Experimental and numerical data for transformation propagation in NiTi shape memory structures

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ARTICLE INFO

Article history:
Received 2 July 2019
Received in revised form 7 September 2019
Accepted 19 September 2019
Available online 1 October 2019

Keywords:
Martensitic transformation
Shape memory alloys
NiTi
Functionally graded material

ABSTRACT

This article provides experimental and numerical data for the propagation of stress-induced martensitic transformation within NiTi structures with uniform and nonuniform geometries. This article is related to the research paper entitled “Computational and experimental analyses of martensitic transformation propagation in shape memory alloys” [1]. The heterogeneous transformation evolutions within geometrically graded NiTi structures are presented by thermal images recorded by a high-resolution infrared camera during tensile loading. The modelling of transformation and deformation behaviours of those structures is presented by finite element computational method.

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1. Data

The dataset in this article describes the propagation of stress-induced martensitic transformation within NiTi structures through experimental and numerical analyses. Fig. 1 displays the experimental setup including a tensile testing machine and an infrared camera. Fig. 2 describes the temperature variation along the longitudinal direction of a nonuniform NiTi sample under tension. Figs. 3–5 present the evolution of local strain and stress fields of nonuniform NiTi structures with series, parallel-continuous-plate, and parallel-multiple-stripe configurations, respectively, during tensile loading. Videos 1 and 2 display the martensitic transformation propagation within NiTi structures with uniform and nonuniform geometries, respectively.
2. Experimental design, materials, and methods

One of the methods to alter and engineer the properties of NiTi shape memory alloys to suit different applications is to design functionally graded NiTi materials [2,3]. The main idea of this method is to combine the unique behaviour of shape memory alloys (SMAs), i.e., shape memory effect and superelasticity, and the functionality of the graded material structures to achieve desired performance or new properties for various applications. Gradient of functional properties of NiTi can be achieved in three ways: compositional gradient [4–6], microstructural gradient [7–9], and geometrical gradient [10–12]. Geometrically graded NiTi can provide a stress or strain gradient for progressive transformation. Based on the relationship between the loading direction and the gradient direction, the various designs of geometrically graded NiTi can be categorized into two types: the series design [13], in which the loading direction is parallel to the gradient direction, and the parallel design [14], in which the loading direction is perpendicular to the gradient direction. Parallel design configuration can be created in continuous structures (e.g. tapered NiTi plates) [15] or in discrete structures (e.g. multiple NiTi wires or strips) [16].

Thin plates of Ti-50.8at%Ni with the thickness of 0.2 mm were used to make NiTi samples with uniform geometry or geometrical gradient (series and parallel configurations) by means of electrical discharge machining. The actual deformation behaviour of the NiTi alloy under tensile loading is shown in Fig. 1(b) of Ref. [1]. The material exhibited perfect pseudoelastic deformation behaviour at the room temperature with the forward transformation stress of ~330 MPa and the transformation strain of ~0.06. Fig. 1 shows the experimental setup. Instron 5982 machine was used for tensile loading under displacement-control condition. The strain rate for tensile tests was ~10^{-3}/sec. The room temperature was maintained at 296 K for all experiments. Nippon Avionics infrared camera (Model R500EX) with a resolution of 1280 × 960 pixels was used to acquire thermal images of the samples during tensile loading.

![Fig. 2. The martensitic transformation propagation within a NiTi structure with nonuniform geometry during tensile loading: (a): thermal field captured by the infrared camera at \( \varepsilon = 0.01 \), (b): temperature variation along longitudinal direction at progressive loading levels.](image-url)
2.1. NiTi structures with uniform geometry

In this experiment, a uniform NiTi strip with the gauge section of $2 \times 30$ mm was used. The video of the thermal field evolution was recorded by the infrared camera and is presented as a video component, which accompanies the electronic version of this manuscript. To access this video component (Video 1), click on the image visible below (online version only). The global deformation behaviour (stress-strain curve) of this sample is also shown in Fig. 2(b) of Ref. [1].

2.2. NiTi structures with nonuniform geometry

In this experiment, a geometrically graded NiTi plate with series design configuration and the gauge length ($L$) of 30 mm, the maximum width ($w_2$) of 6 mm, and the width ratio ($\alpha$) of $2/3$ was used. Fig. 2(a) shows the thermal image of this sample captured by the infrared camera at $\varepsilon = 0.01$ in addition to the geometrical parameters. The nominal strain ($\varepsilon$) is defined as the total elongation divided by the initial gauge length of the sample ($L$). The tensile loading is along the $x$-axis defined in Fig. 2(a). It is seen that the transformation starts at the narrow end with the minimum width ($w_1$). It is expected that the transformation propagates along the loading direction from the narrow end to the wide end as illustrated in Ref. [1].

