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Flex bending fatigue testing of wires, foils, and ribbons

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ABSTRACT

Medical devices, such as guide wires, valves, needles, and stents are often subjected to cyclic loading conditions in service, while there is also an increasing demand for smaller devices made with materials that are difficult to machine. Fatigue testing of such structures is complicated by their small dimensions, particularly under fully reversed loading conditions. This paper summarizes our recent work on a variety of different materials (e.g. 316LVM, Cu–15Ni–8Sn, Nitinol, amorphous metals) where flex bending fatigue has been utilized to develop fatigue-life curves of as-received materials (e.g. wire, foil, sheet) under fully reversed conditions.

1. Introduction

Flex bending fatigue testing was initially developed by the electronics industry in order to enable evaluation of the cyclic fatigue performance of various thin materials and/or structures of interest to that community. This initially comprised thin metal foils and ribbons, although a variety of wires, flat cables, and thin ribbons have since been of interest to a number of communities, including the automotive, aerospace, and biomedical communities. A description of the development of these test techniques was first provided in an ASTM Special Technical Publication (STP) [1] and subsequently standardized through ASTM [2]. Initial applications of the technique evaluated the performance of a number of Cu-based thin foils and flexible circuitry [3–5]. Since then, a number of related techniques have been developed to test wires [6,7] and foils, although most rely on the need to cycle the material over a mandrel(s) of different diameter(s) in order to generate the dependence of fatigue life on the cyclic strain imparted in the technique.

The technique of flex bending fatigue enables the testing of materials at different levels of cyclic strain, typically controlled by the thickness/diameter of the material and/or the mandrel over which the material is cyclically bent. Fatigue life curves can be constructed to capture the low cycle fatigue (LCF) and high cycle fatigue (HCF) regimes in the manner proposed and modeled by Coffin [8], and Manson [9]. These techniques have been successfully used by a number of investigators on materials ranging from AISI 316LVM [10] to various amorphous metal systems [6,11,12] in order to examine the factors controlling the fatigue lives of such thin materials.

The present paper summarizes work conducted on a variety of different crystalline and amorphous materials in order to demonstrate the usefulness of this technique as applied to these very different materials systems. General guidelines for improved performance for such thin members tested under LCF and HCF conditions will be provided based on the available data generated. Crystalline materials investigated include AISI 316LVM in the hard and annealed conditions, Cu–15Ni–8Sn heat treated to vary the strength and ductility, and a superelastic NiTi alloy. In addition, both Fe-based and Al-based amorphous metal ribbons produced via melt spinning were also evaluated.

2. Experimental procedures

2.1. Materials

316 LVM wires and stoichiometric NiTi dental archwires with different diameters were examined in this study. The non-magnetic 316 LVM individual wires tested were either 100 μm or 254 μm in diameter and were supplied by Fort Wayne Metals, Fort Wayne, IN in both the annealed and full hard (i.e. as drawn) condition. The surface roughness of the as-received 316 LVM wires measured via Laser Scanning Confocal Microscopy was

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Ra = 0.3 μm. Metallographic cross sections of the wires revealed an average grain size of 5 μm for the annealed and hard conditions.

NiTi dental archwires used in orthodontia were manufactured by 3 M and supplied by the CWRU Dental School. The archwires were manufactured from stoichiometric NiTi and processed to exhibit superelastic behavior, as revealed by the tension tests described below. The general processing conditions of these NiTi dental archwires were not provided, although x-ray diffraction analyses on a Bruker D8 diffractometer revealed a fully austenitic structure.

Cu–15Ni–8Sn sheet used for this research was produced by Ametek Specialty Metal Products Division (Wallingford, CT) via a proprietary P/M process. The P/M process involved blending elemental powders of Cu, Ni, and Sn, followed by sintering, and rolling to final sheet thickness. The copper alloy designation for Cu–15Ni–8Sn, C72900, corresponds to ASTM B-740 [13]. Experiments were conducted on two tempers. TB00 (solutionized) and TD02 (solutionized and ½ hard) designations correspond to standard tensile strength specifications [13]. Chemistry analysis via inductively coupled plasma (ICP) revealed TB00 and TD02 to possess, in wt%: Fe (0.04, 0.03), Zn (0.02, 0.02), Ni + Co (15.1, 14.8), Sn (7.8, 8.0), Mn (< 0.01, < 0.01), trace amounts of Mn, Nb, Mg, and Pb, with the remainder Cu. Oxygen content measured by LECO was 0.0065 wt%. Heat treatment of the as-received Cu–15Ni–8Sn TB00 and TD02 sheet was conducted in air at 370 °C for 5 h and 3 h, respectively, followed by air cooling in order to produce the peak strength condition, as documented elsewhere [14]. Fatigue sample surfaces were polished to 600 grit (15 μm) after heat treatment to remove oxide scale.

