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# Nitinol Fatigue Life for Variable Strain Amplitude Fatigue

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**Nitinol fatigue testing results are presented for variable strain amplitude cycling. The results indicate that cycles smaller than the constant amplitude fatigue limit may contribute to significant fatigue damage when they occur in a repeating sequence of large and small amplitude cycles. The testing utilized two specimen types: stent-like diamond specimens and Z-shaped wire specimens. The diamond specimens were made from nitinol tubing with stent-like manufacturing processes and the Z-shaped wire specimens were made from heat set nitinol wire. The study explored the hypothesis that duty cycling can have an effect on nitinol fatigue life. Stent-like structures were subjected to different in vivo loadings in order to create more complex strain amplitudes. The main focus in this study was to determine whether a combination of small and large amplitudes causes additional damage that alters the fatigue life of a component.**

**Keywords** advanced characterization, biomaterials, failure analysis

## 1. Introduction

Nitinol fatigue life predictions are usually based on constant strain amplitude fatigue tests. According to Ref 1, this is not a conservative approach, because load interaction effects caused by variable strain amplitude fatigue are not considered even though it has been demonstrated that fatigue life with variable strain amplitude loading can be as low as 10% of what is predicted by using constant strain amplitude data (Ref 2-4). Research has found that "large loads in a service load history decrease the crack opening stress and as a result increase the effective strain range for subsequent small cycles. A new strain-life fatigue test is introduced in which periodic large strain cycles reduce the crack opening stress for subsequent smaller cycles (Ref 1)". Variable strain's effect on fatigue life has been observed in steel, a traditional structural material. The purpose of this paper is to determine if the effect of variable strain amplitude fatigue can be observed in nitinol. Electropolished (diamond specimens) and non-electropolished (Z-shaped wire specimens) samples were studied in order to determine if the effect is surface finish dependent.

## 2. Development of Z-Shaped Wire and Stent-Like Diamond Specimens

### *2.1 Stent-Like Diamond Specimen*

The stent-like diamond specimens were embedded into a stent framework (Fig. 1) so that they could undergo standard stent manufacturing processing. The specimens were manufactured from nitinol tubing that met ASTM F2633-07 (Ref 5) and the processing steps included laser cutting, heat setting, and electropolishing (Ref 6). The diamond geometry of the specimens was designed to be similar to the geometry of a typical nitinol stent. Individual diamond specimens were cut from the stent framework (Ref 6).

### *2.2 Z-Shaped Wire Specimen*

The advantages of a Z-shaped wire specimen are that it is inexpensive, stable, widely available, and able to be tested in tension-tension, tension-compression, and compression-compression modes in a high cycle multi-specimen fatigue tester (Ref 7). The Z-shaped wire specimen can be used to investigate nitinol fatigue resistance under non-electropolished conditions.

The Z-shaped design used a 1.75 mm centerline radius. The final design started with an as-drawn 0.508 mm (0.020 in.) diameter superelastic wire. The vendor supplied raw material data stated that there was 45% cold work, an $A_f$ of 13 °C (DSC), an upper plateau stress of 579 MPa (84 ksi), and 15% elongation to break. Sequential parts from a single wire lot were formed into "Z" shapes by heat setting the parts in the machined grooves of steel dies. After each of two forming steps, the parts were annealed for 5 min in a 500 °C salt bath (Fig. 2).

