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FRACTURE BEHAVIOR OF THE Fe-8Al ALLOY FAP-Y*

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ABSTRACT

The tensile and impact properties of two heats of the reduced aluminum alloy FAP-Y have been measured and compared to the Fe_3Al alloy FA-129. The FAP-Y material has similar yield strengths up to 400°C, and much better ductility and impact properties, as compared to the FA-129. Despite excellent room-temperature ductility, the ductile-to-brittle transition temperature is still quite high, around 150°C. The material is found to be strain-rate sensitive, with a significant increase in the yield strength at strain rates of about 10^3 s^{-1}. It is believed that this strain-rate sensitivity is responsible, at least in part, for the high ductile-to-brittle transition temperature.

INTRODUCTION

Iron-aluminum alloys based on the Fe_3Al iron aluminide offer an attractive combination of excellent oxidation and sulfidation resistance with low cost and acceptable strength. Work at Oak Ridge National Laboratory (ORNL) and many other locations has resulted in significant improvements in the mechanical properties of these alloys. Although these alloys have potential for many applications, they can suffer from low ductility at room temperature due at least in part to environmentally induced embrittlement [1], and they have poor impact properties [2-4]. Recent work has shown that improvements in the tensile properties of iron-aluminum alloys can be achieved by reducing the aluminum content to about 8 weight percent [5]. Two heats of a low aluminum content alloy designated FAP-Y have been fabricated, and the tensile and impact properties have been measured for comparison to earlier data for an Fe_3Al-type alloy called FA-129 [4]. Some results from the first heat of FAP-Y have already been reported [6].

EXPERIMENTAL PROCEDURE

Two heats of FAP-Y were prepared at ORNL. The nominal composition of FAP-Y is Fe-8.5Al-5.5Cr-0.2Zr-2.0Mo-0.026C-0.1Y (wt %). The Fe_3Al-based alloy FA-129 [7] has the nominal composition of Fe-15.9Al-5.5Cr-1.0Nb-0.05C. The lower level of aluminum in FAP-Y will result in a disordered body-centered cubic (BCC) structure rather than the ordered B2 or DO_3 structure that the higher aluminum alloys would have. The FAP-Y alloy matches the FA-129 chromium content, with a molybdenum addition for pitting resistance [5]. The zirconium and carbon additions are intended to provide some control of the grain size. The alloy also contains a yttrium addition intended to enhance the corrosion resistance of the alloy to compensate for its lower aluminum content [8,9].

The first heat of FAP-Y (heat number 14953) was vacuum-induction melted, cast into a 75-mm-diam ingot, extruded into 15-mm-diam bar (extrusion ratio of 25:1), annealed for 1 h at 800°C, and air cooled. The second heat (15512) was also vacuum induction melted, cast into a 75-mm-diam ingot, and extruded to a diameter of 13 mm, for an extrusion ratio of approximately 36:1. The bar was annealed in air for 1 h at 800°C and then air cooled.

Full-size Charpy V-notch (CVN) impact specimens were fabricated from the extruded bars. The specimens were oriented along the length of the bars, with their notch perpendicular to the extrusion axis. The small diameter of the second bar resulted in the corners of these specimens being rounded. The specimens were not heat treated after machining.

The CVN specimens were tested on a semiautomated impact test machine. Specimens tested above 300°C were heated in a small box furnace to the desired temperature, as indicated on a dummy specimen instrumented with thermocouples. When the test temperature was reached, the specimen was removed from the furnace, located on the anvils with the aid of specially designed tongs, and broken as quickly as possible. No estimate of the drop in temperature has been made, and the furnace temperature has been used as the test temperature.

Small tensile specimens were fabricated from the broken halves of the CVN specimens by electrodischarge machining. Therefore, all of the specimens were oriented parallel to the extrusion direction. The specimens had a reduced section $1.78 \times 2.54 \times 6.35$ mm long ($0.070 \times 0.100 \times 0.250$ in.) and were tested on a screw-driven electromechanical testing machine at a constant crosshead speed of 2.1×10^{-3} mm/s (0.005 in./min) for an initial strain rate of 3×10^{-4} s^{-1}. High-temperature testing was conducted with a split-tube furnace, and temperature was monitored throughout the test with a thermocouple spotwelded on one end of the specimen. All tests were conducted in laboratory air.

