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Effects of Cyclic Loading on the Uniaxial Behavior of Nitinol

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The widespread development and use of implants made from NiTi is accompanied by the publication of many NiTi material characterization studies. These publications have increased significantly the knowledge about the mechanical properties of NiTi. However, this knowledge also increased the complexity of the numerical simulation of NiTi implants or devices. This study is focused on the uniaxial behavior of NiTi tubing due to cyclic loading and had the goal to deliver both precise and application-oriented results. Single aspects of this study have already been published (Wagner in Ein Beitrag zur strukturellen und funktionalen Ermüdung von Drähten und Federn aus NiTi-Formgedaechtnislegierungen, Ph.D. Thesis, 2005; Eucken and Duerig in Acta Metall 37:2245-2252, 1989; Yawny et al. in Z Metallkd 96:608-618, 2005); however, there is no publication known that shows all the single effects combined in a "duty cycle case." It was of particular importance to summarize the main effects of pre-strain and subsequent small or large strain amplitudes on the material properties. The phenomena observed were captured in an extended Abaqus® Nitinol material model, presented by Rebelo et al. (A Material Model for the Cyclic Behavior of Nitinol, SMST Extended Abstracts 2010). The cyclic tensile tests were performed using a video extensometer to obtain accurate strain measurement on small electro-polished dog-bone specimen that were incorporated into a stent framework so that standard manufacturing methods could be used for the fabrication. This study indicates that a prestrain beyond 6% strain alters the transformation plateaus and if the cyclic displacement amplitude is large enough, additional permanent deformations are observed, the lower plateau and most notably the upper plateau change. The changes to the upper plateau are very interesting in the sense that an additional stress plateau develops: its "start stress" is lowered thereby creating a new plateau up to the highest level of cyclic strain, followed by resuming the original plateau until full transformation. This study was conducted in the course of the work of a consortium of several stent manufacturers, SAFE Technology Limited and Dassault Systèmes Simulia Corp., dedicated to the development of fatigue laws suitable for life prediction of Nitinol devices.

Keywords cyclic properties, fatigue, finite element analysis, nitinol, pre-straining, tensile tests

1. Introduction

The widespread development and use of implants made from Nitinol has been accompanied by the publication of many Nitinol material characterization studies. As a result, information available on the mechanical properties of Nitinol has increased significantly; however, much remains to be learned about the effects of pre-straining and cyclic straining of this material.

Eucken and Duerig (Ref 1) investigated the effect of pre-straining on the tensile behavior in aged Nitinol. They found that that the plateau stress is reduced and that distinct plateaus in the stress-strain behavior are created when the specimen is deformed beyond the original pre-strain. The authors call it the "yield phenomena" and explained it by the theory of persisting martensite nuclei that remain in the austenite matrix.

Yawny et al. (Ref 2) investigated pseudoelastic pull-pull cycling of Nitinol wires at different temperatures. They investigated the effect of incremental pre-straining on the stress-strain behavior up to 6% total strain. For the last incremental straining to 6% strain the upper stress plateau was a series of stress plateaus that corresponded to individual previous strain cycles. Another experiment was cycling to a strain of 5% for 30 times at different temperatures. The stress-strain behavior showed a number of changes: the onset of the upper stress plateau is reduced, the lower plateau stress is reduced (less pronounced), and the development of a small permanent set was observed. The authors propose a dislocation-based explanation for the evolving stress levels of the loading and unloading plateaus during pseudoelastic cycling, however, not all phenomena observed could be explained.

Though certain aspects of this study were previously reported in published literature (Ref 1–3), there is no publication known that shows all of the single effects combined in typical in vivo loading. The published data describe the changes in the stress-strain behavior for single experiments and proposes explanations for the findings. However, for the stress and strain

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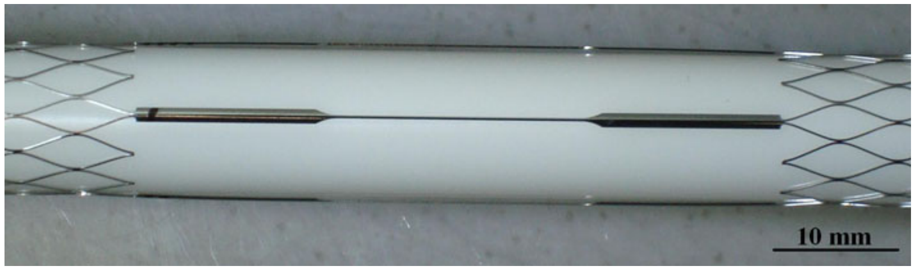