## 3. Test Methods

### *3.1 Stent-Like Diamond Specimen Test Method*

Fatigue testing of the diamond specimens was conducted with custom equipment (Ref 6). Fatigue testing was conducted

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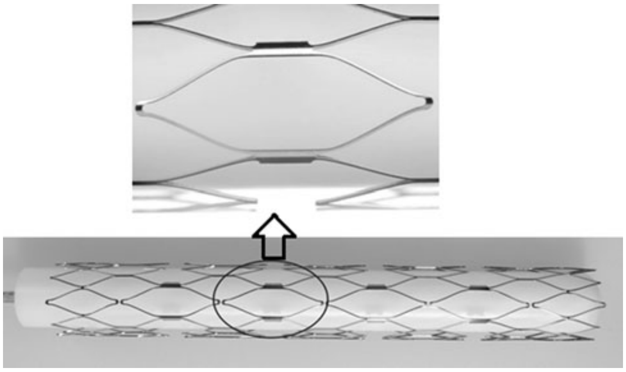

**Fig. 1** Stent-like diamond specimen is incorporated into stent framework (one diamond specimen is highlighted)

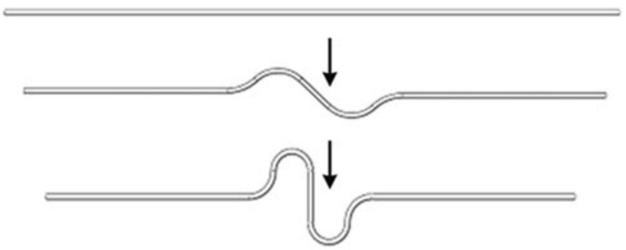

**Fig. 2** Z-shaped wire specimen has two-stage wire forming sequence

at 30 Hz and each of the specimens was individually displacement controlled. Each test specimen, containing two V shapes, was clamped in a set of custom grips. At a given strain condition, eight diamond specimens (16 V specimens) were tested simultaneously in 37 °C water. The run-out was set at $10^7$ cycles.

A study by Zipse et al. (Ref 6) determines that the fatigue strain limit of the diamond specimens was 0.38% since all 16 tested specimens survived $10^7$ cycles (run-out).

The FEA to determine fatigue strain on the diamond specimens is follows: A quarter symmetry model of the diamond specimen was built with Abaqus/CAE. Linear fully integrated hexahedron elements were used; a mesh convergence study led to the use of 12 elements through both strut thickness and width, with similar mesh density along the length. The material model used is a modified version of the Abaqus Nitinol superelastic material model, which takes into account the modifications observed in the stress-strain curve due to cyclic loading (Ref 8). Although the maximum strains obtained are at the surface, they are not exactly at the edges. The state of stress/strain at these locations is still very close to uniaxial. Nevertheless, the strain values reported here correspond to the maximum principal strains reported by the software.

### *3.2 Z-Shaped Wire Specimen Test Method*

Fatigue testing of the Z-shaped wire specimens was conducted with a Bose ElectroForce 3300 Multi-Specimen fatigue instrument. The fatigue test was displacement controlled at a frequency of 20 Hz. Each of the test specimens was clamped in a set of custom built grips. At a given strain condition, five specimens were tested in 37 °C water simultaneously. The run-out was set at $10^6$ cycles.

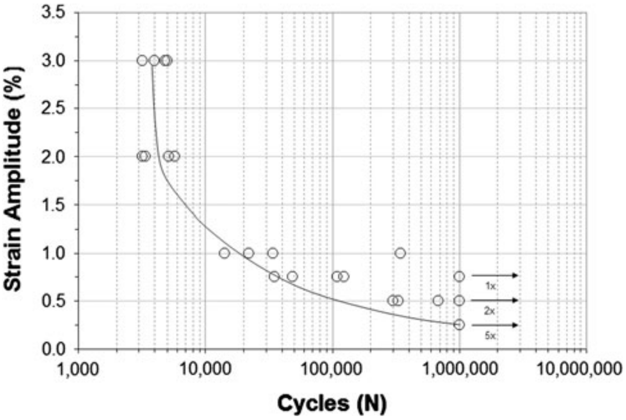

**Fig. 3** Fatigue life N (Z-shaped wire specimens) as function of strain amplitude at mean strain of 3.0%. The arrows show those specimens ran out at $10^6$ and the number indicates the number of run-out specimens

The fatigue strain limit was estimated from a S-N (strain versus life) curve where fatigue life was determined by constant strain amplitude fatigue. Figure 3 plots strain amplitude (6 levels) versus fatigue life for Z-shaped wire specimens at a mean strain ($\varepsilon_m$) of 3%. From the curve, the fatigue strain limit is determined to be 0.25% since all five tested specimens survived $10^6$ cycles (run-out).

