Shape memory alloys fatigue and self-heating of NiTi

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ABSTRACT. *The employment of shape memory alloys (SMA) in a large number of applications in the fields of aeronautical, biomedical, and structural engineering has been the motivation for the study of fatigue properties of these materials. Many models for SMA are available in the literature but just a few information on fatigue properties are available. In this paper we study fatigue properties at low and high number of cycles of NiTi wires using classil technique and self heating measurements. Then the two techniques are compared and the classic method validates the fast one.*

INTRODUCTION

The shape memory alloys (SMA) are materials able to recover a large elastic deformation (up to 8%) under thermomechanical loading. These properties are due to a very particular aspect of the mechanical behaviour: the superelasticity. When these materials are loaded at a temperature higher than the Af temperature (Austenite Finish), an reversible strain occurred and can reach 8% to 10%. The strain mechanism at the origin of this phenomen is based on a solid-solid phase transformation [1]. The properties of these alloys make them interesting for innovative applications. For example they are used for biomedical applications or in transport. The effect most commonly used in industrial applications is the superelasticity. For example it is used for the realization of endodontic instrument. These instruments are used in the dental field to perform some operations on the root canals of teeth. Superelastic NiTi property allows instruments a good adaptation to the anatomy of the roots canal.

The thermomechanical behaviour of these alloys has been studied since several years. Several models have been developed to describe the behaviour [2][3][4]. Unfortunately, the fatigue property of these alloys remains an unexplored area. Currently in the design phase of structures using SMA, fatigue is not considered. For example in the case of endodontic instruments, file separation by fatigue can occur and complicates the result of the operation.

This is the reason for which we try to determine fatigue properties of nickel-titanium (NiTi) is studied in this study.

This study begins by conducting fatigue tests at low and high number of cycles. Thus we obtain Wöhler curves (amplitude loading as a function of the number of cycles to failure). In parallel, we use a fast technique based on self-heating measurements to determine the fatigue properties of the materials. This technique has been validated for many grades of steel but not for the case of NiTi. This method is so used for this alloy. Realized classic fatigue tests are used to validate the fast technique. Once this rapid method is validated, we will study the influence of different parameters on the fatigue properties of NiTi wires can be studied more easily.

MATERIAL AND SPECIMENS

Before performing fatigue tests on instruments, we focus on the material which is the base of files. It is important to mention that endodontic files are made of NiTi wires but the realization of tests directly on wires is not easy. Buckling or failure in the jaw can occur during tests. So fatigue samples have been realized from wire. A circular cut is made on the wire. This machining is done with the same manufacturing process that for dental instruments. This geometry allows to overcome the failure problems of breaking in the jaw. Figure 1 shows the details of the adapted geometry for fatigue samples.

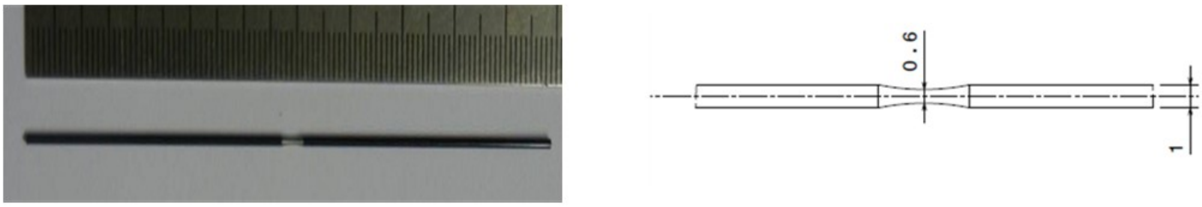

Figure 1 Dog bone fatigue sample geometry obtained by 1mm NiTi wires

To determine the behaviour of considered NiTi a tensile test is realized. Figure 2 shows the behaviour of the alloy.