Fig. 1 Tensile test specimen incorporated into stent framework

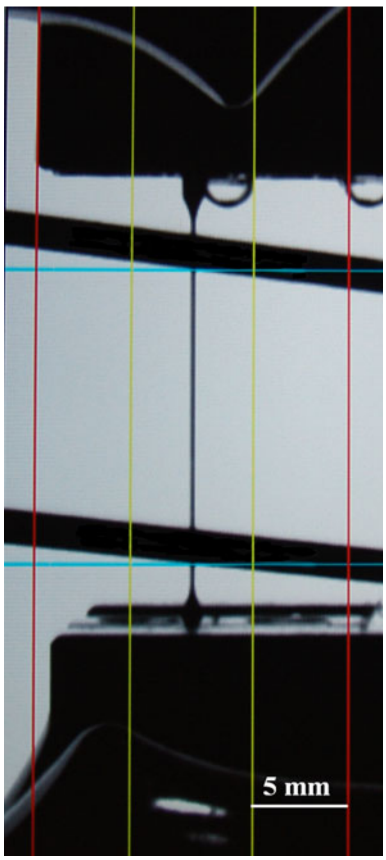

Fig. 2 Location of the markers captured in a video extensometer photo

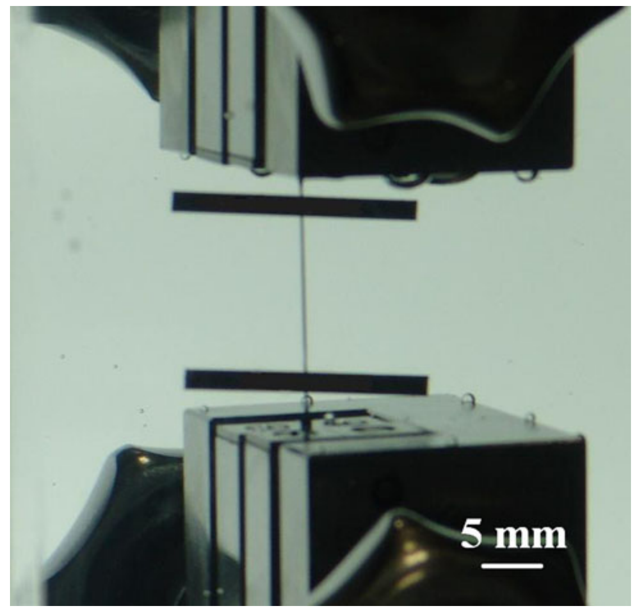

Fig. 3 Test specimen within the tensile test machine

analysis of components made from Nitinol the stress-strain behavior must be properly implemented into the method used.

This study therefore focused on the uniaxial behavior of Nitinol tubing due to pre-straining and cyclic deformation with the goal of delivering both precise and application-oriented results. It was of particular importance to summarize the main effects of pre-straining and subsequent small or large strain amplitudes on the material properties because the phenomena observed are captured in an extended Abaqus Nitinol material model (Ref 4).

2. Materials and methods

The test specimens were manufactured from tubular pieces of ASTM F2633-07-compliant Nitinol. The specimen was incorporated into a stent framework (see Fig. 1) to allow the specimens to undergo the same standard manufacturing methods as the commercial stents they were attached to. The specimens were laser cut, expanded, heat-treated, and surface finished prior to testing. The cross section of each test specimen was approximately 0.05 mm^2 (0.205×0.245 mm), while the length of the specimens was 20 mm.

Cyclic tensile tests were performed on the specimens using a standard tensile test machine (Zwick 1446). A video extensometer (Zwick ME46) was used to obtain precise strain measurements. Because of the narrow nature of the test specimens, special markers were developed and mounted on the specimens. These markers can be seen in a picture taken by the video extensometer in Fig. 2. Also shown is a photo taken of a test specimen mounted in the test fixture (Fig. 3).