Sections parallel and transverse to the extrusion axis for both materials were metallographically polished and etched. The grain sizes were estimated by comparison to the ASTM standards for grain size. The fracture surfaces of the tensile and CVN specimens were examined in a scanning electron microscope.

RESULTS

The microstructures of the two heats are shown in Fig. 1. Both bars had equiaxed grain structures, with rows of inclusions aligned parallel to the extrusion axis. The inclusion content of the two heats appeared to be similar. However, the grain sizes of the two heats were very different. The first heat had a fine grain size, estimated to be ASTM grain size 7. This converts to an average linear intercept grain size of 28 μm. The second heat had a larger grain size, with ASTM number 5, an average linear intercept of 57 μm [10]. Thus, the grain size of the second heat was approximately twice as large as that of the first heat.

The tensile results are shown in Fig. 2. The yield strengths of the two heats of FAP-Y are similar, despite the difference in grain size, and are close to the FA-129 material [6]. At higher temperatures the ordered FA-129 retains it strength while the FAP-Y shows a decrease in strength with increasing test temperature. The tensile strength of the FAP-Y is higher than for FA-129 because of the premature failure of the FA-129 until the test temperature exceeds 400°C. At 600°C where the FA-129 has high ductility, it has a higher ultimate tensile strength. The ductility of the FAP-Y material is very high. The total elongation is about 40% at room temperature and rises as the test temperature increases. The FA-129 alloy has very low ductility up to at least 400°C.

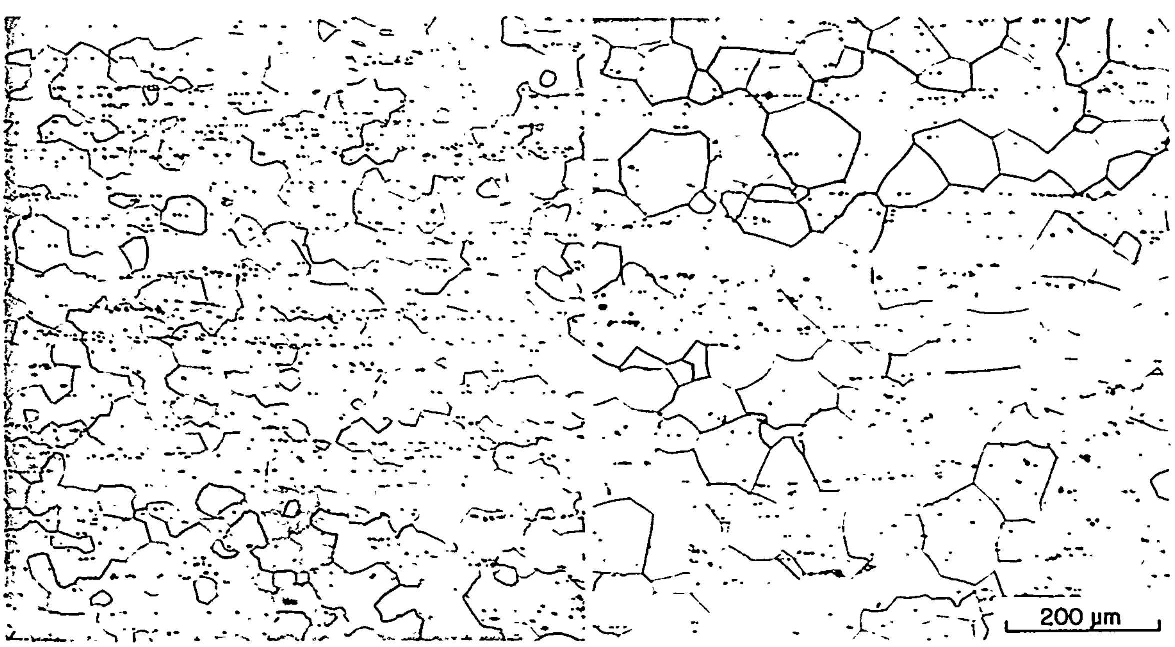

Fig. 1. Microstructures of the FAP-Y materials. Left: first heat. Right: second heat. Note the difference in grain size, and the particles aligned along the extrusion direction (left to right).

