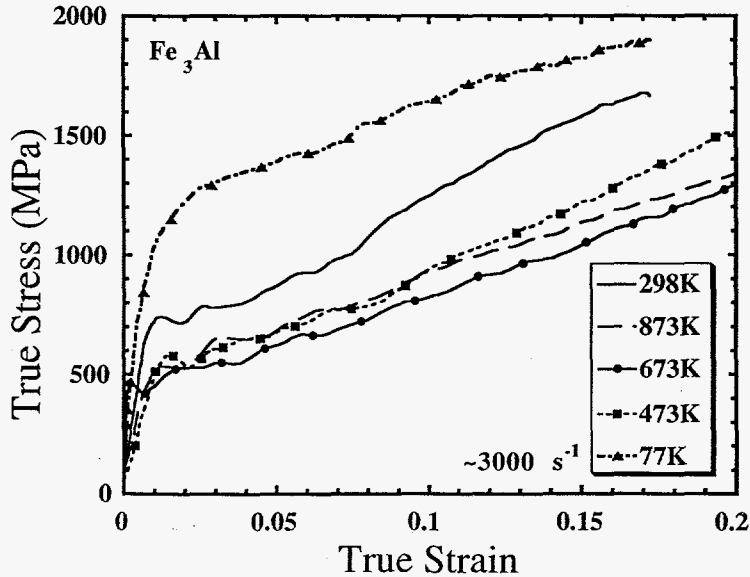


Figure 12 - High-rate response of Fe₃Al as a function of temperature.

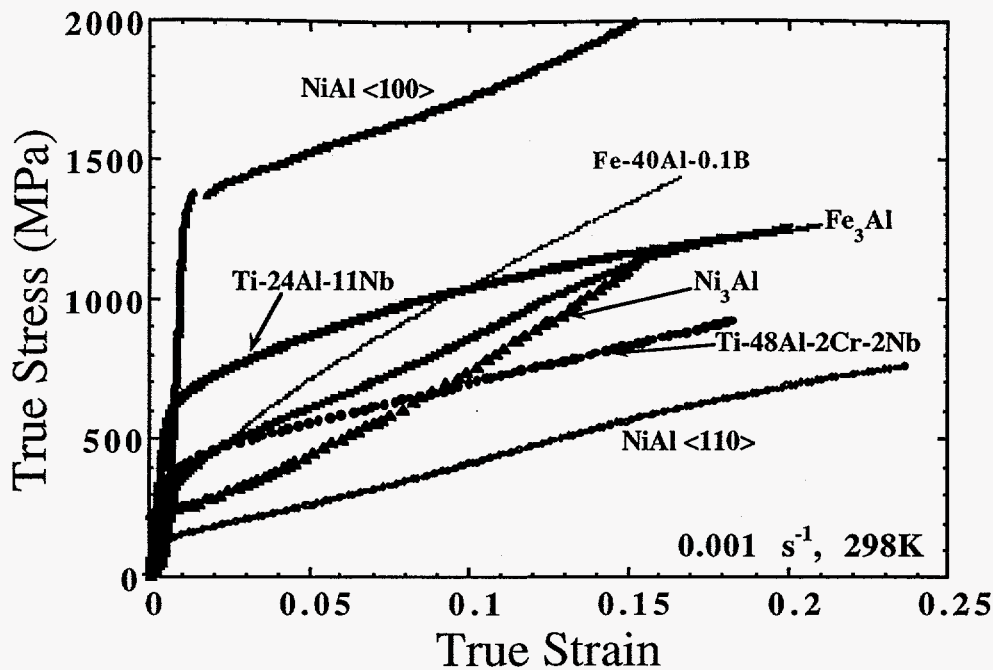


Figure 13 - Quasi-static stress-strain response for aluminides at 298K.