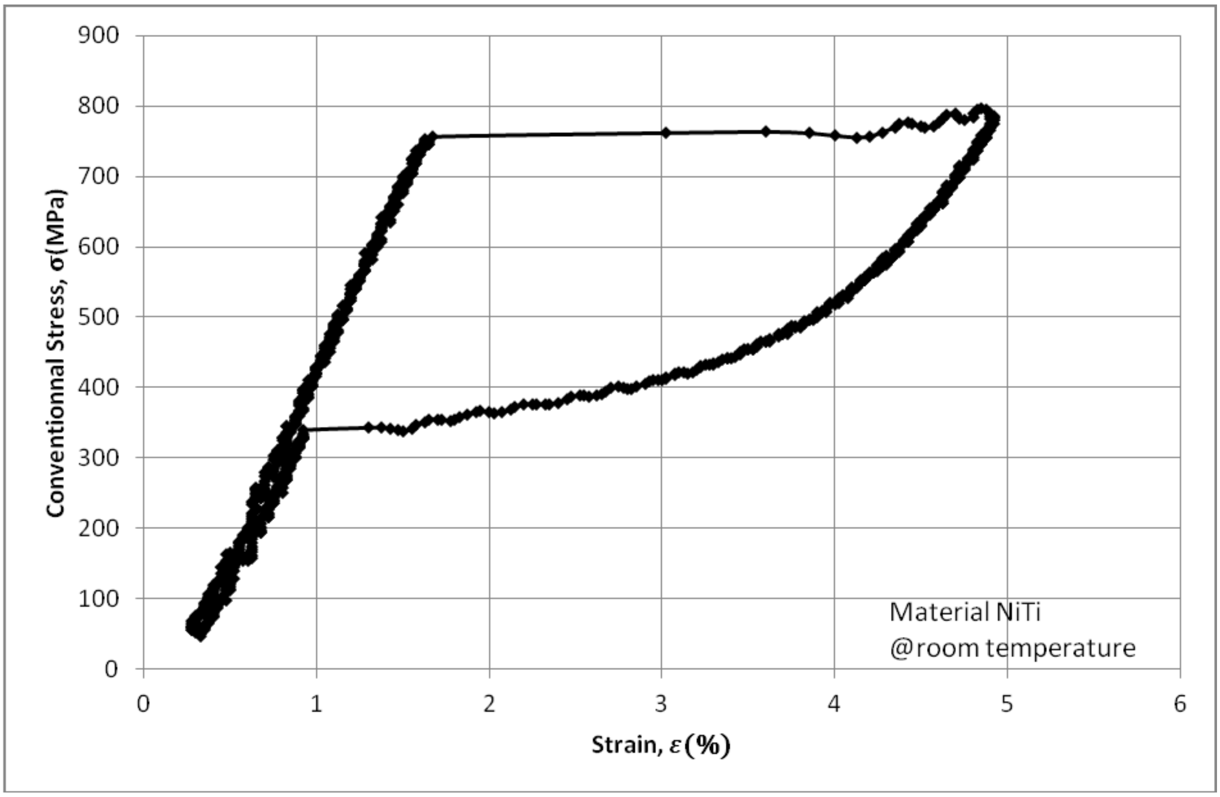

Figure 2 Superelastic behaviour of the NiTi SMA during tensile test at room temperature

This behaviour is obtained by a tensile test on a dog bone sample. The extensometer is placed on both sides of the thin zone. So strain is not representative. However this curve allows us to obtain the transformation yield stress. This curve lets also the choice of loading amplitude for fatigue tests. All the fatigue tests are realized at the amplitudes lower than the identified transformation yield stress which is about 750MPa.

CLASSIC FATIGUE TEST

Fatigue tests are performed on a Bose Electroforce testing machine. The load cell capacity is about 3kN. All the tests are realized at 30Hz frequency. This frequency permits to have a low temperature rise which does not influence the mechanical properties of the specimens. This frequency permits also the fatigue curve determination relatively quickly (about 20 hours to achieve 2 million cycles for each amplitude). Its determination is possible by the failure of each specimen at each loading amplitude (between 300 MPa and 700MPa). However, if the specimen failure is not obtained after 2 million cycles, the test is stopped. Then, the failure number of cycles according to the maximum applied stress is reported (see figure 3).