The following strains were applied to the specimen and investigated within this study:

- Pre-straining to 1, 2, 3, 4, 5, 6, 7, 8, and 9 % strain.
- Small strain amplitudes (0.2%) after a pre-strain of 8%.
- Large strain amplitudes (1.0 %) after a pre-strain of 8%.

The tests investigating the effect of small and large strain amplitudes were performed according to the following protocol: pre-strain to 8% strain, unload completely, strain to a mean strain of the cycles, cycle 100 times, unload completely and finally load to fracture. This approach is referred to as straining "from above." For testing of small amplitudes there is also a straining "from below," in which no complete unloading occurs following the pre-straining of 8%. The specimen is unloaded to the lowest strain level that occurs during cycling and then the cycling begins. The tensile testing was performed according to ASTM F2516-06 and conducted at 37 ± 1 °C in a water bath. The maximum pre-straining values were derived from the expected deformation a stent might experience during manufacturing, while the strain amplitudes are assumptions for deformations a stent might be subjected to in arteries.

3. Results

Figure 4 shows the true stress versus true strain results of the testing at various pre-straining levels. The study found that specimens pre-strained to strain conditions of 1-6% did not evidence changes in plateau stresses or develop a permanent set (results not shown). When increasing the pre-straining to a strain value beyond the end of the upper plateau (~6%), the level of the lower plateau is reduced and a permanent set occurs. As such, the study found that the effects increase with increasing pre-straining. These results are consistent with previously published data (Ref 3).

Shown in Fig. 5 is the stress strain curve when applying small amplitudes of strain (0.2%) to the specimens. Although no effects resulted from the small amplitude strain, Fig. 3 shows some note-worthy data. Our results indicate that the slope of the curves within the cycles differed depending on how the specimen is loaded, i.e., from below (not completely unloaded) or from above (after complete unloading).

Figure 6 shows the results of the large amplitude testing. As can be seen, amplitude of 1% strain alters the stress-strain response. After 100 cycles the specimens developed a permanent set and the shape of the hysteresis loop is changed.

Two general rules characterize the behavior of the upper plateau observed in this study: (1) the level of the plateau stress is reduced with increased number of cycles, and (2) towards the

