Experimental Investigation of Heterogeneous Strain Fields Created in Metallic Materials

Bashir S Shariat
Department of Mechanical Engineering, The University of Western Australia
35 Stirling Highway, Perth, WA 6009, Australia.
bashir.samsamshariat@uwa.edu.au

Abstract. This study reports experimental evaluation of inhomogeneous strain fields created in NiTi structures during stress-induced martensitic transformation. A superelastic NiTi thin plate was used to create samples with uniform and non-uniform geometries. Digital image correlation technique was employed to measure the local strain variation in the NiTi samples under mechanical loading. Clear Lüders band formation and propagation were observed during experiments. The local strain contours revealed that the deformation was localised and spatially inhomogeneous in all samples. In the geometrically non-uniform sample, the transformation initiation and propagation were controlled by geometrical gradient. Also, the global deformation behaviour exhibited stress-gradient during forward and reverse transformations because of geometrical non-uniformity.

1. Introduction
Because of their martensitic transformations, shape memory alloys (SMAs) show unique thermomechanical behaviours, most remarkably pseudoelasticity and shape memory effect [1, 2]. Pseudoelasticity is denoted as the recovery of deformation well beyond the elastic limit of metals spontaneously upon unloading. Shape memory effect is denoted as the recovery of that large deformation upon heating. Owing to these distinct features, they have been used in varied engineering applications, such as sensors, actuators, and medical devices [3, 4]. The most broadly used SMAs are near-equitatomic NiTi alloys, which undertake B2↔B19' martensitic transformations, where B2 is the austenite (A) and B19' is the martensite (M) [5]. The A↔M transformations can be induced by application of either stress or temperature change. During stress-induced transformations, NiTi typically experiences a Lüders-like deformation, which yields in a stress plateau over the transformation strain of 6–8% [6, 7].

The deformation behaviour of SMAs including NiTi is very different from that of conventional metallic materials due to the participation of martensitic transformation. A generic metal displays typically a smooth stress-strain curve involving elastic and plastic deformations. In contrast, NiTi alloy exhibits a large stress plateau in a Lüders-like manner prior to proceeding to the more conventional elastoplastic deformation similar to that of a generic metal. This stress plateau, which is also sensitive to temperature, provides a discontinuity in the stress-strain curve and represents a case of mechanical instability with a zero strain hardening coefficient. Because of Lüders band formation and propagation, the deformation of NiTi is localised and spatially inhomogeneous during tensile loading, which creates heterogeneous strain field within the structure upon loading. In the case of geometrical non-uniformity, the variation in geometry causes the structure to experience an
inhomogeneous stress field upon loading, thus progressive martensitic transformation occurs within the structure. This increases the level of complexity and inhomogeneity of the transformation field and the local strain field within the structure [8, 9]. This phenomenon has attracted much attention for researchers to develop theoretical understanding of the deformation behaviour of SMAs with geometrical non-uniformity [10, 11]. The geometrical non-uniformity can be created by regular variation of geometry as in geometrically graded structures [12, 13] or by irregular variation of geometry as in perforated or porous structures [14, 15]. In geometrically graded NiTi structures, the propagation of transformation is affected by the geometrical gradient direction [16, 17]. It has been reported that the directional transformation propagation can also be created by microstructural or compositional gradients within NiTi structures [18, 19].

This article presents an experimental investigation of the heterogeneous strain fields created in NiTi specimens with uniform and non-uniform geometries during tension. Digital image correlation (DIC) technique was used to capture the Lüders band formation and propagation and to obtain the strain field variation within the NiTi samples during tensile loading.

2. Materials and methods

A Ti-50.8at%Ni plate of 0.12 mm thickness was used to create geometrically uniform and non-uniform samples. The samples were fabricated by means of electrical discharge machining. Before each tensile experiment, a stochastic pattern was created on the surface of the sample by black and white paints for DIC measurement. Tensile experiments of the NiTi samples were conducted using an Instron 5982 machine with a slow strain rate of ~5×10^-4/sec. DIC method was applied to acquire local strain fields during tensile deformation. The testing temperature was 294 K.

In this paper, the nominal stress (σ) is defined as the load over the initial maximum cross-sectional area of the sample. Also, the nominal strain (ε) is defined as the elongation over the initial gauge length of the sample. For a geometrically graded sample, the width aspect ratio is defined as \( \alpha = w_1/w_2 \), where \( w_1 \) and \( w_2 \) are the minimum and the maximum widths, respectively.