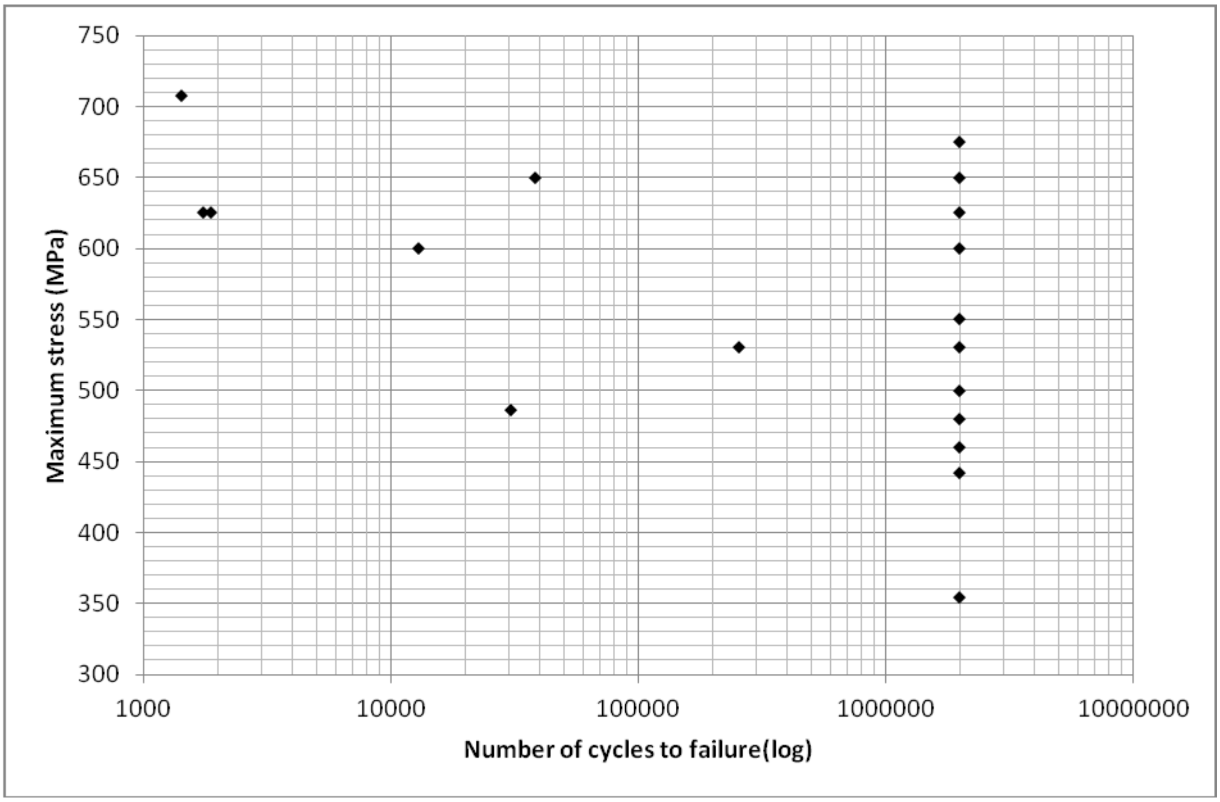

Figure 3 Wöhler curve of considered NiTi

These tests allow the limit endurance determination. For the studied material, it is about 470MPa.

It is important to add that after machining, instruments undergo a surface treatment. It is an electropolishing. This treatment permits to improve the surface state and cutting performances of the instruments. Indirectly dentists have noticed a change of fatigue properties of these instruments. In this paper the influence of this process parameter on the fatigue properties is studied. This surface treatment is applied to initial specimens. Then fatigue tests as the previous case are realized (see figure 4). The limit endurance is determined. In the case of electropolished material, it is about 660MPa.