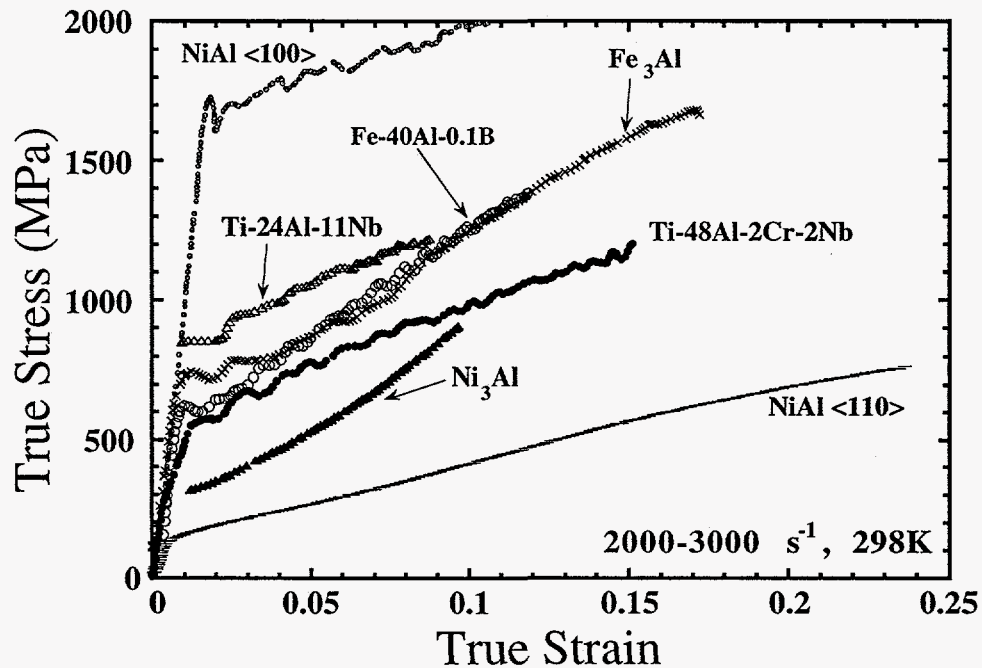


Figure 14 - High-strain Rate stress-strain response for aluminides at 298K.

The remarkable linear Stage-II stress-strain behavior in the Fe-40Al-0.1B, NiAl and Ti-48Al-2Cr-2Nb are seen to persist to true strains in excess of 0.20. In some instances, such as for Ti-48Al-2Cr-2Nb, sequential reloading with relubrication can be used to strain aluminides in compression to flow stresses > 2 GPa prior to failure by non-crystallographic shear[42]. These stress levels are equivalent to $\sim E/10$ which are quite impressive flow stress for any material to stably support. Overall, the stable high rate of work-hardening exhibited by nearly all the aluminides, often at hardening rates $\gg \mu/100$, and sustained to absolute flow stresses > 1500 MPa is consistent with the suppression of dynamic recovery processes in ordered intermetallic compounds[42]. Although microcracking is evident in many of these aluminides tested in

compression, damage evolution within most aluminides in compression is insufficient to significantly alter the stable high rate of work-hardening typical in these materials.

The rate sensitivities, "m" ($= \ln \sigma / \ln \dot{\epsilon}$), for all the aluminides were calculated using the flow stress values at a plastic strain of ~2% to avoid the inaccurate yielding definition difficulty for the Split-Hopkinson-Pressure Bar data as mentioned in the experimental procedure section. The rate sensitivities for all the aluminides are listed in Table II. While the rate sensitivity should be rigorously assessed via a strain rate jump test[63] to assure constant structure, previous experience has shown that the current range in strain rates, over 10^6 , leads to essentially the identical calculated rate sensitivity as from a jump test over a much lower strain rate range[33, 36]. Overall, the Fe-, Ni-, and Ti-aluminides studied all exhibit strain-rate sensitivities equal to or in excess of their high-purity disordered base-metal with the exception of Ni_3Al . Ni_3Al displays an extremely low dependency of its yield strength on strain rate at 298K which is consistent with the lack of any significant Peierls Barrier to dislocation motion[30]. The lack of rate dependency at 298K in Ni_3Al is unique among the aluminides discussed in this paper and in addition to its anomalous flow stress dependency on temperature, to be addressed later in this paper, presents a fascinating and widely contested topic of discussion in the literature[54, 55]. In this discussion strain rate effects on yield and hardening phenomena have played a pivotal role as delimiters for differentiating new defect model descriptions for Ni_3Al .

Table II:

Summary of rate sensitivity and work-hardening response of intermetallics studied at 298K.

Aluminide	Rate Sensitivity @ 298K	Work-Hardening Rate @ 0.001 s^{-1} [MPa / unit strain]	Work-Hardening Rate @ 2000 s^{-1} [MPa / unit strain]
Ni_3Al	very low	5800	8000
NiAl [100]	0.024	4000	4000
NiAl <110>	0.085	2900	3560
Ti-24Al-11Nb	0.014	1680	3600
Ti-48Al-2Cr-2Nb	0.02	2800	4500
Fe_3Al	0.039	5000	6500
Fe-40Al-0.1B	0.047	6500	6500
Nickel (polycrystalline)	0.01	3000	5000
Titanium (polycrystalline)	0.015	1000	2400
Iron (polycrystalline)	0.05	1100	1600

Comparison of the work-hardening rates of the various aluminides as a function of strain rate or temperature at high rate reveals that the rate of strain hardening is predominantly invariant again with the exception of Ni_3Al and to some extent Ti-48Al-2Cr-2Nb. In the majority of the aluminide data shown in Figures 1-12 increasing strain rate and/or temperature at high rate is seen to only shift the hardening curves up or down; the nearly invariant hardening rates resulting in a family of parallel curves. The observation of a pronounced increase in yield and flow stress with decreasing temperature and/or increasing strain rate is typical for BCC and lower symmetry crystal structures and has been traditionally explained by a high Peierls stress[64]. In the case of Ti-48Al-2Cr-2Nb the stress-strain data in Figure 5 supports a pronounced rate sensitivity but with an increase in hardening at 77K and high-strain rate also prevalent. In this instance, unlike the other aluminides (except again for Ni_3Al), a single deformation mechanism is dominant in controlling plastic deformation; dislocation glide. Contrarily in the case of Ti-48Al-2Cr-2Nb, deformation twinning in addition to slip is known to contribute to plastic flow. With increasing strain rate and/or decreasing temperature the propensity of twin formation in TiAl is seen to increase. Increasing amounts of deformation twinning is seen to correlate with an increased rate of work hardening[36, 65].