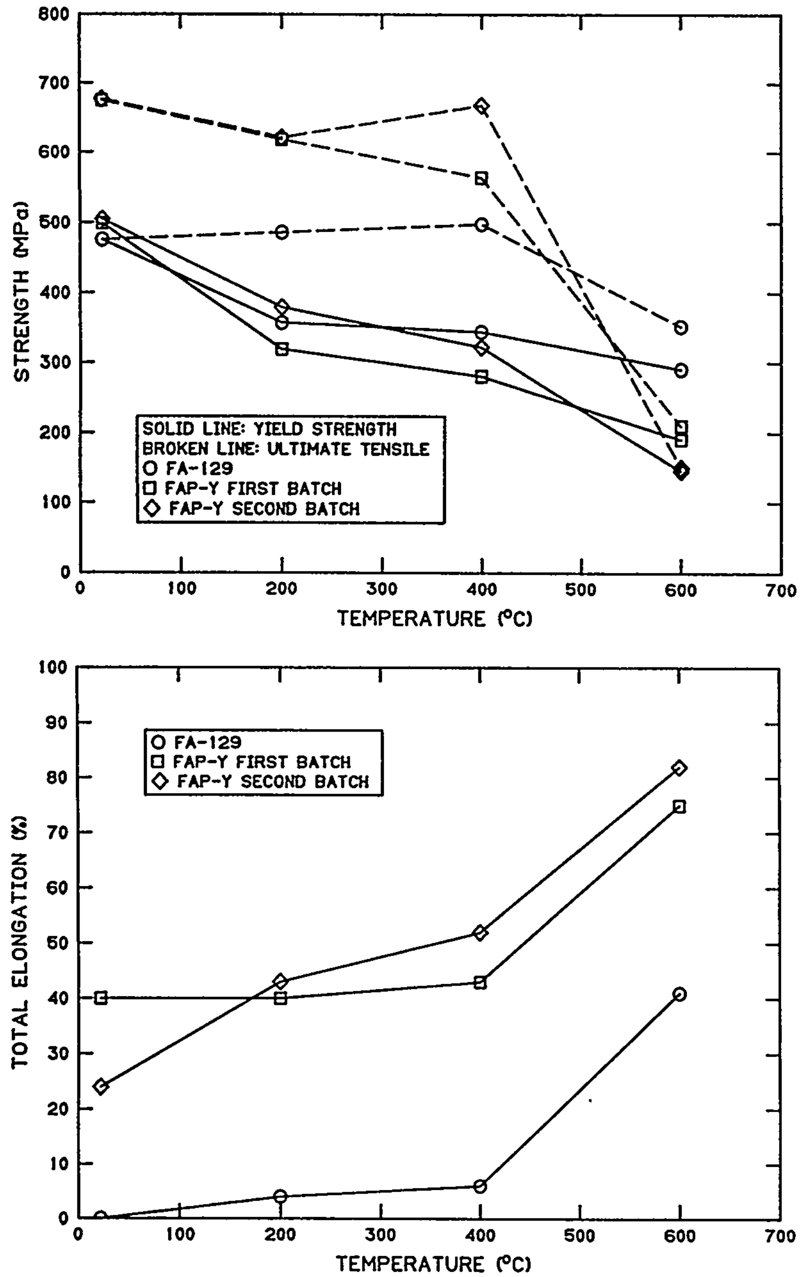

Fig. 2. Tensile properties of FAP-Y and FA-129. Top: yield strength and ultimate tensile strengths as a function of test temperature. Bottom: total elongation as a function of test temperature.

