Fatigue crack growth of $Fe_{81}B_{13.5}Si_{3.5}C_2$ amorphous metal using magnetostrictive behaviour to generate ΔK

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The fatigue crack growth behaviour of $Fe_{81}B_{13.5}Si_{3.5}C_2$ amorphous metal (Metglas 2605SC) was examined. An experimental apparatus was developed to generate the applied stress intensity range, ΔK, using the magnetostrictive behaviour of the material. Cycles of elastic strain were accumulated at the natural frequency of the specimens (44 or 56 kHz) with the crack length being monitored optically at certain cycle increments. Through-the-thickness, centre-cracked panel specimens were tested in the as-cast and annealed conditions. Annealing temperatures were 250 and 450 °C. Several specimens annealed at 300 °C, while being subjected to a transverse magnetic field, were also tested. Examination of the fatigue crack growth rate data indicated no differences between the as-cast and the annealed only specimens. The specimens that were annealed while being subjected to the transverse magnetic field, however, exhibited much greater resistance to fatigue crack growth. Microscopy using a Kerr-effect magneto–optical microscope revealed that the magnetic domain boundaries within the material exerted a significant influence on the direction of the fatigue crack propagation and the overall crack growth rate behaviour.

1. Introduction

A number of deformation, fatigue and fracture studies have been conducted for amorphous metal alloys by utilizing traditional servo-hydraulic testing apparatus [1–7]. The objective of this study was to replace the servo-hydraulic test system with the use of the magnetostrictive behaviour of the material to generate specimen strain. Magnetostriction was used to cause a cyclic strain in the specimen resulting in an applied stress intensity range, ΔK, at the crack tip and fatigue crack growth.

All ferromagnetic and ferrimagnetic materials that are below the Curie temperature (i.e. below the temperature where magnetic moments become random and spontaneous magnetization vanishes) are composed of small regions called domains [8]. These regions are typified by mutual atomic spin alignment in the same direction for all magnetic dipole moments, as represented in Fig. 1.

Within each domain the dipoles are aligned. The direction of alignment varies from one domain to another. Adjacent domains are separated by a "wall" which is characterized by a gradual change in magnetic dipole orientation as shown in Fig. 2.

Upon magnetization ferromagnetic materials undergo an expansion or contraction in the direction of the applied magnetic field due to alignment of the domains. This results in a change in length or induced strain in the material known as magnetostriction. The length change, and therefore the strain, is proportional to the field over a certain range, but eventually saturates as the magnetic field becomes large and all of the domains are preferentially aligned. The spontaneous magnetostrictive strain in each domain occurs at magnetic field saturation and is designated by λ_S, which is the magnetostriction value at saturation [9]. This is, therefore, equivalent to the material strain for amorphous metals with randomly oriented domains, and is typically reported as a material property for "as-cast" amorphous metals. The published value for the amorphous metal that was used in this investigation, for example, is 30×10^{-6}.

In order to include the direction dependency of domains, material strain due to domain rotation has been shown to be equivalent to [9]:

$$\varepsilon = 3\lambda_S/2(1 - \cos^2\Psi) \quad (1)$$

where Ψ is the angle of domain rotation due to

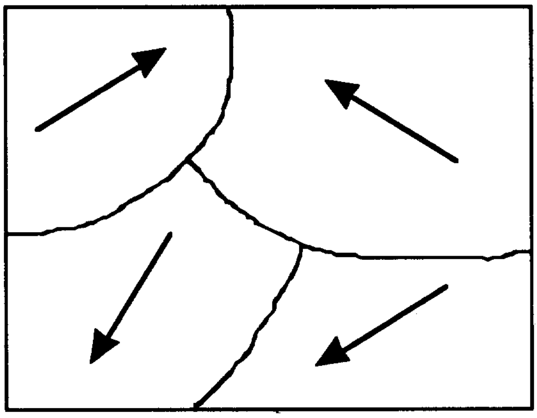

Figure 1 Schematic representation of domains in amorphous metals. Arrows represent atomic magnetic dipoles.