The other feature observed to be common among a number of the aluminides studied is an anomalous increase in the flow stress at high-strain rate as a function of increasing temperature. This phenomena for the Ni, Fe, and Ti-aluminides is summarized in Figure 15. For the aluminides investigated the low-strain flow stresses of Ni₃Al, Ti-48Al-2Cr-2Nb, and Fe-40Al-0.1B are seen to exhibit an anomalous increase in stress level with increasing temperature at high-strain rate. The anomalous increase in flow stress in Fe-40Al-0.1B with increasing temperature above 600K is first seen to be preceded by a pronounced fall in flow strength upon increasing temperature from low temperature. This U-shaped flow stress behavior with temperature is consistent with the constitutive response of Fe-40Al-0.1B and Ti-48Al-2Cr-2Nb being Peierls stress dominated a low temperature and then involving additional hardening mechanisms upon increasing temperature.

Whether these involve a Kear-Wilford mechanism or one of another cross-slip mechanisms where cross-slipped segments pin [5, 44, 55] or related to vacancy-induced hardening[56] remains a subject of current debate. NiAl, Ti-24Al-11Nb, and Fe₃Al on the contrary display a decrease in their high-strain-rate flow stresses with increasing temperature. This observation is consistent with previous observations on these intermetallics[66]. [66]. This later behavior is also more typical of disordered metals and alloys where fall-off in the yield strength of a material is commensurate with the decrease in shear modulus with increasing temperature. The one unique feature in the current observations of the anomalous yield increase with temperature is the lack of an eventual down-turn at very high temperatures. Unlike the usual fall-off in yield at very high temperatures due to the activation of additional slip systems, such as cube slip in Ni₃Al, or climb related processes in FeAl[48] high-strain-rate loading is observed to prevent this high-temperature deformation mode change. Up to the temperatures attained in the Split-Hopkinson-Bar testing the high-strain-rate yield strengths of Ni₃Al[30], Fe-40Al-0.1B[40], and Ti-48Al-2Cr-2Nb[36] have not been seen to decrease in the temperature range tested to date.

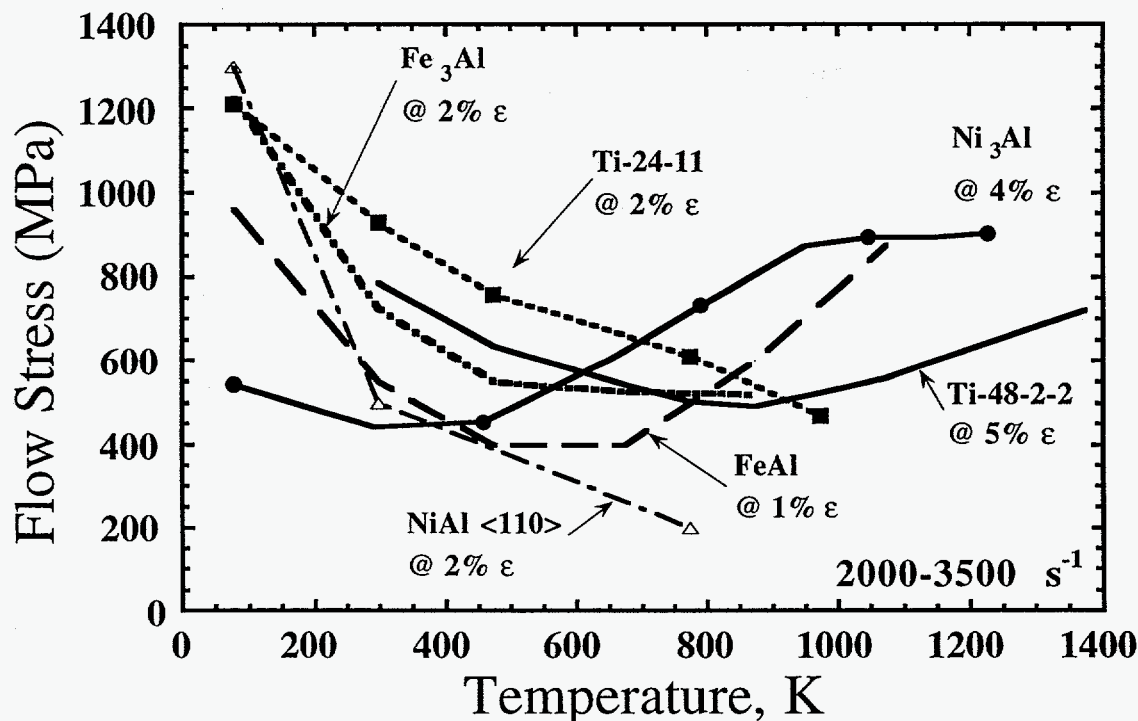


Figure 15 - Plot of flow stresses at fixed plastic strains versus temperature for various intermetallics at high strain rate.