The results of the impact testing are shown in Fig. 3. The two heats of FAP-Y have similar behavior. Both show much greater levels of energy absorption on the upper shelf than the FA-129 [4] but have a high ductile-to-brittle transition temperature (DBTT) of about 150°C. Although this is much better than the DBTT of the FA-129, which is about 300°C, it is still surprisingly high for a material that shows such high ductility at room temperature.

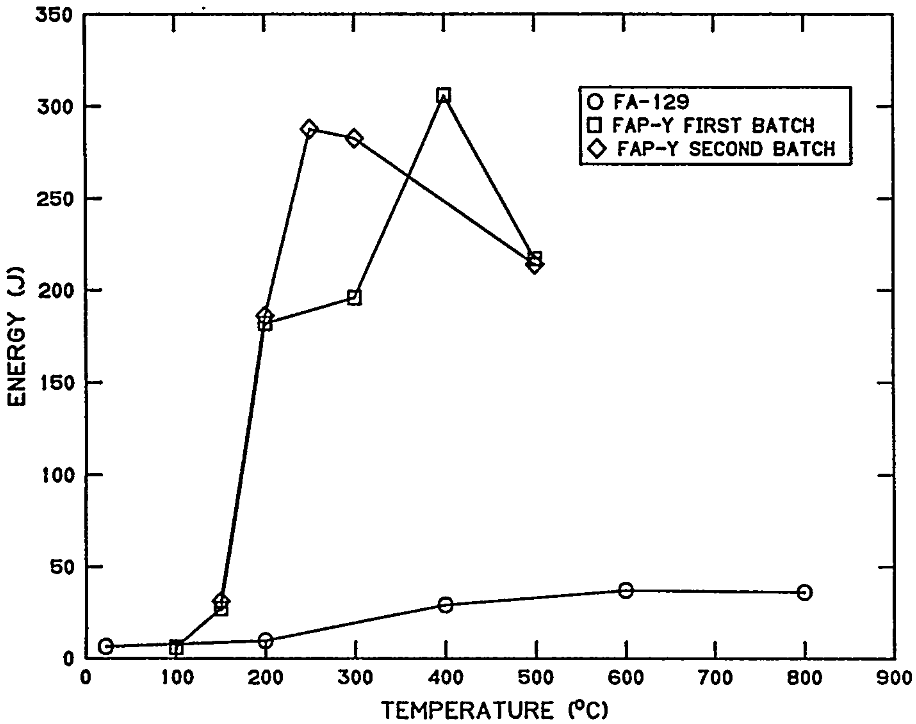

Fig. 3. Absorbed energy in impact vs test temperature for FAP-Y and FA-129.