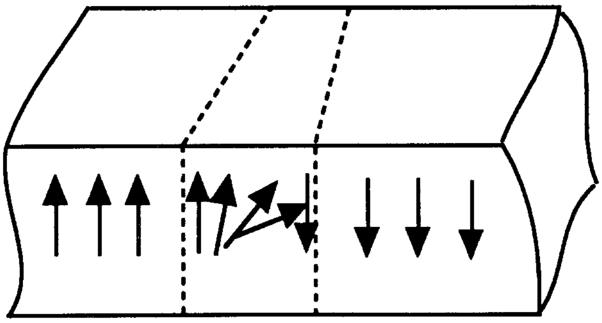

Figure 2 Gradual change in magnetic dipole orientation across a domain wall.

magnetization. As can be seen, if domain alignment is transverse to the magnetization field, Ψ is $\pi/2$ and the material strain will be maximized at $3\lambda_S/2$ during magnetization. In order to investigate the effect of this maximum strain on fatigue crack growth, material samples were included in the testing which had been subjected to transverse field annealing in order to assure maximum domain rotation. These two levels of strain (i.e. λ_S and $3\lambda_S/2$) were also used in the ΔK calculations for the materials that were investigated, and is further explained in Section 2.2.

The fatigue crack growth testing included three categories of material samples, i.e. as-cast, annealed and transverse field annealed. The effects of annealing below the crystallization temperature (T_x) has been previously shown to cause a general degradation in fatigue performance when subjected to low temperature annealing (i.e. 200–600 °C) [5]. Transverse field annealing was utilized, as previously indicated, to provide maximum material strain.

In addition to the fatigue crack growth testing, fracture behaviour of all specimens was investigated using Kerr-effect microscopic techniques.

2. Experimental procedure

2.1. Material description and test sample preparation

This analysis was based on a commercially available $Fe_{81}B_{13.5}Si_{3.5}C_2$ amorphous metal (Metglas 2605SC) [10]. This alloy was selected because of its relatively high magnetostriction at magnetic saturation (λ_S). Typical material properties of Metglas 2605SC, as reported by Allied Corporation [10], are shown in Table I.

A total of 25 material samples were prepared having the geometry shown in Fig. 3. All of the samples contained a 1.27 mm (0.050 in) long, through-the-thickness crack. The crack was introduced by using a steel punch that was constructed specifically for this research.

Ten of the samples were annealed for 30 min at temperatures of 250 and 450 °C (five samples at each temperature.) All annealing temperatures were below the crystallization temperature of 480 °C. Previous investigations by Alpas *et al.* [5] indicated that heat treatments of a nickel based metallic glass at 440 °C for 7 min improved the ΔK_{th} value and reduced low crack growth rates. Another group of 10 samples were annealed at 300 °C for 30 min while being subjected to a transverse magnetic field of approximately 5 kOe. Five samples were left unannealed (as-cast).

2.2. Fatigue crack growth testing

Each of the material samples was individually placed into a plastic test cavity. A sketch of the test cavity assembly and orientation within the solenoidal coils is shown in Fig. 4. These samples were subsequently fixtured within a solenoidal magnetic field generator (Fig. 5) to magnetically excite the material and induce strain.

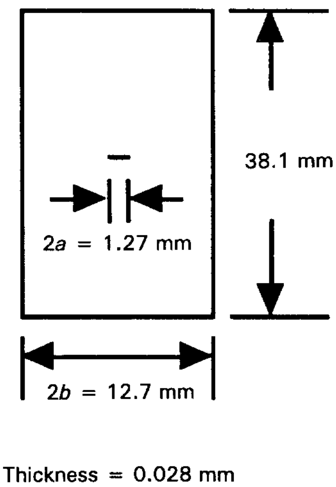

Figure 3 Through-the-thickness crack geometry used in test specimens and life prediction model.