$Fe_{78}Si_9B_{13}$ amorphous materials were obtained commercially and were produced via melt spinning using a rotating copper wheel that was internally water cooled. The ribbons had 20 mm width and thickness approximately 30 μm. The amorphous Al alloy ribbons based on the Al–Gd–Ni (Table 1) system having thickness of 50–55 μm and width of 1.7–1.9 mm were prepared at Ames Laboratory via melt spinning with a chilled copper wheel rotating at 16 m/s. X-ray diffraction of both air and wheel side conducted on a Scintag X1 model diffractometer revealed a broad peak on all Fe-based and Al-based ribbons, characteristic of the lack of long range order in amorphous materials. The thermal stabilities and tensile properties of the Al-based ribbons are summarized elsewhere [12]. Laser confocal microscopy on the Fe-based ribbons revealed a surface roughness Ra = 2.9 μm on the air side and Ra = 1.2 μm on the wheel side. Similar roughness was obtained on the Al-based ribbons.

2.2. Tensile testing

Tensile testing of small size wires, foils, and ribbons with conventional friction grips typically produces failure at the grips. However, due to the relatively low load required to break such samples and because of their small cross sectional area, many were directly glued to the grips (without the need to use the gripping action) using acetocyanoacrylate (i.e. super glue). All tensile tests on the wires were carried out to failure using a 30 mm span with displacement rate of 0.5 mm/min using a screw driven tabletop Instron Model 1130, Instron Corporation, Norwood, MA equipped with a 10 lb load cell and MTS Testworks software, MTS systems, Eden Prairie, MN.

Tension testing of the amorphous metal ribbon samples produced via melt spinning generally followed ASTM-E8M-99 [15] using the same Instron described above. Flat pneumatic Instron grip model 3C-Instron India, Chennai, India were used to obtain proper gripping and alignment. The Fe–Si–B and Al–Gd–Ni–X samples were prepared using a specially designed polishing fixture to produce a reduced hourglass gage section. The sides of the Fe–Si–B ribbon samples were initially reduced using a DREMEL 400 grinding tool followed by subsequent polishing using SiC grit papers through 1 μm diamond paste. The resulting tension samples were 60 mm long with a 20 mm wide grip section. The reduced hourglass section was approximately 10 mm long, had a radius of curvature of 18 mm and minimum gage width of 18 mm. The calculated stress concentration factor was 1.25. Similar techniques were used to produce the Al–Gd–Ni–X samples albeit with smaller dimensions [12].

The Cu–15Ni–8Sn sheet specimens were tested in accordance with ASTM E8 for sheet and used a calibrated ½ in. clip-on extensometer. The sub-sized dogbone geometry had 6.35 mm gage width and 25.4 mm gage length. Two tests were performed on each as-received TB00 and TD02, while four tests were performed on each of the heat treated samples. Samples were tested on an Instron 1125 at 0.5 mm/min, producing an initial strain rate of $3.3 \times 10^{-4}\,s^{-1}$. In all tension tests, the load vs displacement data were analyzed to obtain the 0.2% offset yield stress (when exhibited), while the UTS was calculated at maximum load. Engineering stress was calculated using the applied load divided by the cross sectional area of the samples.

2.3. Fatigue testing

Fatigue tests were carried out on a variety of thin materials using the Flex bending fatigue machine tester shown in Fig. 1. Procedures for using this device were developed for the determination of the ductility and low cycle fatigue behavior of thin metallic foils used in the electronics industry [1,2] as summarized earlier. As reviewed elsewhere [3–5] some of the advantages of the Flex bending fatigue machine include: the ability to apply symmetric load; cyclic strain application; cyclic fatigue in strain-controlled mode; constant strain amplitude throughout test

Table 1
Mechanical properties of various alloys at room temperature.

	E (GPa)	σ_y (MPa)	UTS (MPa)	ε_f	RA (%)	σ_f (MPa)
316LVM as-drawn [10,18]	225	2224	2550	0.5	40	4250
316LVM annealed [10,18]	196	592	884	2.3	90	8840
316LVM 1 × 7 [10,18]	193	1135	1239	2.3 ± 0.3	89.9 ± 3.8	5400 ± 1490
NiTi [19]	–	447 ± 3	1672 ± 2	0.85 ± 0.01	57.3 ± 0.38	7162 ± 67
$Al_{86}Gd_6Ni_7Fe_1$ [12,28]	82.2[b]	1050[a]	1055	0	< 1%	1055
$Al_{86}Gd_6Ni_7Co_1$ [12,28]	82.4[b]	1065[a]	1075	0	< 1%	1075
$Al_{85}Gd_6Ni_7Fe_2$ [12,28]	84.7[b]	1160[a]	850	0	< 1%	850
$Al_{85}Gd_6Ni_7Fe_1Co_1$ [12,28]	84.5[b]	1075[a]	950	0	< 1%	950
$Al_{87}Gd_6Ni_7$ [12,28]	81.6[b]	970[a]	880	0	< 1%	880

[a] Calculated from hardness test [12,28].
[b] Measured via instrumented nano-indentation test [12].