The FEA to determine fatigue strain on the Z-shaped wire specimens is follows: High resolution 3D constitutive symmetrical half model was created in Abaqus CAE (Dassault Systemes Simulia). The model utilized the Abaqus superelastic nitinol material code (Ref 9). The mesh contained 20-node second-order continuum reduced integration hex nonlinear elements with more than 52,000 degrees of freedom. The strain prediction was validated by comparing surface strain measurements within a 20-µm patch along the inner radius of a Z-shaped wire specimen to the FEA predictions of the matching finite element model region (see Fig. 4). The strain values were found to be comparable within 0.001 in./in.

In a complete variable strain fatigue period, the specimen was fatigued at a large strain amplitude for a preset number of cycles and then fatigued at a small strain amplitude for another preset number of cycles (see Table 1 for the test matrix of the variable strain fatigue study). The large strain amplitude was defined as a strain amplitude that was greater than the fatigue strain limit. The small strain amplitude was defined as a strain amplitude that was equal to or less than the fatigue strain limit.

## 4. Results and Discussion

Variable strain fatigue appears to worsen the fatigue life when testing was conducted using the stent-like diamond specimens. Figure 5 plots the variable strain fatigue data points (solid circles and solid diamonds) along with two sets of constant strain fatigue data points (open circles and open squares). The first set of variable strain fatigue data is labeled with solid circles: 16 V specimens (8 diamond specimens). The variable strain fatigue test was cycled at strain amplitude of 1.15% for 10 cycles followed by a strain amplitude of 0.38% for 50 cycles, with the sequence being repeated until stent fracture or run-out was achieved. At the end of the fatigue test, only the large strain amplitude (1.15%) cycles were counted because the small strain amplitude (0.38%) cycles at the fatigue strain limit should not cause specimen fracture. The other set of variable strain fatigue data is labeled with solid diamonds: 16 V specimens (8 diamond specimens). The variable strain fatigue test was cycled at a strain amplitude of 1.15% for 100 cycles followed by a strain amplitude of 0.38% for 500 cycles, with this sequence repeated until stent fracture or run-out was achieved at $10^7$ cycles. At the end of the fatigue test, only the large strain amplitude (1.15%) cycles were counted because the small strain amplitude cycles at the fatigue strain limit should not cause specimen fracture. Both the open circles and the open squares represent two separate constant strain fatigue tests. Each test contained 16 V specimens (8 diamond specimens) that were fatigued at a constant strain of 1.15% until stent fracture or run-out was achieved. The variable strain fatigue worsening fatigue life was observed.

Figure 6 shows a small experiment that was conducted to verify that conditioning with small strain fatigue does not worsen the specimen's fatigue life with a larger constant strain amplitude. In this experiment the 16 V specimens (8 diamond specimens) were fatigued simultaneously at strain amplitude of 0.38% for $10^5$ cycles followed by fatigue at 1.15% strain until fracture (shown as open diamonds in Fig. 6). The fatigue life is comparable to the fatigue life of specimens fatigued at a constant strain amplitude of 1.15% (labeled with open circles and open squares in Fig. 6).