Of the aluminides reviewed here which display the anomalous increase in yield strength with temperature at high-strain rate the overall magnitude of the temperature effect on yielding and post-yield flow stresses is most evident in Fe-40Al-0.1B as seen in Figure 10 and 15. Previous studies have documented this phenomena in FeAl, in particular in the work of Baker et. al.[44, 48-50]. The yield stress of Fe-39 at.% Al single crystals has been observed to display a nearly

constant yield stress of ~200 MPa from ambient temperature to 600K followed by a positive temperature dependence with a peak temperature at 873K when tested at a strain rate of $1.7 \times 10^{-4} \text{ s}^{-1}$ [44]. The anomalous slip transition in FeAl has been related to the decomposition of $[111]$ dislocations while the change in slip vector from $\langle 111 \rangle$ to $\langle 001 \rangle$ type occurs microscopically around the peak temperature [44] and most recently to vacancy hardening [56].

The last mechanism mentioned, i.e., that of vacancy-induced hardening by George and Baker [56], represents an example as mentioned in the introduction where strain rate data can provide insights into modeling of defect processes in intermetallics. The vacancy-hardening mechanism presents an intriguing model in which the anomalously increasing portion, termed Region III, of the temperature-dependent yield behavior of FeAl is related to vacancy hardening due to condensed vacancies restricting dislocation motion [56]. The vacancies concentration is known to increase with temperature because of the high activation enthalpy for vacancy formation. Sufficient time at temperature, with times $> 0.5 \text{ h}$ being shown to give a yield strength independent of hold time, results in the attainment of an equilibrium concentration of vacancies. As conceived this mechanism suggests a rather low strain-rate dependency should be operative in the anomalous regime where vacancy hardening is leading to increasing yield strength levels.

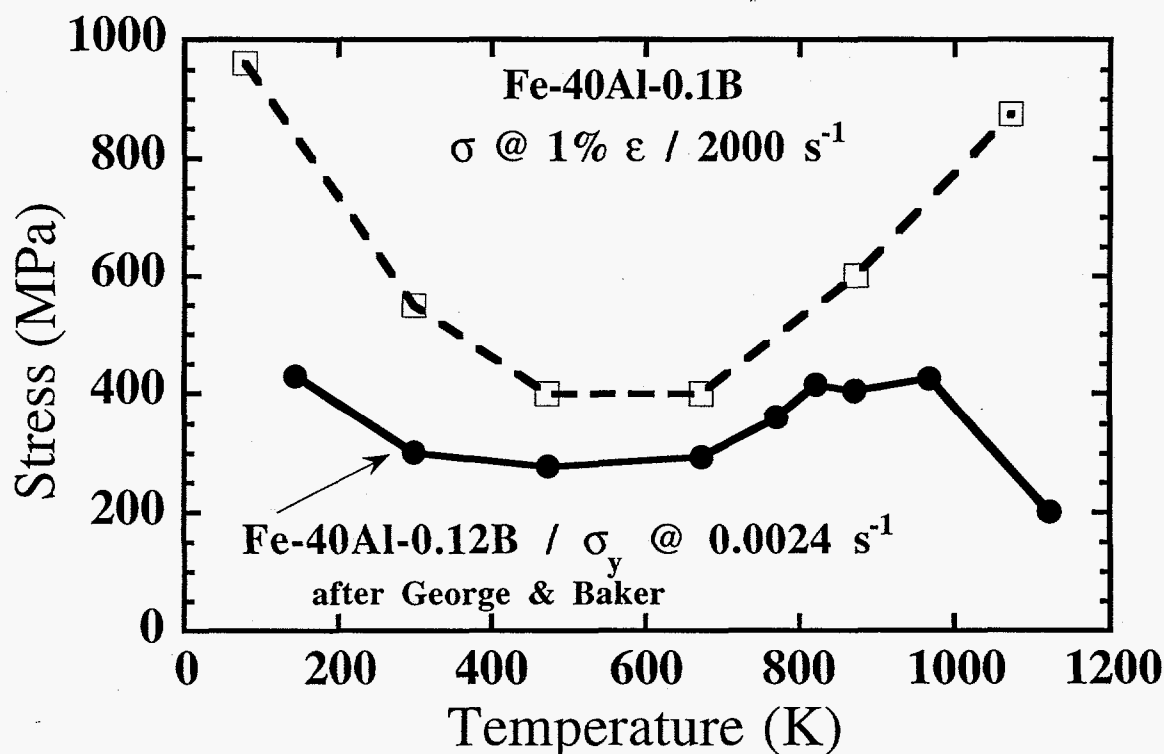


Figure 16 - Plot of yield strength at 0.0024 s^{-1} for Fe-40Al-0.12B versus temperature after George & Baker [56] cross-plotted against the flow stress at 1% strain for Fe-40Al-0.1B at 2000 s^{-1} [40] shown in Figure 10.