TABLE I Material properties of 2605SC

Curie temp., T_c (°C)	Cryst. temp., T_x (°C)	Max. perm., μ_{max}	Density (g cm^{-3})	Yield strength (kg mm^{-2})	Elastic modulus (kg mm^{-2})
370	480	3×10^{-5}	7.32	370	16.9×10^{-3}

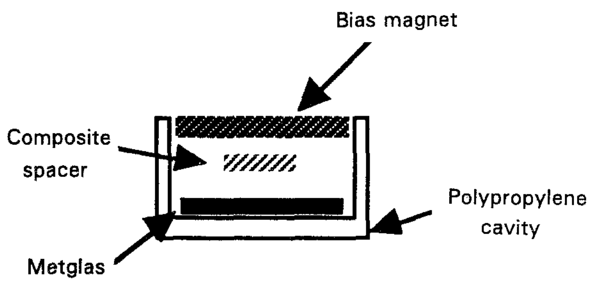

Figure 4 Test cavity assembly used for all material testing.

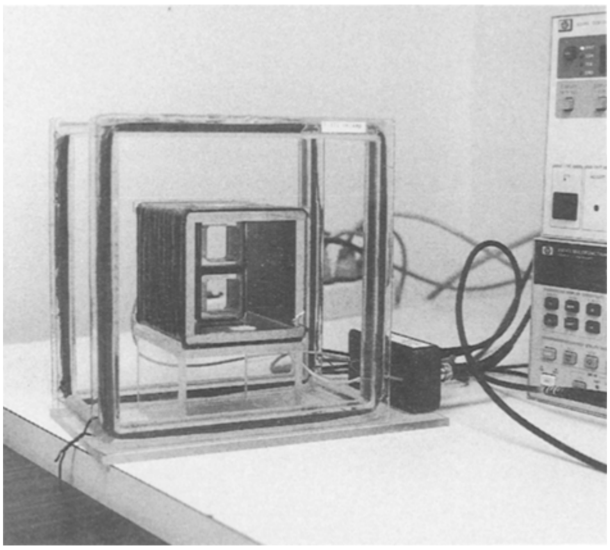

Figure 5 Solenoidal coils used to generate magnetic fields.

Each sample was excited at its resonant frequency which was, typically, in the vicinity of 56 kHz. The transverse field-annealed samples, however, were found to have resonant frequencies in the vicinity of 44 kHz. Amplitudes of 10 V were used for all specimens. Due to the relatively high resonant frequencies of the samples, it is obvious that a large number of fatigue cycles, due to magnetostriction, were accumulated each second.

Visual inspections were made every 5 min to determine the crack length ($2a$) that was observed at the specified number of fatigue cycles (N). The data was tabulated as half-crack lengths (a) versus cycles (N) for each of the material samples that were previously described. From the a versus N data the secant method of data reduction was utilized to generate $\Delta a/N$ versus ΔK data [11]. Graphs representing $\mathrm{d}a/\mathrm{d}N$ versus ΔK were also constructed for each material sample. A stress of 0.7605 $\mathrm{kg\,mm^{-2}}$ was utilized to determine ΔK for the transverse field-annealed material. A lower stress of 0.507 $\mathrm{kg\,mm^{-2}}$ was used for the as-cast and annealed ΔK calculations. The lower stress is attributed to reduced strain due to the random domain orientations of these specimens as compared to the transverse domain specimens. Unlike the transverse field-annealed specimens where strain is equivalent to $3\lambda_S/2$, the strain for the as-cast and annealed specimens is equivalent to λ_S [9].

Although these two stress levels (i.e. 0.7605 $\mathrm{kg\,mm^{-2}}$ and 0.507 $\mathrm{kg\,mm^{-2}}$) are representative of uniform, unnotched specimens, they are also presumed to apply to the notched and propagating cracked specimens. The test conditions are, therefore, presumed to be representative of constant amplitude loading. This presumption is based on the following:

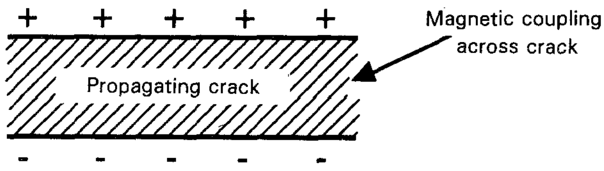

Figure 6 Magnetic coupling which lowers magnetostatic energy.