The Z-shaped wire specimen data confirms that variable strain fatigue tends to worsen fatigue life. Figure 7 shows the variable strain fatigue data points (solid diamonds or solid circles) overlaid with the constant strain fatigue S-N data points (open circles). At strain amplitude of 0.75% (solid circles), the average fatigue life of five variable strain fatigue specimens is shorter than the average fatigue life of five constant strain fatigue specimens. The variable strain fatigue test was cycled at a strain amplitude of 0.75% for 10 cycles followed by a strain amplitude of 0.10% for 50 cycles. This sequence was repeated until the stent fractured or run-out was achieved. At the end of the fatigue test, only the large strain amplitude (0.75%) cycles were counted because the small strain amplitude (0.10%) cycles were below the fatigue strain limit and would not cause specimen fracture. At a strain amplitude of 1.0% (solid

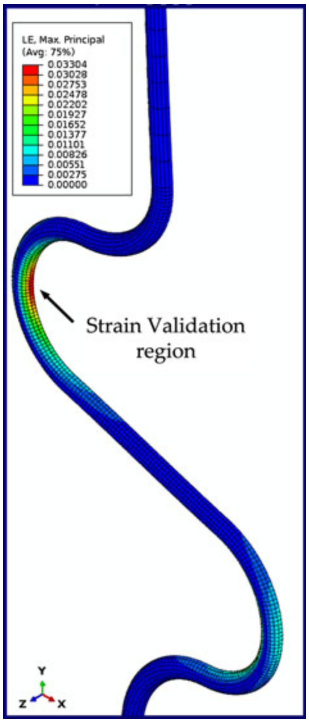

**Fig. 4** Abaqus high resolution FE model of the Z-shaped wire specimen at 3.3% strain

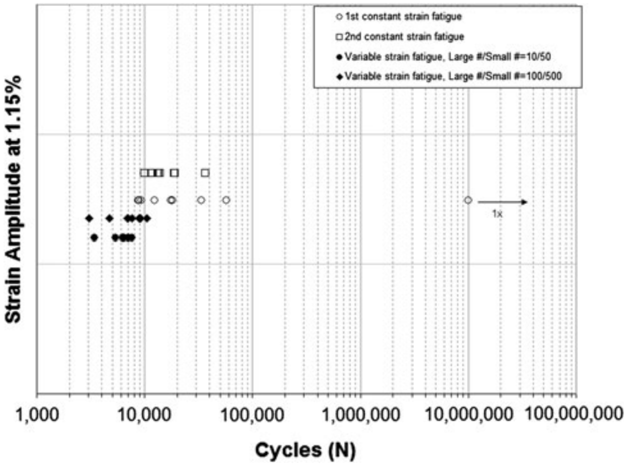

**Fig. 5** Diamond specimen's variable strain fatigue test data are compared with constant strain fatigue data. The open circles and the open squares are two constant strain fatigue tests with strain amplitude of 1.15%. Each constant strain fatigue test has 16 V specimens (8 diamond specimens). The black solid circles are the variable strain fatigue test data points with following fatigue sequence in a complete period: 1.15% strain amplitude for 10 cycles followed by 0.38% strain amplitude for 50 cycles. The black solid diamonds are the variable strain fatigue test data points with following fatigue sequence in a complete period: 1.15% strain amplitude for 100 cycles followed by 0.38% strain amplitude for 500 cycles. The mean strain for all data points in the figure was 2.5%

**Table 1 List of test matrix of variable strain fatigue using both diamond specimens and Z-shaped wire specimens**

| Specimen type | Mean strain, % | Large strain amplitude, % | Small strain amplitude, % | Ratio of large cycle # over small cycle # |
|---|---|---|---|---|
| Z-shaped wire specimen | 3.0 | 0.75 | 0.10 | 10/50 |
| | | 1.00 | 0.25 | 10/50 |
| | | 1.00 | 0.25 | 10/10 |
| Diamond specimen | 2.5 | 1.15 | 0.38 | 10/50 |
| | | 1.15 | 0.38 | 100/500 |