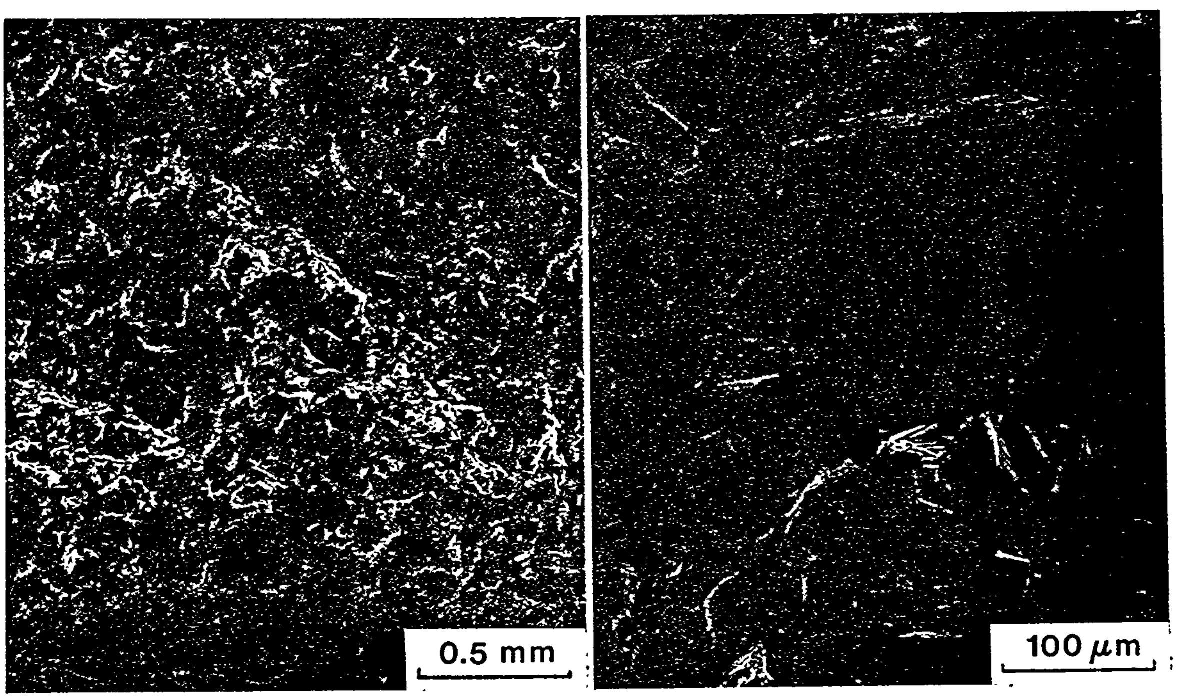

Fig. 4. Fractography for first heat of FAP-Y. Left: low magnification view of fracture surface of Charpy specimen tested at 150°C. Right: higher magnification, showing primarily cleavage fracture with some intergranular fracture.

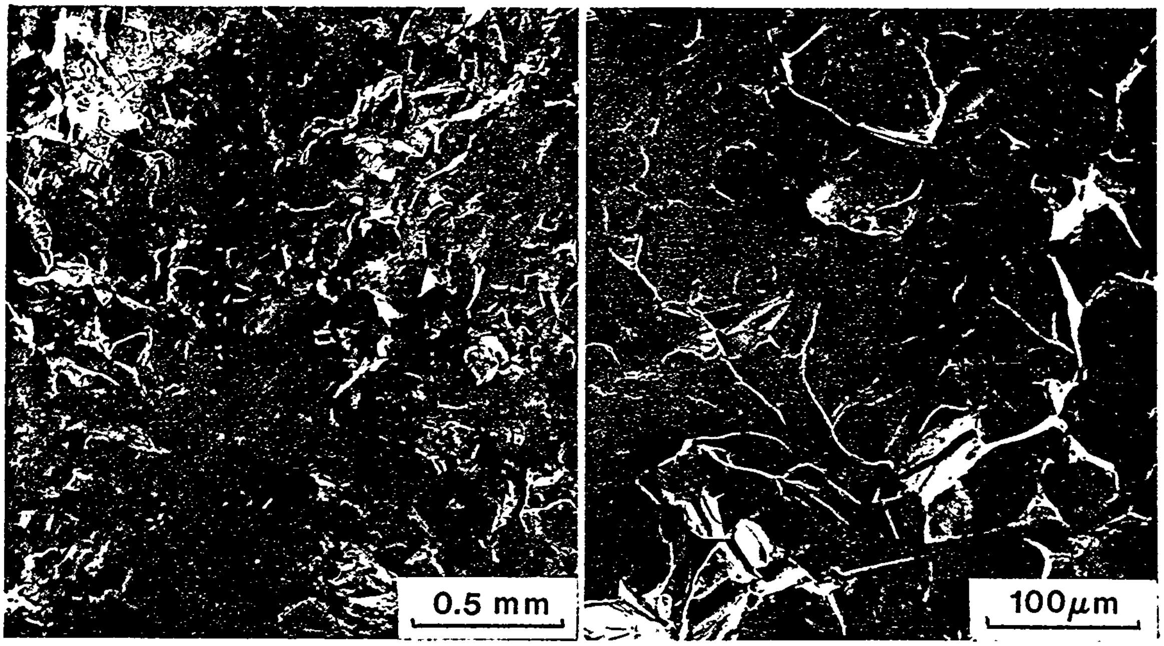

Fig. 5. Fractography for second heat of FAP-Y. Left: low magnification view of Charpy specimen tested at 150°C. Note the many particles on the fracture surface. Left: higher magnification showing cleavage fracture.

