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Influence of Strain Rate and Temperature on the Mechanical Behavior of Iron Aluminide-Based Alloys

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Iron aluminides are receiving increasing attention as potential high temperature structural materials due to their excellent oxidation and sulfidation resistance. Although the influence of strain rate on the microstructure / property relationships of pure iron and a variety of iron alloys and steels has been extensively studied, the effect of strain rate on the stress-strain and deformation response of iron aluminides remains poorly understood. In this paper the influence of strain rate, varied between 0.001 and 10^4 s^{-1}, and temperature, between 77 & 1073°K, on the mechanical behavior of Fe-40Al-0.1B and Fe-16.12Al-5.44Cr-0.11Zr-0.13C-1.07Mo-0.06Y, called FAP-Y, (both in at.%) is presented. The rate sensitivity and work hardening of Fe-40Al and the disordered alloy based on Fe-16% Al are discussed as a function of strain rate and temperature.

Key Words: High strain-rate, Iron Aluminides, High Temperature, Work Hardening, Cryogenic Temperature

1. Introduction

The structure/property behavior of Fe-based aluminides has attracted recent interest as high temperature alloys exhibiting excellent oxidation and sulfidation resistance and retention of good strength to intermediate temperatures[1-4]. The mechanical response of FeAl, which is a B2 compound, exhibits a wide range of behavior due to its wide composition range(~36.5 to ~50 at.% Al at 298°K), the change in slip vector from <111> to <001> with increasing temperature, test environment, and cooling rate following annealing[3, 5]. Similar to $L1_2$ intermetallics, such as Ni_3Al, FeAl exhibits a positive temperature dependence of the yield strength[2, 3]. 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 600°K followed by a positive temperature dependence with a peak temperature at 873°K when tested at a strain rate of $1.7x10^{-4}s^{-1}$[2]. The anomalous slip transition in FeAl has been related to the decomposition of [111] dislocations while the change in slip vector from <111> to <001> type occurs macroscopically around the peak temperature[2]. Conversely, the yield strength of Fe_3Al-based intermetallics decreases with increasing[4].

While the influence of higher strain rate deformation on the structure / property response of pure iron and a variety of steels and iron-based has been extensively studied, the effect of high-rate deformation on the mechanical response of iron aluminides remains poorly understood. The yield strength of Fe-45 at.% Al was found to be independent of strain rate over the range from 10^{-6} to 1 s^{-1}[6]. In addition, the coincident influence of temperature on the structure/property response of FeAl under high-rate conditions is unknown. A recent study on polycrystalline Ni_3Al revealed that the positive temperature dependence of the flow stress in this alloy is still operative at strain rates of 3500 s^{-1}[7]. The purpose of this paper is to report results of a study examining the effect of strain rate and temperature on the mechanical response of Fe-40Al and a disordered Fe-16Al alloy.

2. Experimental Procedures

2.1 MATERIALS

The materials used for this investigation were Fe-40Al(composition in at. % of 40Al, 0.1B, and bal. Fe) and Fe-8Al (called FAP-Y with composition in at.% of 16.12Al, 5.44Cr, 0.11Zr, 1.07Mo, 0.13C, 0.06Y and bal. Fe). Both alloys were supplied by Oak Ridge National Laboratory. The FAP-Y was extruded from a 76-mm-dia. cast ingot to 12.5-mm-dia. bar, a reduction of ~36:1, and then annealed in air for 1 hour at 1073°K and air cooled. The Fe-40Al was arc cast and then extruded in a heavy-walled mild steel can at 1173°K with a reduction of 9:1 followed by annealing in vacuum for 1 hour at 1273°K resulting in an equiaxed grain structure of ~150 μm. To remove quenched-in vacancies the Fe-40Al was annealed for 5 days at 673°K and then bench cooled.

2.2 MECHANICAL TESTING

The mechanical responses of the Fe-40Al and FAP-Y 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 0.1s^{-1}. 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. High temperature tests were performed in a vacuum furnace mounted on the Split-Hopkinson Bar[8]. 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 inherent oscillations in the dynamic stress-strain curves and the lack of stress equilibrium in the specimens at low strains make the determination of yield inaccurate at high strain rates. Accordingly, the Hopkinson Bar data at strains of less than 1 to 2% are not shown.