A comparison of the strain-rate dependency between the FeAl work reviewed in this paper and quasi-static data on Fe-40Al-0.12B and the potential of explaining this data using the above mentioned vacancy mechanism was made. This comparison was thought to be possible since the Fe-40Al-0.1B in the current study had been well annealed [40] and possesses nearly the same composition as the Fe-40Al-0.12B alloy studied by George and Baker [56]. Having a similar boron and aluminum content as well as a well-annealed starting condition is important given the known effects of composition and annealing on the anomalous temperature behavior [50]. The data of George and Baker [56] and the data from Figure 15 for the current Fe-40Al-0.1B are cross-plotted in Figure 16. The comparison in this figure clearly suggests the

presence of a pronounced strain-rate dependency over the entire range of temperatures evaluated. This effect is thought to reflect primarily the influence of high-strain rate loading since the quasi-static (0.001 s^{-1}) yield strength of the current Fe-40Al-0.1B alloy is $\sim 300 \text{ MPa}$ (Figure 9) which is essentially the identical quasi-static yield of the George and Baker data at 298K. In addition, owing to the relatively short, 5-10 minutes, heat-up prior to a high-rate Split-Hopkinson-Bar test it is unclear if sufficient vacancies could be formed to account for the quite pronounced anomalous increase in yield and flow stresses at temperatures $> 673\text{K}$ at high-strain rate.

This comparison suggests that further examination of the strain-rate dependency of the anomalous yielding phenomena in FeAl and other anomalously temperature dependent aluminides appears warranted. In-depth electron microscopic examination of the deformation substructure evolved during the high-rate high-temperature tests clearly need to be conducted. In general this comparison represents an illustration of how strain rate studies, in addition to their relevancy to many operational questions concerning intermetallic engineering utilization, can provide insight into the details of defect generation and storage processes.

Summary and Conclusions

Based on a study of the influence of strain rate, from 0.001 to 7500 s^{-1} , and temperature, 77 to 1073K , on the compressive mechanical response of Ni-, Fe-, and Ti-based aluminides, the following conclusions can be drawn:

1. The rate sensitivities, "m" ($= \text{dln}\sigma / \text{dln}\dot{\epsilon}$), of all the aluminides are shown to be equal to or greater than that typical for the base metals from which they are derived while their work-hardening rates are significantly higher. Strain hardening, when tested in compression, in most of the aluminides is seen to continue to very high flow stresses.
2. Comparison of the work-hardening rates of the various aluminides as a function of strain rate or temperature at high rate reveals that the rate of strain hardening is predominantly invariant again with the exception of Ni_3Al and to some extent Ti-48Al-2Cr-2Nb . The observation of a pronounced increase in yield and flow stress with decreasing temperature and/or increasing strain rate is typical for BCC and lower symmetry crystal structures due to a high Peierls stress contribution.
3. For the aluminides investigated the low-strain flow stresses of Ni_3Al , Ti-48Al-2Cr-2Nb , and Fe-40Al-0.1B at strain rates of $\sim 2000 \text{ s}^{-1}$ are all seen to exhibit an anomalous increase in stress level with increasing temperature.
4. Studies of the high-strain-rate response of aluminides, in addition to their relevancy to many operational questions concerning intermetallic engineering utilization, can provide insight into the details of defect generation and storage processes in ordered intermetallic compounds.

Acknowledgments

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References

1. M. Yamaguchi and Y. Umakoshi, "The Deformation-Behavior of Intermetallic Superlattice Compounds," Prog. Matls. Sci., 34 (1990), 1-148.
2. B. Baudelet, "Industrial Aspects of Superplasticity," Mat. Sci. Eng., A137 (1991), 41-55.
3. J. Beddoes, L. Zhao, J.-P. Immarigeon, and W. Wallace, "The Isothermal Compression Response of a Near γ -TiAl + W Intermetallic," Mat. Sci. Eng., A183 (1994), 211-222.
4. H.S. Yang, W.B. Lee, and A.K. Mukherjee, "Superplasticity in TiAl and Ti₃Al", in Structural Intermetallics, vol. ed. R. Darolia, J.J. Lewandowski, C.T. Liu, P.L. Martin, D.B. Miracle, and M.V. Nathal, (TMS, 1993), 69-76.
5. I. Baker and P. Nagpal, "A Review of the Flow and Fracture of FeAl", in Structural Intermetallics, vol. ed. R. Darolia, J.J. Lewandowski, C.T. Liu, P.L. Martin, D.B. Miracle, and M.V. Nathal, (TMS, 1993), 463-473.
6. H. Li and T.K. Chaki, "Hydrogen Embrittlement of Ni₃Al at Various Hydrogen Contents and Strain Rates", in High-Temperature Ordered Intermetallic Alloys V, vol. 288, ed. I. Baker, R. Darolia, J.D. Whittenberger, and M.H. Yoo, (Materials Research Society, 1993), 989-994.
7. X. Pierron and I. Baker, "An Overview of Environmental Effects in Iron Aluminides", in Design Fundamentals of High Temperature Composites, Intermetallics, and Metal-Ceramics Systems, vol. ed. R.Y. Lin, Y.A. Chang, R.G. Reddy, and C.T. Liu, (TMS, 1995), 271-285.
8. E.P. George and C.T. Liu, "Review of Environmental Effects in Intermetallics", in High-Temperature Ordered Intermetallic Alloys VI, vol. 2, ed. J. Horton, I. Baker, S. Hanada, R.D. Noebe, and D.S. Schwartz, (Materials Research Society, 1995), 1131-1145.
9. M. Yamaguchi and H. Inui, "Structural Intermetallics", in Structural Intermetallics, vol. ed. R. Darolia, J.J. Lewandowski, C.T. Liu, P.L. Martin, D.B. Miracle, and M.V. Nathal, (TMS, 1993), 127-142.
10. M.H. Oh, H. Inui, M. Misaki, M. Kobayashi, and M. Yamaguchi, "Environmental Effects on the Room Temperature Ductility of Polysynthetically Twinned (PST) Crystals of Binary and Some Ternary TiAl Compounds", in High-Temperature Ordered Intermetallic Alloys V, vol. 288, ed. I. Baker, R. Darolia, J.D. Whittenberger, and M.H. Yoo, (Materials Research Society, 1993), 1001-1006.
11. A. Kimura, A. Koya, T. Morimura, and T. Misawa, "Impact Properties of Intermetallic Compounds," Matls. Sci. Eng. A, 176 (1994), 425-430.
12. J.E. Hack, J.M. Brzeski, and R. Darolia, "Fracture and Deformation of NiAl Single-Crystals," Mat. Sci. Eng. A, 193 (1995), 268-276.
13. K.S. Chan and Y.W. Kim, "Rate and Environmental-Effects on Fracture of a 2-Phase TiAl-Alloy," Metall. Trans. A, 24 (1993), 113-125.
14. H. Inui, Y. Toda, and M. Yamaguchi, "Plastic-Deformation of Single-Crystals of a DO(19) Compound with an Off-Stoichiometric Composition (Ti-36.5 at.% Al) at Room-Temperature," Philos. Mag. A, 67 (1993), 1315-1332.
15. M.H. Oh, H. Inui, M. Misaki, and M. Yamaguchi, "Environmental-Effects on the Room Temperature Ductility of Polysynthetically Twinned (PST) Crystals of TiAl," Acta Metall. et Materialia, 41 (1993), 1939-1949.

