Fracture and Fatigue Crack Propagation in a Nickel-Base Metallic Glass

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This work is an investigation of fracture and fatigue in thin ribbons of a nickel-base metallic glass: Ni<sub>78</sub>Si<sub>18</sub>B<sub>12</sub>. The fracture and fatigue crack propagation behavior of this high tensile strength and high toughness amorphous alloy is of interest for two reasons: (1) the alloy has no normal microstructure, and (2) the alloy shows an unusual form of plastic deformation which proceeds by nucleation and propagation of localized shear bands. On uniaxial tensile loading, failure of uniform ribbons occurs instantaneously at the yield stress by shear rupture through an intense shear band inclined at 55 deg to the loading axis. The development of a local plastic zone at the crack tip in single edge-notched specimens under monotonic tensile loading has been studied by a replication technique. Under plane stress conditions, these plastic zones are dominated by shear bands elongated in the direction of crack extension. Dugdale’s “strip yield” model offers a reasonable description of the plastic zone sizes and displacements at the crack tip. The relationship between fatigue crack growth per cycle, \( da/dN \), and the alternating stress intensity factor, \( \Delta K \), has been determined at \( R = 0.1 \). For growth rates in the range 10<sup>-6</sup> through 5 × 10<sup>-4</sup> mm/cycle, the Paris law (with an exponent \( m = 2 \)) is obeyed. The mechanism of fatigue crack extension is shown to depend on the deformation microstructure of the alloy. At intermediate growth rates, the plastic zone consists of a number of shear bands similar in shape to the Prandtl slip line field for nonhardening materials. Decohesion along these bands produces undulating fracture morphologies. At near threshold values of \( \Delta K \), growth rates deviate from the Paris law producing an extremely low \( \Delta K_{TH} \) (=0.5 MPa√m). This is attributed to the ease of shear band nucleation, and a simple geometrical model of crack growth at low \( \Delta K \) levels is proposed.

I. INTRODUCTION

At ambient temperatures, fracture of metallic glasses is always preceded by localized plastic deformation. This type of deformation takes the form of narrow shear bands which may sustain large shear strains.\(^\text{1,2}\) The deformation microstructure and the morphology of shear bands have been studied in stress states such as bending,\(^\text{3-5}\) uniaxial compression,\(^\text{6-7}\) and cold rolling.\(^\text{8}\) These investigations confirmed that metallic glasses are inherently ductile materials in contrast to oxide glasses. However, because of the lack of a mechanism of spreading plastic deformation,\(^\text{7,9}\) the maximum extension of thin metallic glass ribbons is very low, being approximately equal to the ribbon thickness.\(^\text{10,11}\) Fracture of unnotched specimens occurs instantaneously at the yield stress by shear rupture through an intense shear band.\(^\text{12,13}\)

Studies on notched and precracked specimens loaded in tension\(^\text{14-17}\) and in pure shear\(^\text{18}\) showed that the fracture toughness values of metallic glasses vary between 10 and 70 MPa√m depending on composition, purity, cooling rate, and specimen thickness.

The deformation of some notched Ni- and Pd-base glasses has been investigated in detail.\(^\text{13,19}\) In these alloys, plastic flow was concentrated as shear bands at the crack tip and the plastic zone size increased with applied load. The specimens finally failed by a mode III type shear fracture. Crack growth resistance curves \( R \) curves of metallic glasses have also been studied,\(^\text{20}\) and in thin specimens, a small amount of stable crack growth was seen before instability.

Metallic glasses exhibit low fatigue limits in the range of 10 to 25 pct of their tensile strengths.\(^\text{21,22,23}\) Fatigue cracks associated with shear bands usually nucleate at the surface of the specimen\(^\text{24}\) by a mechanism similar to that proposed by Forsyth\(^\text{25}\) for ductile crystalline alloys. Current knowledge on the propagation behavior of fatigue cracks in metallic glasses is largely based on early studies by Ogura \textit{et al.}\(^\text{26,27}\) who observed that fatigue crack tips are attended by plastic zones composed of a large number of shear bands. In common with crystalline alloys, fatigue crack growth rates, \( da/dN \), in amorphous metals and alloys can be expressed as a function of alternating stress intensity factors \( \Delta K \) by a power law relationship of the form \( da/dN = C\Delta K^m \) as originally proposed by Paris and Erdogan.\(^\text{28}\) The cyclic stress intensity exponent \( m \) is found to fall within a relatively narrow range of 2 to 4.\(^\text{14,15,29}\) At high \( \Delta K \) levels, crack growth proceeds by a ductile striation mechanism, but crack growth mechanisms at low \( \Delta K \) values have not been identified.

The aim of the present study is to clarify the fracture and crack propagation behavior in a nickel-base metallic glass. Crack extension and fracture of this alloy under mode III type shear loading have recently been studied by the authors.\(^\text{30}\) In this work, the mechanism of fracture and crack growth under monotonic and cyclic loading conditions will be discussed in terms of the distribution, density, and geometric features of shear
bands, the basic deformation features of which can be observed by present microscopic techniques.