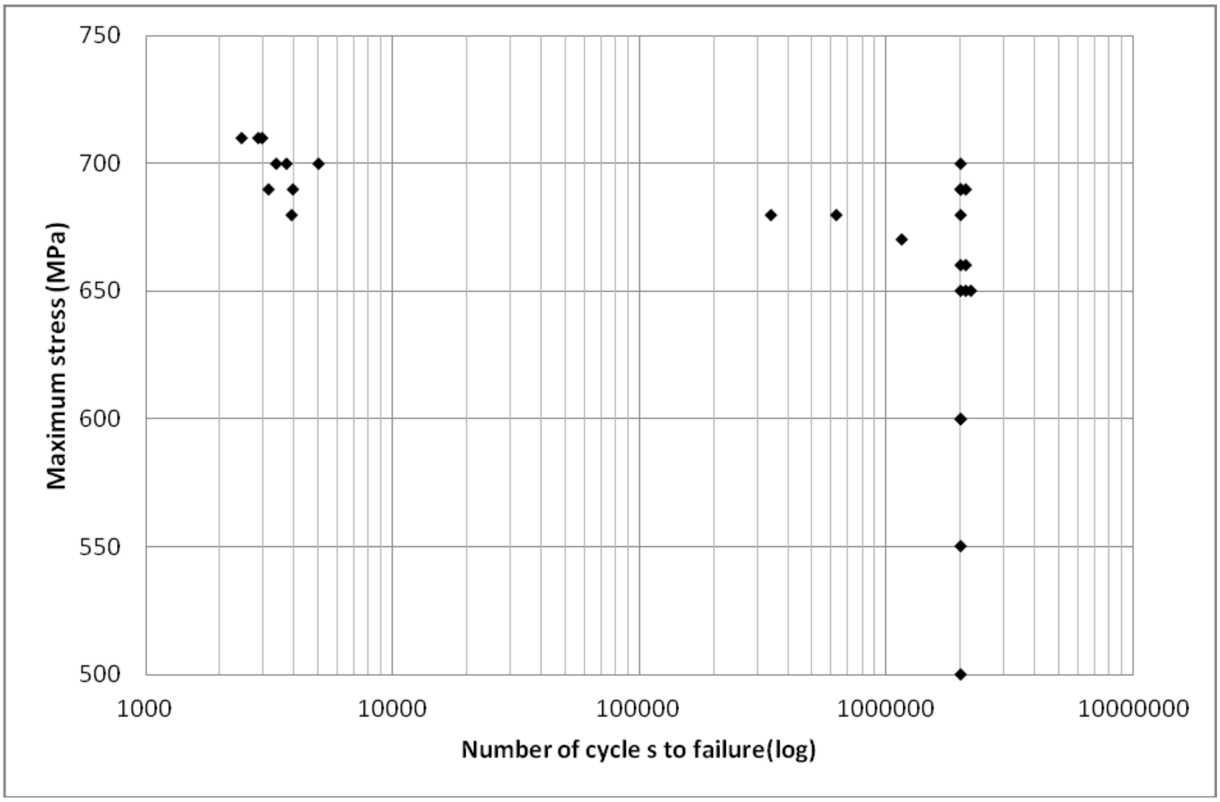

Figure 4 Wöhler curve of electropolished NiTi

Thanks to this operation, there is an increase of fatigue properties of electropolished specimens. The endurance limit is 660MPa against 470MPa before. It is possible that this surface treatment has a positive effect on the fatigue properties of the considered alloy.

One of the main goals of this study is to determine the influence of instrument processing parameters on their fatigue properties. For this, different time consuming fatigue tests should be realized. To reduce the necessary time to determine the effect of each parameter, a fast technique to determine the fatigue properties is so considered. The considered fast technique is self-heating under cyclic loading.

SELF-HEATING STUDY

Self-heating techniques

During last years, a new technique to determine the fatigue properties of metallic materials for high number of cycles has been developed. It is the self-heating of the material under cyclic loadings. Its “base” is the observation of variation of the stabilized temperature subject to increasing block of cyclic loadings (see figure 5).