Examination of the fracture surfaces of Charpy specimens from the first heat of FAP-Y showed that fracture at low temperatures occurred primarily by cleavage, with some intergranular fracture (Fig. 4). At higher temperatures ductile fracture occurred by microvoid coalescence. Second-phase particles were associated with the ductile dimples. Specimens from the second heat showed larger fracture facets reflecting the larger grain size of the second heat. No intergranular fracture was observed, but many particles were present on the fracture surface (Fig. 5).

DISCUSSION

The reduced aluminum alloys offer similar strength levels to FA-129, but with much greater ductility. This improvement has been attributed to a reduced susceptibility to environmental embrittlement as a result of the lower aluminum content, since it is believed that the aluminum reacts with water vapor in the atmosphere to generate hydrogen that is responsible for the embrittlement [1,5]. In addition, dislocation movement should be much easier in the disordered BCC structure in the reduced aluminum alloys than in the ordered structure in FA-129. The FAP-Y alloy should also benefit from its fine, equiaxed grain structure. It is not clear whether this is due to the yttrium addition or the processing procedures.

An unexpected result is the similarity in the tensile and impact properties of the two heats of FAP-Y despite the factor of two difference in the grain size. The finer grain size of the first heat might be expected to result in a higher yield strength and a lower DBTT as compared to the second heat, but this is not observed. Grain boundary strengthening should be significant for this material, as there is not expected to be any contribution from second phases or precipitates in the matrix. The lack of effect of the grain size on the mechanical properties requires further investigation. Refinement of the grain size by appropriate processing should improve the impact properties of this material.

The high DBTT for the FAP-Y of about 150°C is surprising, considering the excellent tensile properties present at room temperature. Retained vacancies have been shown to have a significant effect on the mechanical properties of FeAl alloys [11]. Although it was not expected that vacancies would play a role in this disordered alloy, some Charpy specimens from the second heat were annealed at 400°C for 120 h. This heat treatment is effective for reducing the concentration of vacancies in FeAl alloys [12]. However, this anneal had no effect on the DBTT of the FAP-Y alloy.

Another possible explanation is that the alloy may be strain-rate sensitive. Recent work with thin sheet specimens of FAP-Y has indicated very little effect of strain rate on the yield strength of this alloy for strain rates from 10^{-6} to 10^{0} s^{-1} [8]. However, it seems likely that this material will exhibit strain-rate sensitivity at higher strain rates such as those associated with an impact test. To investigate this possibility, tensile specimens from the first heat were tested at faster speeds. The crosshead speed of the mechanical tester was increased up to 0.21 mm/s (0.5 in./min) for a strain rate of 3×10^{-2} s^{-1}. Speeds up to 70 mm/s (165 in./min) were obtained on a servohydraulic test machine for a strain rate of 11 s^{-1}. The load-stroke data were captured with a storage oscilloscope and then dumped to an X-Y plotter for analysis. Material from the second heat was also tested at several different strain rates at Los Alamos National Laboratory [13]. A split Hopkinson bar apparatus was used to obtain strain rates in compression as high as 5.5×10^{3} s^{-1}.

These tests showed that this material is strain-rate sensitive, with the yield strength increasing with strain rates above approximately 10^{-1} s^{-1} (see Fig. 6). At the highest strain rates tested the yield strength had risen from 500 to 800 MPa, a 60% increase.