1. Flux density (B) versus magnetic field strength (H) curves which are representative of domain orientations during various levels of magnetization were determined for unnotched, notched and final cracked specimens for each of the three test groups. The resulting B versus H curves resulted in, essentially, identical results within each test group. These results indicate that the crack growths do not affect magnetostriction.
2. Magnetic coupling across the adjacent free surfaces (i.e. cracks) has been shown [9] to occur in order to lower magnetostatic energy by the dilution of free poles (Fig. 6). This magnetic coupling is further presumed to extend, or "bridge", the effects of adjacent domains and maximize the effects of magnetostriction.

A magneto–optical (Kerr-effect) domain viewing microscope was utilized throughout the investigation to examine crack morphology. This instrument utilizes polarized light to interact with the magnetization of the material sample to result in (Kerr) polarization rotation. The resulting microscopy indicates light and dark regions which represent different magnetic spin directions. This technique provides a visual inspection of the domain location and orientation in the specimens relative to the propagating crack.

3. Results and discussion

3.1. Fatigue crack growth in test samples

The resulting $\Delta a/\Delta N$ versus ΔK data indicate two distinct regions (i.e. one region for the as-cast and annealed material specimens and a second region for the transverse field-annealed specimens). The data are shown in Fig. 7. It should also be noted that, because the ΔK do not overlap, the two regions could be on the same curve (i.e. "near threshold" and "linear" regions.)

These data appear to be associated with the near-threshold region of fatigue crack growth. As seen in Fig. 7, the data exhibit significant scatter which may be associated with the ability to measure the crack length optically and the movement of the crack front out-of-plane as the crack tip intersects domain boundaries, as will be discussed later. The secant method of analysis maintains the maximum scatter in crack growth rate data, however, insufficient a versus N data were available to be able to use a scatter reduction

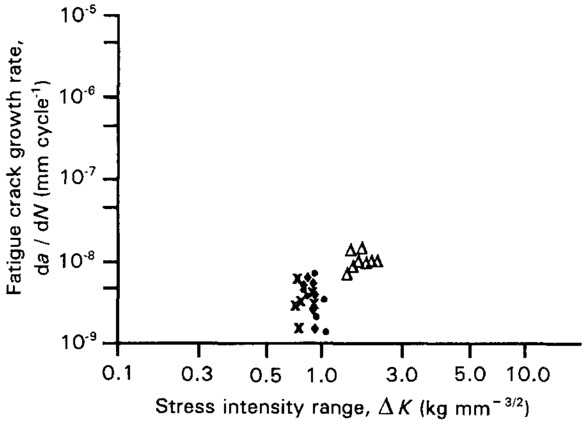

Figure 7 da/dN versus ΔK graph for test specimens. (Δ), Transverse field-annealed (300 °C, 30 min); (×) as-cast (unannealed); (◆) Annealed (250 °C, 30 min); (●) Annealed (150 °C, 30 min).

analysis procedure (seven-point polynomial method [11]).

Observing the data in Fig. 7, there appears to be little effect of annealing at 250 or 450 °C on the fatigue crack growth rates as compared to the as-cast sample data. The scatter in the data do not allow any distinction between the fatigue crack growth rates for these conditions, however. The transverse field-annealed specimens show similar to slightly higher fatigue crack growth rates (again with significant scatter) than the as-cast or annealed samples, but the transverse field-annealed data are at higher levels of ΔK. This tends to indicate that the transverse field-annealing improves the resistance of the material to fatigue crack growth. It should be noted that these observations are based on limited data over a small range of ΔK values. Further testing and examination are necessary over a much wider range of ΔK.