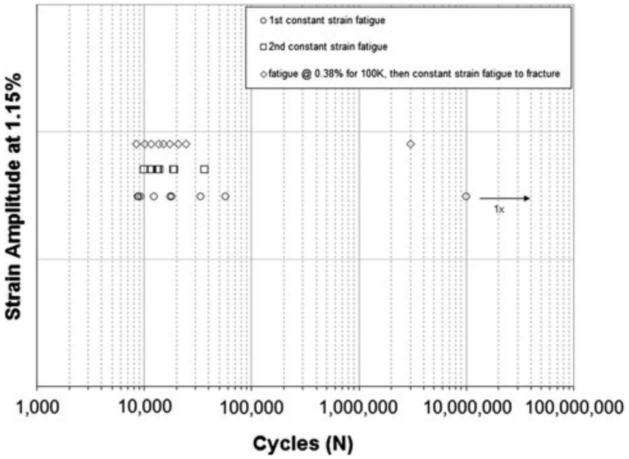

**Fig. 6** Three groups of stent-like diamond specimens: Group 1 (open diamonds)—fatigued at strain amplitude of 0.38% for $10^5$ cycles followed by a strain amplitude of 1.15% until fracture, Group 2 (open circles)—fatigue at strain amplitude of 1.15% until fracture (1st test) and Group 3 (open squares)—fatigue at strain amplitude of 1.15% until fracture (2nd test). There were 16 V specimens (8 diamond specimens) in each group. The mean strain for all data points in the figure was 2.5%

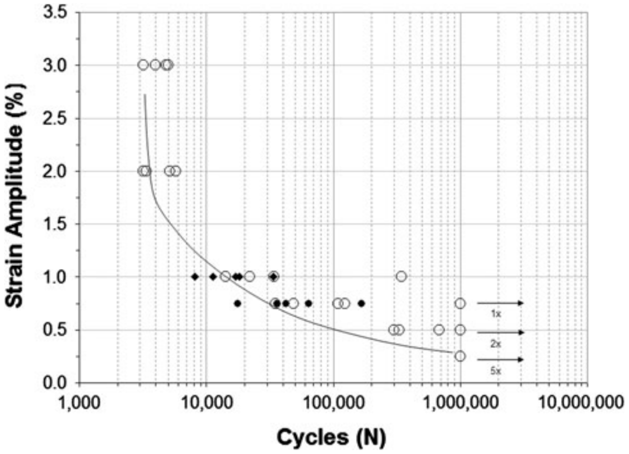

**Fig. 7** Z-shaped wire specimen's variable strain fatigue data overlay on constant strain fatigue S-N curve. The open circles are the constant strain fatigue data points. The black diamonds are the variable strain fatigue test data points with following fatigue sequence in a complete period: 1.00% strain amplitude for 10 cycles followed by 0.25% strain amplitude for 50 cycles. The black solid circles are the variable strain fatigue test data points with following fatigue sequence in a complete period: 0.75% strain amplitude for 10 cycles followed by fatigue at 0.1% strain amplitude for 50 cycles. The mean strain for all data points was 3.0%. The arrows show those specimens ran out at $10^6$ and the number indicates the number of run-out specimens

diamonds), the average fatigue life of five variable strain fatigue specimens is shorter than the average of five constant strain fatigue specimens. The variable strain fatigue test was cycled at a strain amplitude of 1.00% for 10 cycles followed by a strain amplitude of 0.25% for 50 cycles. Again, this sequence was repeated until the stent fractured or run-out was achieved. At the end of fatigue test, only the large strain amplitude (1.00%) cycles were counted because the small strain amplitude (0.25%) cycles were below the fatigue strain limit and would not cause specimen fracture.