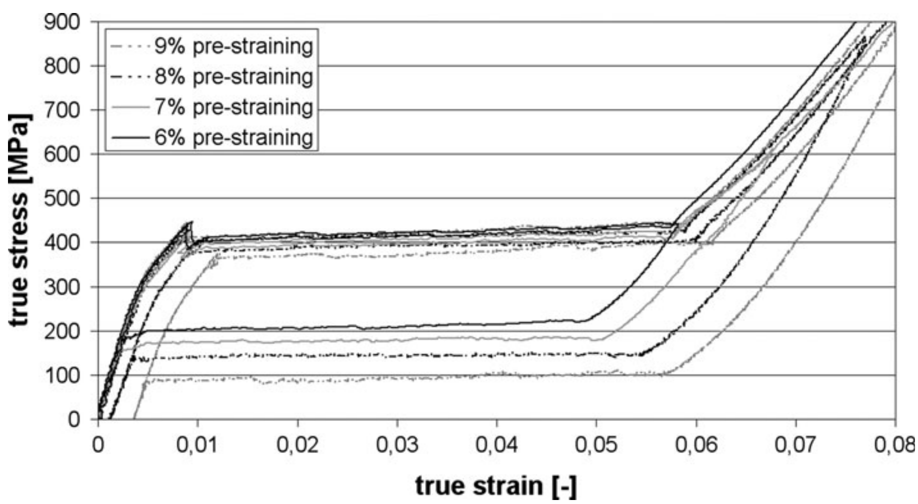

Fig. 4 Results of the pre-loading test

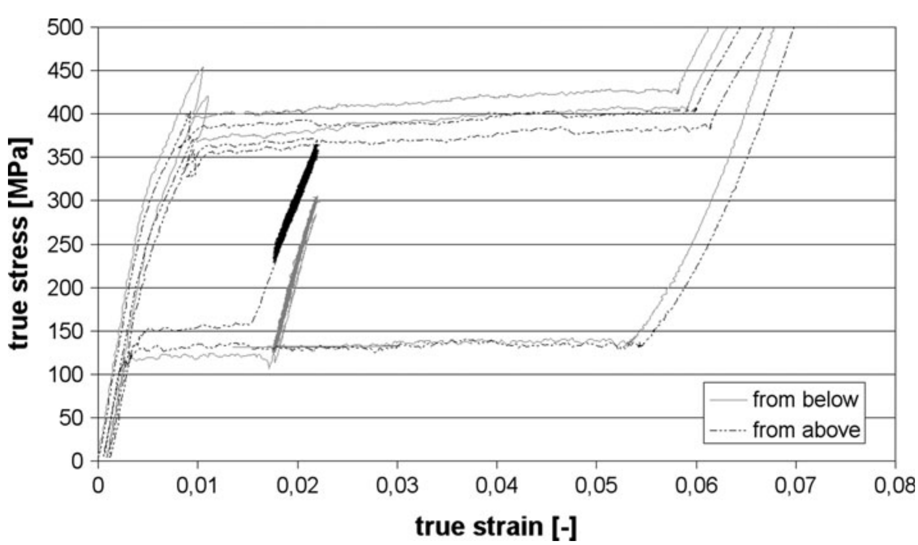

Fig. 5 Effect of small amplitudes (0.2%)

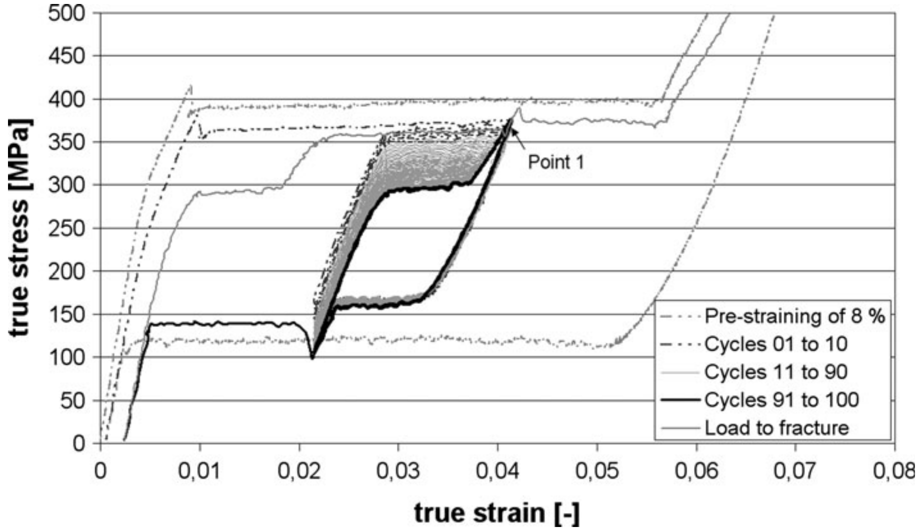

Fig. 6 Effect of large amplitudes (1.0%)

Table 1 Summary of the pre-straining and cyclic effects on superelastic NiTi tensile specimens

	Permanent set	Upper plateau	Lower plateau
Pre-straining of more than 6%	⇑⇑	⇓	⇓⇓
Small amplitudes (0.2%)	...	...	...
Large amplitudes (1.0%)	⇑⇑	⇓⇓	⇓

end of the cycling the slope of the stress level increases and the end point of the straining cycle consequently falls on the original plateau stress level (Point 1). This phenomenon has been described previously and is explained with dislocations that are introduced during the forward transformation (Ref 2). These dislocations are left behind when the specimen is unloaded and act as markers for the transformation path for following cycles. The data also shows that when straining occurs subsequently to a complete unloading, the regions of the material that were "weakened" due to the cycling are strained first. The reduction of the upper plateau is not a function of the strain amplitude; the most reasonable hypothesis is that it is reduced by a set amount when transformation is involved in the cycling.

4. Discussion

This study indicates that a pre-straining level $>6\%$ will alter the plateau stresses and creates a permanent set. When the strain amplitude is great enough, additional permanent deformations were observed, as well as changes to the lower plateau stress, and, more pronouncedly, the upper plateau stress. Table 1 summarizes these effects. The findings correlate well with published data, compare (Ref 1–3).

5. Conclusions

This study evaluated the influence of in vivo straining on the cyclic tensile behavior of Nitinol. The observed effects described herein may now serve as an input for an extended Abaqus material model considering pre-straining and cyclic effects. Whether the magnitude of the pre-straining and cyclic effects is material dependent is the subject of future work.

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