This increase in the yield strength at high strain rates can explain, at least in part, the different behaviors observed in tensile and impact tests. The high ductility observed in the tensile tests occurs at slow strain rates. In the impact tests, the high strain rates will raise the yield stress. In addition, the notched geometry creates a hydrostatic stress field, and suppresses

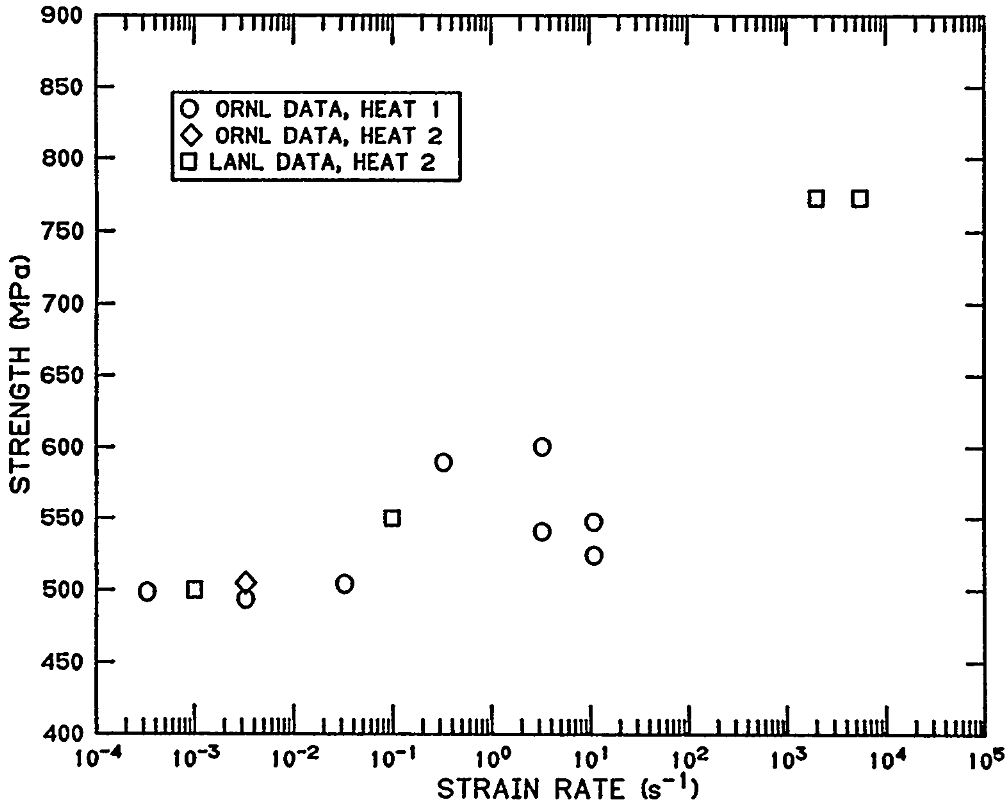

Fig. 6. Effect of strain rate on the room temperature yield strength of FAP-Y. The yield strength begins to increase for strain rates greater than about 10^{-1} s^{-1}.

plasticity. The notch will also increase the local strain rates even further. The suppression of yielding and the elevation of the yield stress results in the local stresses reaching the cleavage fracture stress, with fracture rather than plasticity being the result.

The FAP-Y material also shows a tendency for intergranular fracture. This may contribute to the poor impact resistance, but since the brittle fracture surface is primarily cleavage, the intergranular fracture is not believed to play a major role.

CONCLUSIONS

The tensile and Charpy impact properties of two heats of the reduced aluminum alloy FAP-Y have been measured. Both heats showed similar ductile-to-brittle transition temperatures of about 150°C, and similar tensile properties, with roughly 40% total elongation at room temperature. The FAP-Y alloy is strain-rate sensitive, with the yield strength increasing by about 60% when the strain rate is increased from 10^{-1} to 10^{3} s^{-1}. The combined effects of the notched geometry in the impact specimens, which creates a triaxial stress field and suppresses plasticity, and the strain rate sensitivity, which elevates the yield stress at high strain rates, are believed to be the reasons for the high DBTT despite the excellent tensile ductility of this material at low strain rates. Developing a better understanding of the processing response of this alloy in order to achieve a refined grain size is necessary to determine whether a finer grain size may be helpful.

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