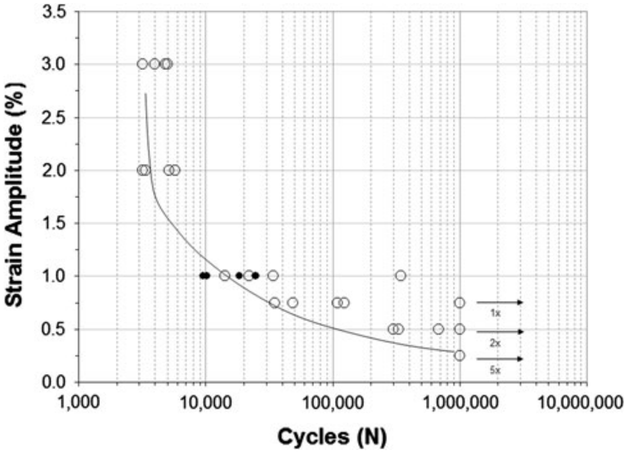

**Fig. 8** Z-shaped wire specimen's variable strain fatigue data overlay on constant strain fatigue S-N curve. The open circles are the constant strain fatigue data points. The black circles are the variable strain fatigue test data points with following fatigue sequence in a complete period: 1.00% strain amplitude for 10 cycles followed by 0.25% strain amplitude for 10 cycles. The mean strain for all data points was 3.0%. The arrows show those specimens ran out at $10^6$ and the number indicates the number of run-out specimens

For the Z-shaped wire specimens, changing the ratio of the number of large fatigue cycles to the number of small fatigue cycles did not change the observation that variable strain fatigue worsened fatigue life as compared to constant strain fatigue. Figure 8 shows the variable strain fatigue data points (solid circles) overlaid with the constant strain fatigue S-N data points (open circles). The average fatigue life of five variable strain fatigue specimens is shorter than the average fatigue life of five constant strain fatigue specimens. The variable strain fatigue test was cycled at a strain amplitude of 1.00% for 10 cycles followed by a strain amplitude of 0.25% for 10 cycles. As before, this sequence was repeated until the stent fractured or run-out was achieved. At the end of the fatigue test, only large strain amplitude (1.00%) cycles were counted because the small strain amplitude (0.25%) cycles at the fatigue strain limit would not cause specimen fracture. The ratio of the number of large fatigue cycles to the number of small fatigue cycles changed from 1:5 in Fig. 7 to 1:1 in Fig. 8; however, the trend that variable strain fatigue shortens fatigue life remains.

Variable strain worsens nitinol fatigue life was first observed in stent-like diamond specimens, and then it was confirmed with Z-shaped wire specimens. According to Ref 1-4, the effect of variable stress fatigue worsens fatigue life because a large stress initiates cracks that lower the fatigue limit. However, a small stress can be harmful in the fatigue life as well This effect can be applied to nitinol, in which the fatigue test is strain-based fatigue, therefore, variable strain fatigue worsens fatigue life.

For nitinol, we hypothesize that energy consumption is an additional contributor to shorten fatigue life on specimens with variable strain fatigue. Superelastic nitinol fatigue can involve stress-induced martensite transformation between austenite and martensite (Ref 10). The transformation in nitinol is a first-order phase transformation and is latent heat relative. In constant strain fatigue, the energy is in a process of minimization. In variable strain fatigue, this energy optimization processing could be interrupted due to frequently switch between high strain and low strain. Therefore the fatigue specimens can consume more energy during fatigue. Generally, the higher energy consumption would result in greater fatigue damage.

## 5. Summary

1. Small strain cycles that are smaller than the constant amplitude fatigue limit become damaging when they are part of a repeating sequence of large and small cycles. This phenomenon has not been reported in previous nitinol fatigue studies. In conventional steels it has been demonstrated that the large cycles reduce the force required to open a micro-crack, allowing the small cycles to open the micro-crack and hence contribute additional fatigue damage.
2. Both stent-like diamond specimen (electropolished) and Z-shaped wire specimen (non-electropolished) show a similar response on variable strain fatigue. A statistical difference between variable and constant strain fatigue life has not been proven due to the limited sample size for both tests.

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### Disclosure

Z. Lin and K. Pike are employees of Abbott Vascular and hold stock in the company. None of the other authors notes any relevant conflicts of interest.

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