16. E.P. George, C.T. Liu, and D.P. Pope, "Mechanical-Behavior of Ni₃Al: Effects of Environment, Strain Rate, Temperature, and Boron Doping," Acta Metall. et Materialia, 44 (1996), 1757-1763.
17. E.P. George, C.T. Liu, H. Lin, and D.P. Pope, "Environmental Embrittlement and other Causes of Brittle Grain-Boundary Fracture in Ni₃Al," Mats. Sci. Eng. A, 193 (1995), 277-288.
18. D.Q. Li, D.L. Lin, Y. Liu, and A.D. Shan, "Effects of Strain Rate and Manganese Addition on Room-Temperature Ductility of FeAl," Scripta Metall. et Matl., 30 (1994), 655-659.
19. A.D. Shan and D.L. Lin, "Effects of Strain Rate and Chromium Addition on Room-Temperature Ductility and Fracture Mode in Fe₃Al," Scripta Metall. et Matl., 27 (1992), 95-99.
20. T.L. Lin and Y. Zhang, "Creep Behavior of Directionally Solidified Ni₃Al Alloys with Alloy Additions", in Structural Intermetallics, vol. ed. R. Darolia, J.J. Lewandowski, C.T. Liu, P.L. Martin, D.B. Miracle, and M.V. Nathal, (TMS, 1993), 445-452.
21. Z. Dong, W. Liming, Z. Dunxu, Y. Mei, and C. Qigong, "Anomalous Strain Rate Dependence of the Flow Stress of TiAl Intermetallic Compounds," J. Matls. Sci., 11 (1992), 1992.
22. S.S. Ezz, Y.Q. Sun, and P.B. Hirsch, "Strain Rate Dependence of the Flow Stress and Work Hardening of Single Crystals of Ni₃(Al,Hf)B", in High-Temperature Ordered Intermetallic Alloys VI, vol. 2, ed. J.A. Horton, I. Baker, S. Hanada, R.D. Noebe, and D.S. Schwartz, (Materials Research Society, 1995), 695-700.
23. I. Baker, "Flow and Fracture of FeAl", in Processing, Properties, and Applications of Iron Aluminides, vol. ed. J.H. Schneibel and M.A. Crimp, (TMS, 1994), 101-115.
24. D.S. Shih, D.S. Schwartz, and J.E. O'Neal, "Effects of Strain Rate and Prestraining on Tensile Behavior of Duplex Gamma Titanium Aluminides", in High-Temperature Ordered Intermetallic Alloys V, vol. 288, ed. I. Baker, R. Darolia, J.D. Whittenberger, and M.H. Yoo, (Materials Research Society, 1993), 579-584.
25. S.A. Maloy, G.T. Gray-III, and R. Darolia, "High Strain Rate Deformation of NiAl," Mat. Sci. and Eng., A192/193 (1995), 249-254.
26. T.-S. Lee, W.-P. Hon, S.-C. Yang, S.-E. Hsu, S. Chin, and D.L. Anton, "The Strain Rate Sensitivity of Polycrystalline and Single Crystal NiAl", in High-Temperature Ordered Intermetallic Alloys VI, vol. 364, ed. J.A. Horton, I. Baker, S. Hanada, R.D. Noebe, and D.S. Schwartz, (Materials Research Society, 1995), 537-542.
27. F. Appel, U. Sparka, and R. Wagner, "Thermally Activated Processes and Dislocation Mobilities in Two-Phase γ -Titanium Aluminides", in High-Temperature Ordered Intermetallic Alloys VI, vol. 364, ed. J.A. Horton, I. Baker, S. Hanada, R.D. Noebe, and D.S. Schwartz, (Materials Research Society, 1995), 623-628.
28. S.A. Maloy and G.T. Gray-III, "The Temperature and Strain Rate Dependence of the Flow Stress of Single Crystal NiAl Deformed along $\langle 110 \rangle$ ", in High-Temperature Ordered Intermetallic Alloys VI, vol. 364, ed. J.A. Horton, I. Baker, S. Hanada, R.D. Noebe, and D.S. Schwartz, (Materials Research Society, 1995), 549-554.
29. H.W. Sizek and G.T. Gray-III, "Mechanical and Microstructural Response of Ni₃Al at High Strain Rates and Elevated Temperatures", in Shock-Wave and High-Strain-Rate Phenomena in Materials, vol. ed. M.A. Meyers, L.E. Murr, and K.P. Staudhammer, (Marcel Dekker, Inc., 1992), 117-125.