3.2. Microscopy

A typical as-cast sample in which crack propagation arrested was examined using the Kerr-effect microscope (× 200 magnification for all examinations.) Careful examination at the crack tip indicated that the crack tip/plastic zone area has intersected a domain wall. This is shown in Fig. 8.

Also indicated in the photograph are what appear to be a number of slip bands which are concentrated in the plastic zone, but stop abruptly at the intersecting domain wall. This shows the effect of the domain wall on the deformation behaviour at the crack tip.

As is indicated in Fig. 7, the crack propagation rates of the annealed samples were the same as the as-cast samples. A typical annealed specimen is shown in Fig. 9. The faint image of a domain boundary (indicated by an arrow) is evident where the direction of crack propagation changes abruptly. This shows the strong influence of domains on the crack propagation behaviour in the near-threshold region.

The best crack propagation behaviour was indicated in the transverse field-annealed samples. Figs 10 and 11 are photographs of transverse field-annealed samples. Both indicate well-defined areas of shear bands which, in the case of Fig. 10, have nucleated in the plastic zone which is adjacent to a dense domain

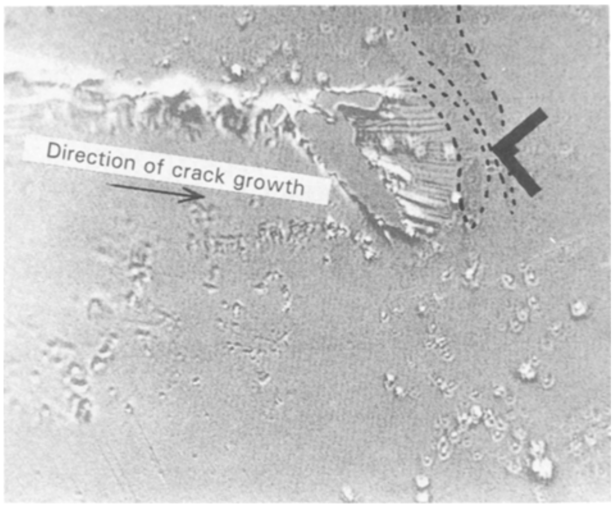

Figure 8 As-cast sample showing crack tip/plastic zone intersection at a domain wall (arrow). A dashed line surrounds the domain.

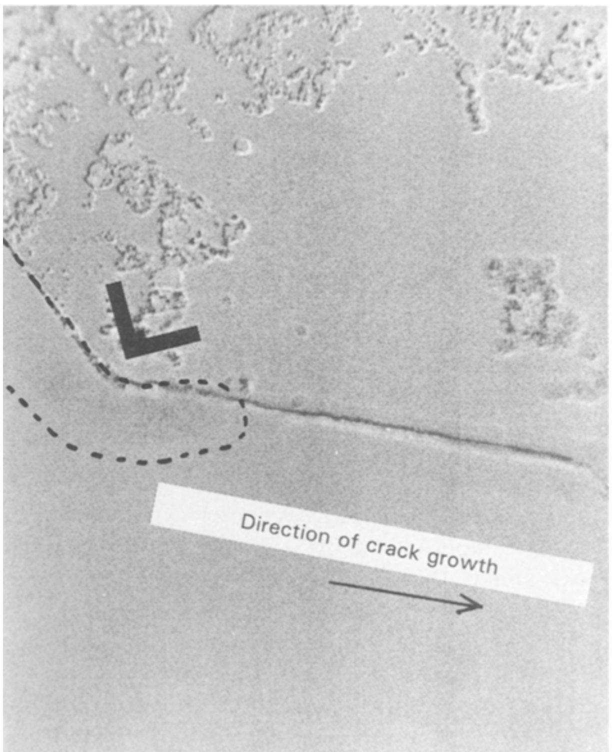

Figure 9 Annealed sample. Arrow indicates domain that influenced the direction of crack propagation. A dashed line surrounds the domain.

region. These support previous investigations by Ogura *et al.* [2, 4] which indicate that shear bands are formed by the propagation of a shear front.