3. Results and discussion

3.1. Uniform geometry

Here, the deformation behaviour of a uniform NiTi strip of 30 mm in gauge length and 2 mm in width under tension is presented. Figure 1(a) shows the global deformation behaviour acquired from the tensile testing machine. The sample was loaded up to 0.07 nominal strain and then unloaded. As observed, the material exhibited good pseudoelastic behaviour and recovery of deformation with a flat stress plateau at ~350 MPa over the forward A→M transformation. Figure 1(b) shows the variation of local strain field (ε_x) of the above sample during loading at progressive nominal strain levels, which was obtained through DIC. As observed, multiple Lüders band formed and the material exhibited inhomogeneous strain field along the x-axis during forward transformation.
$3.2$. Non-uniform geometry

Here, the deformation behaviour of a geometrically graded NiTi strip under tension is presented. The sample was tapered linearly along the gauge length of 30 mm. The maximum width was 6 mm. The width aspect ratio was 0.6. Figure 2 (a) shows the global deformation behaviour acquired from the tensile testing machine. The sample was loaded up to 0.07 nominal strain and then unloaded. As observed, the material exhibited stress gradient over A$\rightarrow$M transformations. Figure 2(b) shows the variation of local strain field ($\varepsilon_x$) during tensile loading at progressive nominal strain levels, which was obtained through DIC. The strain contours reveal heterogeneous strain field within the geometrically graded structure along the $x$-direction during forward transformation. As observed, the A$\rightarrow$M transformation initiated at the top end with the minimum width, where the stress was maximum. Then, the transformation progressively propagated toward the bottom end with the maximum width by the increase of load. This progressive martensitic transformation, which was stimulated by geometrical variation, created stress gradient over transformation as seen in figure 2(a). This experimental observation has been recently modelled by finite element method [20].
4. Conclusion
In this study, the local strain field of NiTi alloy has been investigated through digital image correlation technique. Heterogeneous strain fields were observed in NiTi structures with uniform and non-uniform geometries. This heterogeneity in strain field was due to Lüders-like deformation behaviour of NiTi and also progressive martensitic transformation due to geometrical non-uniformity. In non-uniform NiTi structures, the transformation initiation and propagation were controlled by geometry. In a NiTi strip tapered along the length, the stress-induced transformation initiated from the narrower end and propagated toward the wider end. The global stress-strain curve exhibited stress gradient over forward and reverse transformations.

5. References
[1] Otsuka, K. and X. Ren, Progress in Materials Science, 2005. 50(5): p. 511-678.
[2] Shariat, B.S., Y. Liu, and G. Rio, Intermetallics, 2014. 50: p. 59-64.
[3] Mohd Jani, J., et al., Materials & Design, 2014. 56: p. 1078-1113.
[4] Sun, L., et al., Materials & Design, 2012. 33: p. 577-640.
[5] Bakhtiari, S.R., et al., Scripta Materialia, 2018. 151: p. 57-60.
[6] Hallai, J.F. and S. Kyriakides, International Journal of Plasticity, 2013. 47: p. 1-12.
[7] Shariat, B.S., et al., Materials & Design, 2017. 124: p. 225-237.
[8] Bakhtiari, R., et al., Functional Materials Letters, 2017. 10(01): p. 1740011.
[9] Shariat, B.S., R. Bakhtiari, and Y. Liu, J of Alloys and Compounds, 2019. 774: p. 1260-1266.
[10] Liu, H., J. Wang, and H.-H. Dai, Mechanics of Materials, 2017. 112: p. 40-55.
[11] Shariat, B.S., Y. Liu, and S. Bakhtiari, J of Alloys and Compounds, 2019. 791: p. 711-721.
[12] Shariat, B.S., Y. Liu, and G. Rio, Materials & Design, 2013. 50: p. 879-885.
[13] Shariat, B.S., Y. Liu, and G. Rio, J of Alloys and Compounds, 2013. 577, Supplement 1: p. S76-S82.
[14] S. Shariat, B., Y. Liu, and G. Rio, Materials Science Forum, 2010. 654-656: p. 2091-2094.
[15] Shariat, B.S., Y. Liu, and G. Rio, Journal of Intelligent Material Systems and Structures, 2014. 25(12): p. 1445-1455.
[16] Shariat, B.S., et al., Journal of Alloys and Compounds, 2019. 806: p. 1522-1528.
[17] Shariat, B.S., et al., Data in Brief, 2019. 27: p. 104566.
[18] Meng, Q., et al., Scripta Materialia, 2017. 127: p. 84-87.
[19] Shariat, B.S., et al., Acta Materialia, 2013. 61(9): p. 3411-3421.
[20] Shariat, B.S., S. Bakhtiari, and Y. Liu, IOP Conference Series: Materials Science and Engineering, 2019. 522: p. 012005.
Acknowledgments
We wish to acknowledge the financial support to this work from the Australian Research Council in grant DE150101795.