30. H.W. Sizek and G.T. Gray-III, "Deformation of Polycrystalline Ni3Al at High Strain Rates and Elevated Temperatures," Acta Metall. et Mater., 41 (1993), 1855-1860.
31. M.G. Mendiratta, Y.-W. Kim, and D.M. Dimiduk, "Loading Rate Effects and Fracture in a TiAl Alloy", in High-Temperature Ordered Intermetallic Alloys V, vol. 288, ed. I. Baker, R. Darolia, J.D. Whittenberger, and M.H. Yoo, (Materials Research Society, 1993), 543-548.
32. G.T. Gray, S.I. Hong, and B.J. Marquardt, "Influence of Strain Rate on the Structure/Property Behavior of the Alpha-2 Alloy Ti-24.5Al-10.5Nb-1.5Mo", in Titanium '92 - Science and Technology, vol. ed. F.H. Froes and I.L. Caplan, (TMS, Warrendale, PA, 1993), 1163-1170.
33. D.E. Albert and G.T.G. III, "Mechanical and Microstructural Response of Ti-24Al-11Nb as a Function of Temperature and Strain Rate," Acta Metall. et Materialia, (1996), in press.
34. G.T. Gray, "Influence of Strain Rate on the Structure/Property of Ti-48Al-1V", in Microstructure/Property Relationships in Titanium Aluminides and Alloys, vol. ed. Y.-W. Kim and R.R. Boyer, (TMS, 1991), 263-274.
35. S.A. Maloy and G.T. Gray-III, "High Strain Rate Deformation of Ti-48Al-2Nb-2Cr in the Duplex Morphology", in Gamma Titanium Aluminides, vol. ed. Y.-W. Kim and R. Wagner, (TMS, 1995), 307-314.
36. S.A. Maloy and G.T. Gray-III, "High Strain Rate Deformation of Ti-48Al-2Cr-2Nb," Acta Materialia, 44 (1996), 1741-1756.
37. G.T. Gray-III, S.I. Hong, and B.J. Marquardt, "Effect of Strain Rate on the Mechanical Response of a Ti3Al-Nb-Mo Alloy," Metals & Matls., 2 (1996), 31-36.
38. K. Kitano and T.M. Pollock, "The Kinetics of Low Temperature Deformation in NiAl Single Crystals", in Structural Intermetallics, vol. ed. R. Darolia, J.J. Lewandowski, C.T. Liu, P.L. Martin, D.B. Miracle, and M.V. Nathal, (TMS, 1993), 591-599.
39. B. Viguier, J. Bonneville, K.J. Hemker, and J.L. Martin, "The Temperature Dependence of the Mechanical Properties of Gamma TiAl", in High-Temperature Ordered Intermetallic Alloys VI, vol. 364, ed. J.A. Horton, I. Baker, S. Hanada, R.D. Noebe, and D.S. Schwartz, (Materials Research Society, 1995), 629-634.
40. G.T. Gray-III, "Influence of Strain Rate and Temperature on the Mechanical Behavior of Iron-Based Aluminide Alloys", in Plasticity '95-Dynamic Plasticity and Structural Behaviors, vol. ed. S. Tanimura and A.S. Khan, (Gordon and Breach, 1995), 527-530.
41. Y.-W. Kim and D.M. Dimiduk, "Strain-Rate Effects on the Room Temperature Tensile Properties of a TiAl Alloy", in High-Temperature Ordered Intermetallic Alloys V, vol. 288, ed. I. Baker, R. Darolia, J.D. Whittenberger, and M.H. Yoo, (Materials Research Society, 1993), 671-677.
42. G.T. Gray and J.D. Embury, "The Behavior of Intermetallic Compounds at Large Plastic Strains", in High-Temperature Ordered Intermetallic Alloys-V, vol. 288, ed. I. Baker, R. Darolia, J.D. Whittenberger, and M.H. Yoo, (Materials Research Society, 1993), 585-590.
43. K. Yoshimi, S. Hanada, and M.H. Yoo, "Yielding and Plastic-Flow Behavior of B2-Type Fe-39.5 Mol. Percent Al Single-Crystals in Compression," Acta Metall. et Matl., 43 (1995), 4141-4151.