As was observed for the as-cast and annealed specimens, erratic crack growth and the influence of intersecting domains was also evident in the microscopic analyses for the transverse field-annealed specimens. These results are, again, believed to be caused by the localized influence of intersecting domain walls on the deformation behaviour at the crack tip.

4. Conclusions

Testing of Metglas 2605SC specimens indicates that magnetostriction can be used as the driving force to

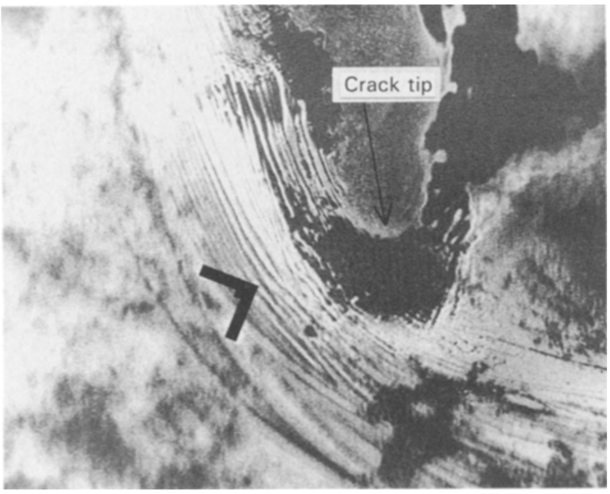

Figure 10 Transverse field-annealed sample at crack tip. Arrow indicates well-developed shear bands which have nucleated in the plastic zone ahead of the crack tip.

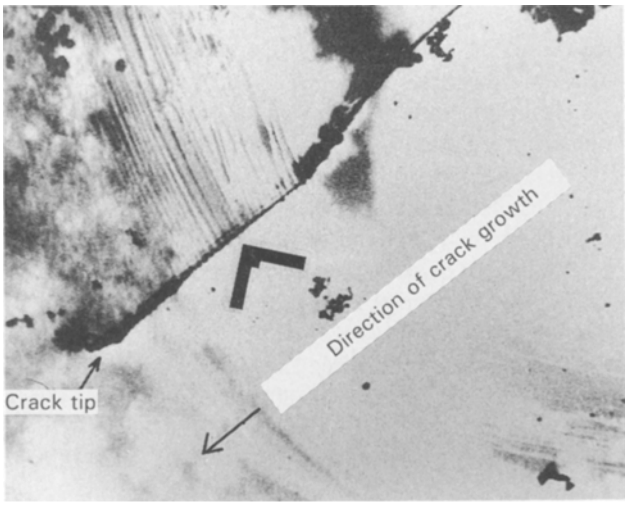

Figure 11 Transverse field-annealed sample. Arrow indicates well-developed shear bands.

generate a stress intensity range, ΔK, at the tip of a crack. This is evident in the fatigue crack growth rate data that is summarized in Fig. 7. A comparison of the da/dN versus ΔK data for the conditions tested indicates that no significant differences in crack growth behaviour exist between the as-cast specimens and the specimens annealed at either 250 or 450 °C. Specimens that were transverse field-annealed appear to have better resistance to fatigue crack growth than the as-cast and the annealed only specimens. As previously indicated, these results are based on limited data over a small range of ΔK and with significant scatter in the data.

Microscopic analyses using Kerr-effect microscopic techniques indicate that domain boundaries significantly influence the deformation and crack growth behaviour of the material. Examples of domains either arresting or redirecting the crack were observed in the specimens, regardless of the annealing condition. Some of the scatter in the fatigue crack growth data is believed to be due to the effect of domain boundaries on the propagating crack. The effect would predominate in the near-threshold region of fatigue crack growth where these experiments were performed. The microscopic analyses did not explain the crack growth rate differences observed between the as-cast or the annealed only specimens and the transverse field-annealed specimens.

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