3. Results and Discussion

The compressive true stress-true strain responses of Fe-40Al and FAP-Y were 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 1073°K (Figures 1-3). The flow stresses of both Fe-40Al and FAP-Y are seen to increase with increasing strain rate at 298°K or decreasing temperature at 0.001 s^{-1}. The rate sensitivity, "m" ($= d\ln\sigma / d\ln\varepsilon$), for Fe-40Al and FAP-Y was measured to be 0.047 and 0.032, respectively. The remarkable linear Stage-II stress-strain behavior in Fe-40Al (to true strains of 0.20) and high strain-rate sensitivity for Fe-40Al are consistent with other ordered intermetallics, such as Ti-48Al-2Cr-2Nb[9] and Ni_3Al[7]. The observation of a rapid increase in yield and flow stress with decreasing temperature or increasing strain rate in BCC metals and several intermetallics has been traditionally explained by a high Peierls stress. The Kear-Wilsdorf mechanism or one of the other cross-slip mechanisms where cross-slipped segments pin dislocations has been proposed to explain the anomalous positive temperature dependence on the yield in Ni_3Al[7] and TiAl[9]. A pronounced rate sensitivity accompanied by a similar work hardening behavior as a function of strain rate, as seen in the current study, is consistent with a high Peierls stress in both Fe-40Al and FAP-Y.

The rate of strain hardening in Fe-40Al is seen to be predominantly invariant with increasing strain rate while it increases for FAP-Y. The stage-II work-hardening rates for Fe-40Al and FAP-Y were measured to be 6500 MPa/ unit strain and 1000 MPa/ unit strain, respectively. Normalizing the quasi-static work hardening rates with the Taylor Factor for a random polycrystal,

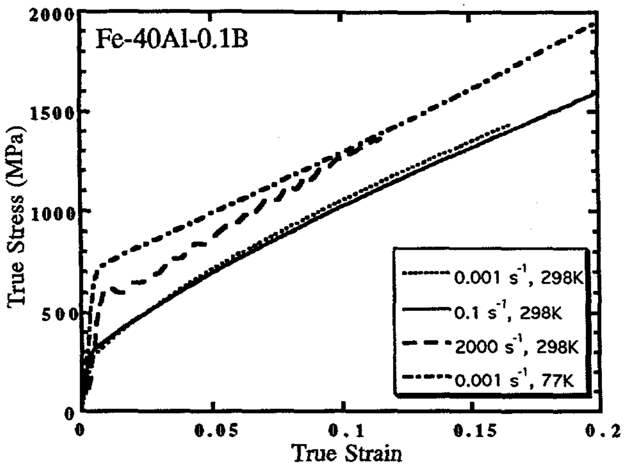

Figure 1 - Stress-Strain response of Fe-40Al as a function of strain rate and temperature.

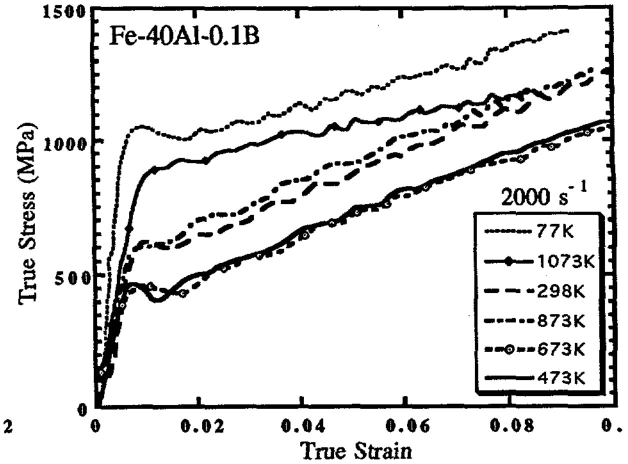

Figure 2 - Stress-Strain response of Fe-40Al as a function of temperature at 2000 s^{-1}.