44. K. Yoshimi and S. Hanada, "Positive Temperature Dependence of Yield Stress in B2 FeAl", in Structural Intermetallics, vol. ed. R. Darolia, J.J. Lewandowski, C.T. Liu, P.L. Martin, D.B. Miracle, and M.V. Nathal, (TMS, 1993), 475-482.
45. K. Jumonji, S. Ueta, M. Kato, and A. Sato, "Temperature-Dependence of Strain Rate Sensitivity, Work-Hardening and Dislocation-Structure in Ni3Al Single-Crystals," Philos. Mag. A, 69 (1994), 1111-1124.
46. Y.D. Hahn and S.H. Whang, "Deformation and Microstructure in L1(0) Type Ti-Al-V Alloys," Metall. and Matls. Trans. A, 26 (1995), 113-131.
47. R.D. Noebe, C.L. Cullers, and R.R. Bowman, "The Effect of Strain Rate and Temperature on the Tensile Properties of NiAl," J. Matls. Res., 7 (1992), 605-612.
48. I. Baker, "A Review of the Mechanical Properties of B2 Compounds," Matls. Sci. and Eng., A192/193 (1995), 1-13.
49. I. Baker, H. Xiao, O. Klein, C. Nelson, and J.D. Whittenberger, "The Effect of Temperature and Fe:Al Ratio on the Flow and Fracture of FeAl," Acta Metall. Mater., 43 (1995), 1723-1730.
50. O. Klein and I. Baker, "The Effect of Boron on the Temperature Dependence of the Flow and Fracture of Fe-45Al," Scripta Metall. et Mater., 30 (1994),
51. B. Viguier, K.J. Hemker, J. Bonneville, F. Louchet, and J.L. Martin, "Modeling the Flow-Stress Anomaly in Gamma-TiAl I: Experimental-Observations of Dislocation Mechanisms," Philos. Mag. A, 71 (1995), 1295-1312.
52. S.S. Ezz and P.B. Hirsch, "The Operation of Frank-Read Sources, Yield Stress Reversibility and the Strain-Rate Dependence of the Flow-Stress in the Anomalous Yielding Regime of L1(2) Alloys," Philos. Mag. A, 72 (1995), 383-402.
53. E.P. Busso and F.A. McClintock, "A Dislocation Mechanics-Based Crystallographic Model of a B2-Type Intermetallic Alloy," Int. J. Plas., 12 (1996), 1-28.
54. K.J. Hemker, M.J. Mills, and W.D. Nix, "A Critical Analysis of Existing Models for Plastic-Flow in Ni3Al: Comparisons with Transient Deformation Experiments," J. Matls. Res., 7 (1992), 2059-2069.
55. P.B. Hirsch and Y.Q. Sun, "Observations of Dislocations Relevant to the Anomalous Yield Stress in L1(2)-Alloys," Matls. Sci. Eng. A, 164 (1993), 395-400.
56. E.P. George and I. Baker, "A Model for the Temperature-Dependence of the Yield Strength of FeAl," Philos. Mag., (1996), in press.
57. K.M. Chang, "Tensile and Impact Properties of Directionally Solidified Fe-40Al Intermetallic," Metall. Trans. A, 21 (1990), 3027-3028.
58. M. Ikebuchi, H. Inui, Y. Shirai, M. Yamaguchi, S. Fujita, and T. Nishisako, "Microstructures of Some Intermetallic Compounds Deformed by Impact Loading," Matls. Sci. Eng. A, 193 (1995), 289-300.
59. G.T. Gray-III, "Influence of Shock Loading on the Structure / Property Response of Ti-48Al-2Cr-2Nb and Ti-24Al-11Nb", in DYMAT 94, vol. ed. (Les Editions de Physique, 1994), 373-378.
60. V.K. Sikka, S. Viswanathan, and C.G. McKamey, "Development and Commercialization Status of Fe3Al-Based Intermetallic Alloys", in Structural Intermetallics, vol. ed. R. Darolia,

J.J. Lewandowski, C.T. Liu, P.L. Martin, D.B. Miracle, and M.V. Nathal, (TMS, 1993), 483-491.

61. P.S. Follansbee: in Metals Handbook-Mechanical Testing, , American Society of Metals, Metals Park, OH, vol. 8, 1985, pp. 198-203.

62. C.E. Frantz, P.S. Follansbee, and W.J. Wright, "New Experimental Techniques with the Kolsky Bar", in High Energy Rate Fabrication, vol. ed. I. Berman and J.W. Schroeder, (Amer. Soc. Mech. Eng., 1984), 229-236.

63. U.F. Kocks: in Mechanical Testing for Deformation Model Development, R.W. Rohde and J.C. Swearingen, eds., American Society for Testing and Materials, vol. ASTM STP 765, 1982, pp. 121-138.

64. U.F. Kocks, A.S. Argon, and M.F. Ashby, "Thermodynamics and Kinetics of Slip," Prog. Matls. Sci., 19 (1975), 1.

65. G.T. Gray: in Twinning in Advanced Materials, M.H. Yoo and M. Wuttig, eds., The Minerals, Metals, and Materials Society, vol. 1994, pp. 337-349.

66. C.G. McKamey, J.H. DeVan, P.F. Tortorelli, and V.K. Sikka, "A Review of recent developments in Fe₃Al-based alloys," J. Mater. Res., 6 (1991), 1779-1805.