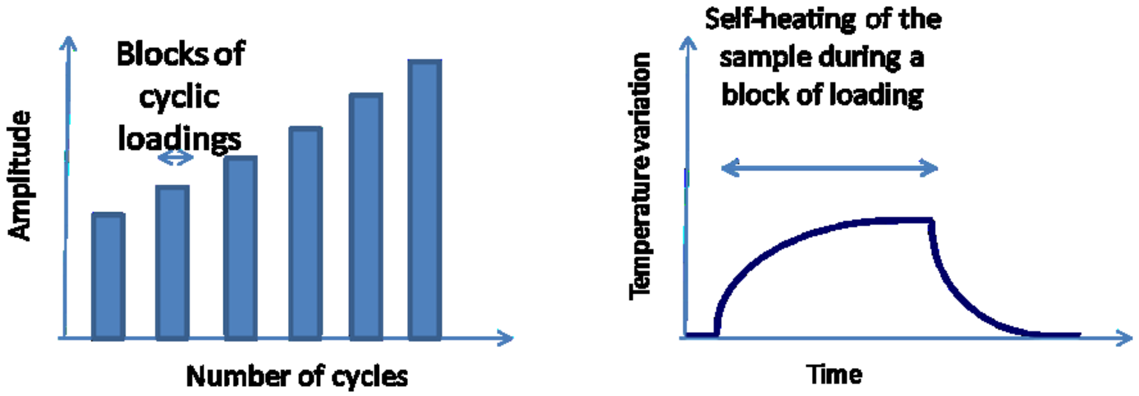

Figure 5 Self-heating techniques

During this sort of tests, it is possible to observe that after a certain level of loading, the average stabilized temperature of the specimen increases significantly. This temperature increasing can be related to the fact that the fatigue limit of the material has been exceeded leading by dissipative mechanisms. In the case of classic metallic materials, the micro-plasticity is the origin of the observed self-heating [5][6].

The main goal of this section is to study the validity of this technique in the case of SMA. In the case of SMA an additional mechanism exists. This is du to phase transformation.

Mechanical test

On the same specimen, successively blocks of 3000 cycles at a maximum constant amplitude is applied. The maximum amplitude increases from one block to another. So 10 blocks from 200MPa to 700MPa with 50MPa increment have been realized. For each block of loading the temperature evolution of the specimen using an infra-red camera is measured. The same tensile machine as the classic fatigue tests has been used.

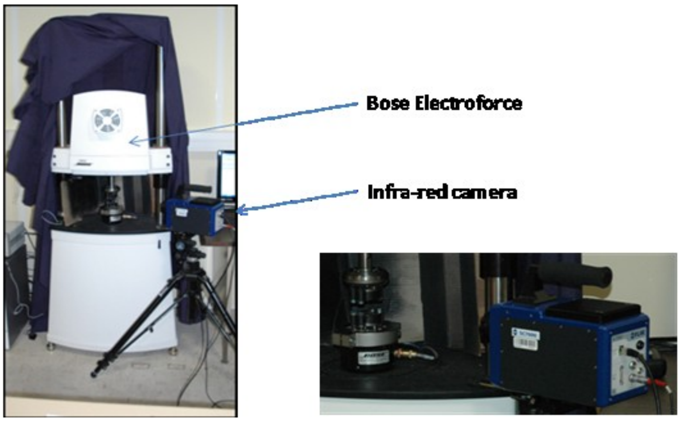

Figure 6 Experimental set up

The temperature measurements have been realized using an infra-red camera. Figure 6 shows the experimental set up.

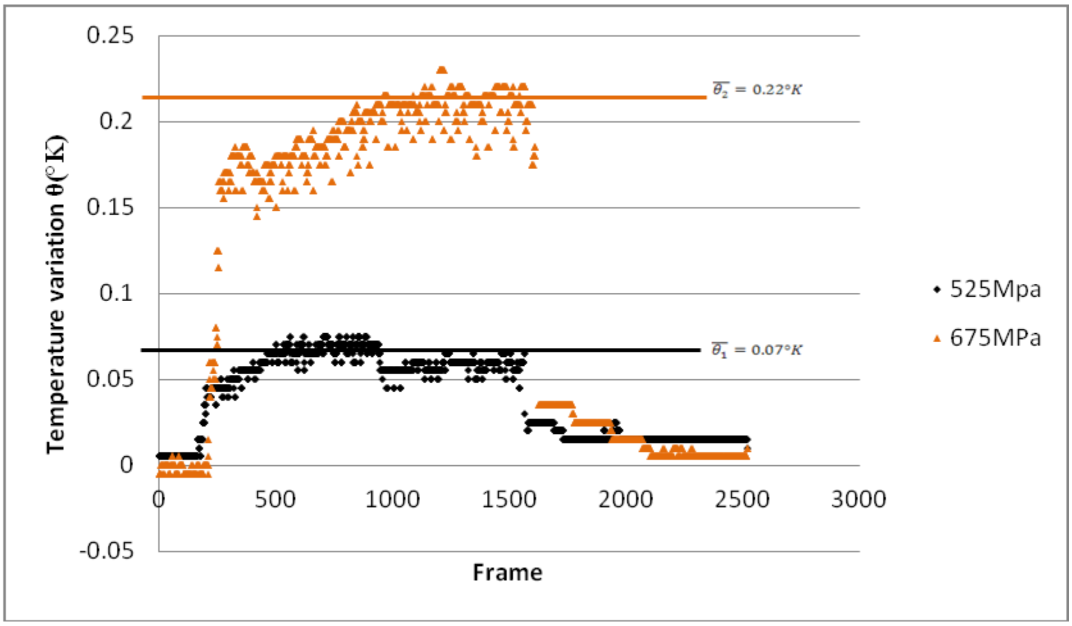

Figure 7 Temperature evolution during 3000 cyclic loadings on dog bone sample for two different loading amplitudes