Fig. 2(b) shows the variation of temperature along the $x$-axis (also denoted in this figure) at progressive loading levels. As observed, the temperature peak moves gradually from the narrow end towards the wide end as the loading level increases from $\varepsilon = 0.0075$ to $\varepsilon = 0.07$.

The video of the thermal field evolution within this sample was recorded by the infrared camera and is presented as a video component, which accompanies the electronic version of this manuscript. To access this video component (Video 2), click on the image visible below (online version only).

**Video 1.** The martensitic transformation propagation within a NiTi structure with uniform geometry during tensile loading.

**Video 2.** The martensitic transformation propagation within a NiTi structure with nonuniform geometry during tensile loading.
3. Numerical analysis

One of the methods to predict the transformation and deformation behaviour of SMAs with complex geometries is finite element analysis (FEA). To simulate the deformation behaviour of the NiTi samples during tensile loading, we use Abaqus FEA code with a built-in UMAT subroutine based on a suitable constitutive model for superelastic SMAs [17]. In this constitutive model, the overall deformation is calculated as the sum of elastoplastic and transformation deformations. The plastic deformation is generated when the recoverable strain limit of the SMA material is exceeded. In the present study, a 3D geometry with C3D20R elements is applied for all simulations in order to achieve realistic outcome by considering all components of normal and shear stresses. The FEA code has been trained with the original deformation behaviour of NiTi under tension before simulating the deformation behaviour of NiTi structures with complex geometries (see Fig. 1(b) of Ref. [1]). In the following subsections, the local stress and strain fields of different types of geometrically graded NiTi structures are presented. It is noted that the evolution of the martensite fraction during loading for these structures are presented in Figs. 3(a), 4(a) and 5(a) of Ref. [1].

3.1. Series design configuration

Here, a geometrically graded NiTi plate with the length \( L \) of 30 mm, the maximum width \( w_2 \) of 6 mm, and the width ratio \( \alpha \) of 2/3 is considered. The tensile loading is along the \( x \)-axis. Fig. 3 shows the variation of normal strain and normal stress components along the \( x \)-axis \( (\varepsilon_x, \sigma_x) \) throughout the structure at progressive nominal strain \( \varepsilon \) levels. It is seen that the martensitic transformation commences at the narrow end with the maximum stress throughout the structure at \( \varepsilon = 0.0075 \) and propagate towards the wide end upon continuation of loading. Considering the transformation stress of ~330 MPa and the transformation strain of ~0.06 for the material, it is understood that about half...
The length of the structure is transformed to martensite at $\varepsilon = 0.04$. The entire structure is in the martensite state at $\varepsilon = 0.07$ with narrower cross-sections strained up to 0.085 in this state.

### 3.2. Parallel design configuration

Here, two types of geometry for NiTi samples are considered: a continuous plate structure and a multiple-strip structure. Both types are tapered at one end as shown in Figs. 4 and 5. For both cases, the total width is 6 mm. The maximum length ($L_2$) is 30 mm. The length ratio ($\alpha$) is 2/3. The tensile loading is along the x-axis. Here, the nominal strain ($\varepsilon$) is defined as the total elongation divided by the initial maximum length of the sample ($L_2$).

Fig. 4 shows the variation of normal strain and normal stress components along the x-axis ($\varepsilon_x$, $\sigma_x$) throughout the tapered plate structure at progressive nominal strain ($\varepsilon$) levels. It is seen that the martensitic transformation commences at the tapered corner on the left side of the sample with the minimum length ($L_1$) and propagates along an oblique direction towards the right side of the sample with the maximum length ($L_2$). From $\varepsilon = 0.02$ to $\varepsilon = 0.04$, most of the structure seems to be in the course of transformation under constant value of stress (~330 MPa), while the strain field is completely nonuniform throughout the structure.

Fig. 5 shows the variation of normal strain and normal stress components along the x-axis ($\varepsilon_x$, $\sigma_x$) throughout the multiple-strip structure at progressive nominal strain ($\varepsilon$) levels. It is seen that the martensitic transformation commences at the shortest strip ($L_1$) and propagates along the y-direction towards the longest strip ($L_2$). From $\varepsilon = 0.02$ to $\varepsilon = 0.04$, all of the strips are in the course of transformation under uniform stress field, while they are strained differently. At $\varepsilon = 0.05$, the shortest strip
is almost in the martensite state. At $\epsilon = 0.06$, the middle strip is also transformed to the martensite. At $\epsilon = 0.07$, the entire structure is in the martensite state.

Acknowledgments

The authors acknowledge the financial support for this study from the Australian Research Council in grants DE150101795 and DP180101744.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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