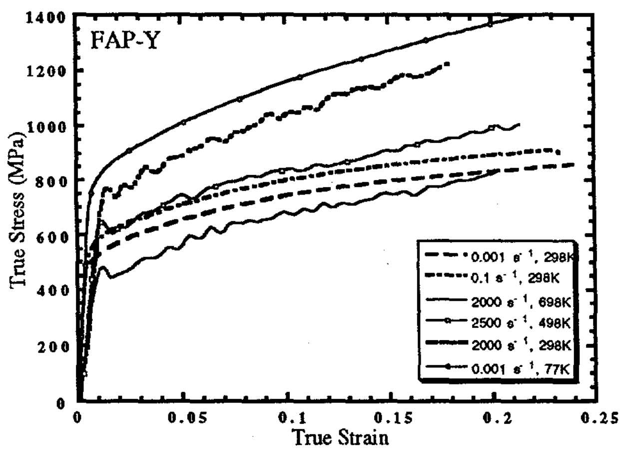

Figure 3 - Stress-Strain response of FAP-Y as a function of strain rate and temperature.

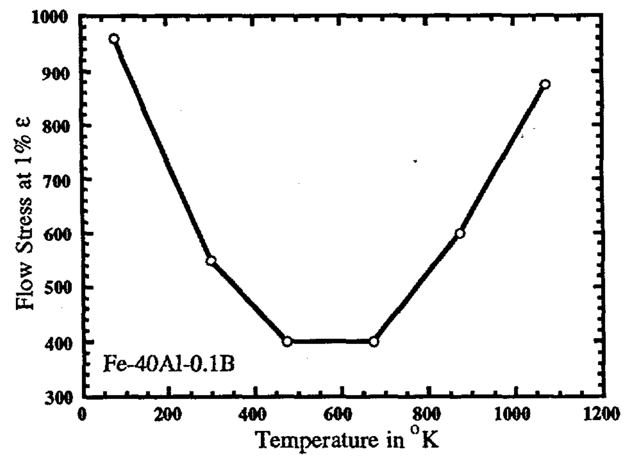

Figure 4 - Plot of flow stress at 1 % ε vs. temperature for Fe-40Al at 2000 s^{-1}.

[$\theta / (3.07)^2$], yields work hardening rates of μ/104 in Fe-40Al and μ/680 for FAP-Y assuming a shear modulus for Fe-40Al and FAP-Y at room temperature of ~72 GPa. This hardening rate in Fe-40Al is similar to the μ/100 for Ni_3Al at 3000 s-1 at 298°K. The normalized quasi-static strain-hardening rate for FAP-Y is consistent with the Stage II-type hardening behavior of μ/500 for pure iron and steels.

Increasing temperature at high strain rate is observed to decrease the flow stress of FAP-Y (Figure 3) while the flow stress in Fe-40Al at 1% strain decreases initially from 77 to 473°K, levels off til 673°K, and then increases again up to 1073°K. A similar yield and flow stress / temperature anomaly was recently documented in Ti-48Al-2Cr-2Nb deformed at high strain-rate from 77 to 1373°K[9]. The persistent temperature anomaly in Ti-48Al-2Cr-2Nb under high-rate deformation conditions has been related to pinned screw orientation <101> dislocations[9]. Increasing temperature is seen to have only a small effect on the strain hardening rate in either Fe-40Al or FAP-Y. The lack of variance in the high-strain-rate strain hardening rates in Fe-40Al as a function of temperature is similar to that recently documented for Ni_3Al[7] and Ti-48Al-2Cr-2Nb[9]. Additional high-rate deformation studies and substructure investigations on FeAl and

Fe_3Al-based intermetallic compounds are required to clarify the defect mechanisms controlling the positive temperature dependence exhibited at high strain rate.

4. Summary and Conclusions

Based on a study of the influence of strain rate, from 0.001 to 7500 s^{-1}, and temperature, 77 to 1073°K, on the mechanical response of Fe-40Al-0.1B and FAP-Y, the following conclusions can be drawn:

1. The rate sensitivity, "m" (= $d\ln\sigma / d\ln\varepsilon$), of Fe-40Al and FAP-Y were measured to be 0.047 and 0.032, respectively.

2. The rate of strain hardening in Fe-40Al was found to be nearly invariant with increasing strain rate while the hardening for FAP-Y increases with increasing rate or decreasing temperature. The stage-II work-hardening rates for Fe-40Al and FAP-Y were measured 6500 MPa/ unit strain and 1000 MPa/ unit strain, respectively.

3. As the temperature is increased from 77 to 1073°K at a strain rate of 2000 s^{-1}, a yield stress anomaly is observed with a minimum yield stress occurring at between 473 and 673°K.

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