Self-heating tests using the explained protocole has been realized. Figure 7 shows the evolution of the average temperature of the specimen for two different blocks of loading. During the block with the maximum level of loading (525MPa), a temperature variation about 0,07°K can be observed. It is important to add that after the end of each block, the specimen returns to its initial temperature. During the block with the maximum level of loading (675MPa) a temperature variation about 0,22°K can be observed. It can be mentioned that for this amplitude the variation is greater. To obtain the self-heating curve, for each block of loading the stabilized temperature is recorded.

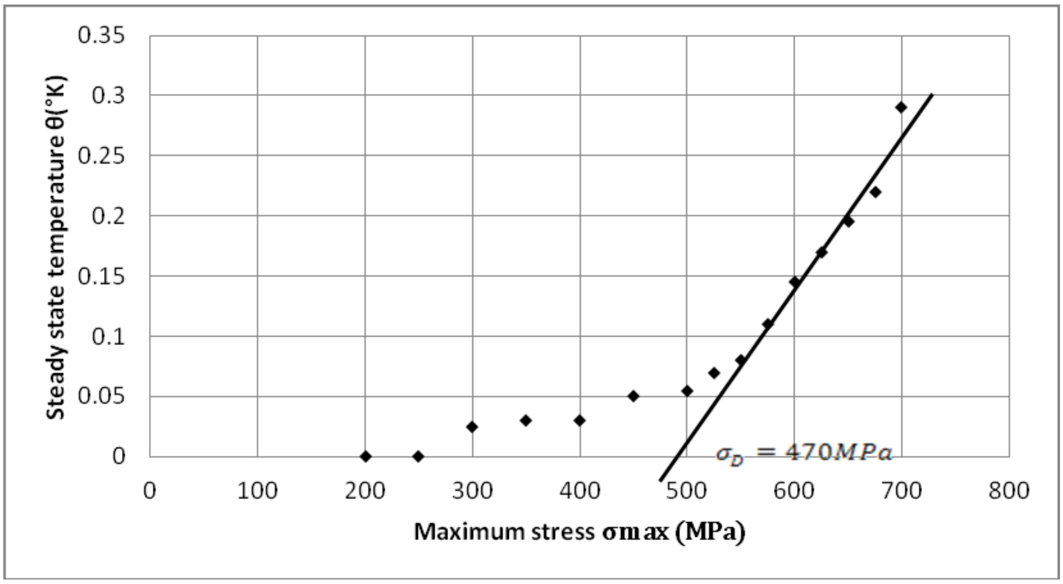

Figure 8 Self-heating curve for NiTi specimen without electropolishing

Empirical method to determine the endurance limit

The self-heating curve represents the evolution of the stabilized temperature according to the maximum stress level applied during the block. It can be noticed that after a certain level of loading the temperature rise becomes more significant. Using an empirical method permits the rapid determination of the endurance limit σ_D. By drawing a line through the last points of the curve (figure8), the endurance limit is determined by the intersection with the x-axis. In the case of realized test the endurance limit is about 470 MPa. This result is similar to the one obtained with the conventional method. It can be concluded that this type of rapid method is applicable to our material. The most important advantage of this technique is its speed. In fact, one sample with a one-hour test provides the same results as a full campaign estimated at 200 hours of testing using multiple samples.

CONCLUSION

In this study, the fatigue of superelastic NiTi has been studied. Two techniques have been used: the classic fatigue tests and the rapid self-heating method. First, by classic fatigue tests the endurance limit has been obtained. Then the rapid method has been conducted and the endurance limit has also been determined. The same results are obtained. This permits to validate the use of self-heating method in the case of SMA where a supplementary strain mechanism du to phase transformation exists. By this rapid technique it is possible to determine the fatigue properties of SMA just with a sample and a one-hour test. This permits the study of the processing parameters influence on the NiTi fatigue properties.

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