II. MATERIAL AND EXPERIMENTAL PROCEDURES

The alloy studied was a nickel-base metallic glass with the atomic compositions Ni_{39}Si_{10}B_{12}. The alloy was produced by a chill-block melt-spinning technique by Vacuumschmelze GmbH and supplied in the form of continuous ribbons, 20 mm wide and 0.057 mm thick. Examination by means of X-ray diffraction showed that specimens were amorphous.

All the specimens for mechanical tests were prepared from strips cut longitudinally from the as-cast ribbons. Unnotched specimens were given a reduced gage section, 3.2 mm wide and 12 mm long, using a spark erosion machine. The heat-affected zones were subsequently removed by mechanically polishing the edges of the specimens. Single edge-notched tensile (SENT) specimens were prepared in the form of rectangular pieces, 40 mm long and 20 mm wide. A notch of about 4-mm depth was put in the middle of one edge of the specimen using a pair of scissors.

Very thin specimens loaded in tension often exhibit premature fracture due to tearing within the grips. To prevent this, both ends of the specimen were clamped between soft aluminum plates before loading. The ends were then compressed between steel grips which were pinned to the clevises of the testing machine using lubricated pins. This arrangement permitted rotation and self alignment of the test pieces to occur during the tests.

A. Tensile Tests

Uniaxial tensile tests were performed to determine the tensile strength and the elastic modulus of the alloy. Unnotched reduced gage section specimens were loaded to fracture in an Instron testing machine using a strain rate of 8.3 × 10^{-4}. Tensile strength was calculated after the fracture of the specimens. Strain measurements were taken from two strain gages positioned in the longitudinal and transverse directions on 40 × 10 mm unnotched rectangular specimens. Microhardness measurements were made under an indentation load of 200 g. The use of this load ensured that the ratio of specimen thickness to impression depth was larger than 10:1.

B. Fracture Toughness Tests

Fracture toughness tests were conducted on an Instron 8031 servo-hydraulic testing machine fitted with a 10 kN load cell. The machine was operated in closed loop configuration under load control. The surfaces of the SENT specimens were polished to 0.1 μm, and a starter notch was introduced. A fatigue precrack was then grown at ΔK = 8 MPa√m. After the crack length reached 6.5 mm (corresponding to (a/w) = 0.33, where a is the total crack length and w is the specimen width), the specimen was loaded monotonically up to fracture, and the value of the load at fracture $P_Q$ was recorded. The load was applied at a rate of 0.01 mm/s and measured to a precision of 1 pct. The provisional value of fracture toughness $K_Q$ was calculated using the following expression:

$$K_Q = \frac{P_Q \sqrt{\pi a}}{wt} \left[ 1.12 - 0.23(a/w) + 10.6(a/w)^2 - 21.7(a/w)^3 + 30.4(a/w)^4 \right]$$

The plastic zone sizes and the crack tip opening displacements (CTOD) were measured by optical microscopy from cellulose acetate replicas applied to the crack tip region during incremental loading (by ~10 pct of $K_Q$) of the specimens.

C. Fatigue Crack Growth Tests

Fatigue crack growth tests were performed on the Instron 8031 machine, fitted with a high sensitivity load cell of 500 N load capacity. The SENT specimens used were similar to those used for the fracture toughness tests with the exception of having shorter notches—about 1 mm in depth. Crack measurements were done optically and without interrupting the tests. The measuring device was a low power traveling microscope (50 times magnification) with a minimum graduation of 0.01 mm. Specimens were fatigued under $R = 0.1 (R = K_{min}/K_{max})$ using a sinusoidal waveform. All tests were carried out at room temperature (~21 °C) and in laboratory air (~55 pct humidity). The frequency was kept constant at 30 Hz except at high ΔK levels, where it was reduced to 10 Hz.

A constant load amplitude was used to determine crack growth rates above 10^{-4} mm/cycle. In this method, the length of the crack (a) grown at constant cyclic load amplitude (ΔP) was measured as a function of the number of cycles (N) at intervals of about 0.1 mm. Crack growth rates were calculated using a secant technique, and cyclic stress intensity factors, ΔK, were computed using Eq. [1] (by replacing $P_Q$ by ΔP).

Fatigue crack propagation rates below 10^{-4} mm/cycle were measured under conditions of constant ΔK. To maintain ΔK constant at a given level, after the crack length was measured, the new load required was determined from Eq. [1], and the applied load amplitude was adjusted accordingly. Typically, ten measurements of crack length were made at a given ΔK level. The crack growth rate (da/dN) was then obtained using a linear least mean squares fit.

Stress intensity threshold Δ$K_{th}$ was approached by systematic reductions of ΔK. The corresponding reductions in load were typically 10 to 15 pct. The cyclic stress intensity range, where no crack growth could be detected after 10^6 cycles, is defined as Δ$K_{th}$. The minimum detectable crack growth increment was 0.02 mm, giving growth rate less than 2 × 10^{-8} mm/cycle at Δ$K_{th}$. Fatigue crack propagation data are presented as plots of log (da/dN) vs log ΔK in which the crack growth rates are the average values obtained from three to five tests.

D. S-N Tests

$S$-$N$ curves were determined using the Instron 803 machine with a 500 N load cell. Tests were performed...