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Estimation of Residual Stress in Additive-Manufactured NiTi Alloy through Beam Mechanics and Finite Element Analysis

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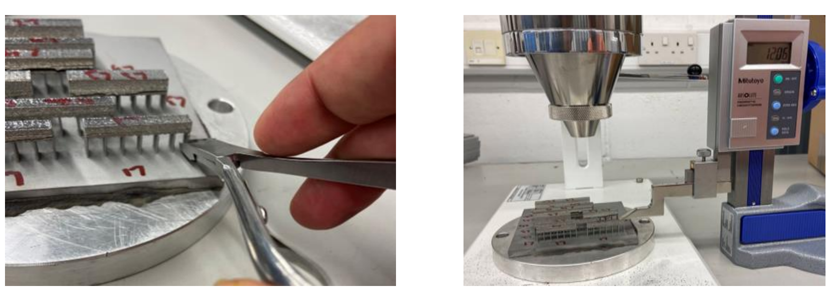
Introduction

Due to the unique characteristics of nitinol (NiTi) such as shape memory and super-elasticity, it is widely utilized in various industries, particularly in aerospace and biomedical applications [1]. Additive manufacturing technology can provide the accurate dimensioning of NiTi components, even for those with intricate and complex geometries [2]. However, the presence of residual stresses poses a significant concern from additive manufacturing. These residual stresses can adversely impact the structural integrity and performance of the manufactured parts, necessitating careful consideration and management [3]. This study delves into a distinctive approach for predicting residual stresses within additive manufactured NiTi components, employing a simple, non-destructive, and cost-efficient method that integrates beam mechanics equations with finite element analysis (FEA). This work aimed to develop a rapid and accurate method for measuring the residual stress from additively manufactured nitinol beams which will be validated via established techniques such as hole-drilling, XRD and/or neutron diffraction.

Methodology and Experimental Results

Gas-atomised nitinol powder consisting of 52% Nickel and 48% Titanium (Austenitic phase at room temperature) was employed to produce the samples along with several sets of thin support structures via powder bed fusion using laser beam (PBF-LB) technology. Aconity MINI (GmbH) metal 3D printer with a 200 W fibre laser manufactured by IPG Photonics with a wavelength of 1068 nm was deployed. NiTi beams were manufactured in the specified dimensions: 4 x 4 x 30 mm (sample 1 and 2), 4 x 4 x 50 mm (sample 3 and 4), 6 x 6 x 30 mm (sample 5 and 6), and 6 x 6 x 50 mm (sample 7 and 8). Additionally, the support structures had approximately 0.7 mm diameter and were 10 mm in length. Upon removal of the support structures (Fig. 1a), the beams exhibited observable distortions due to the residual stress present in them. These deflections were measured using height gauge (Fig. 1b) and implemented in beam mechanics equations (1) and (2) to calculate the forces required for the measured level of deflection and the resulting stress at each ends of a sample. These calculated force values were then integrated into finite element modelling using Ansys software to estimate the overall distribution of stresses within the printed samples. Laser power was varied between 150 W (sample 1, 2, 7 and 8) and 180 W (sample 3, 4, 5 and 6), while keeping the scanning speed, spot size, layer thickness and hatch spacing constant at 1000 mm/s, 70 µm, 60 µm and 80 µm, respectively. Sample 1 was damaged during the process and was not suitable for measurements.



(a) (b)

Figure 1: Pictures of (a) support structure removal and (b) deflection measurement using height gauge.

$$\delta = \frac{W(3L^4 - 4a^3L + a^4)}{24EI} \quad (1)$$

$$\sigma_{max} = \frac{3W(L - a)}{b^2} \quad (2)$$

The beam mechanics equations [4] were established to consider the cantilever beam configuration. For Ansys Workbench simulations, the uniformly distributed load calculated using equation (1) was applied to determine the von-Mises (Equivalent) stresses (Fig 2). Treating each half of a sample akin to a cantilever beam, one end was fixed using the 'Fixed support' option on Ansys Workbench and the 'Remote load' option was used to apply equal loads at specific points where the support pillars were removed.

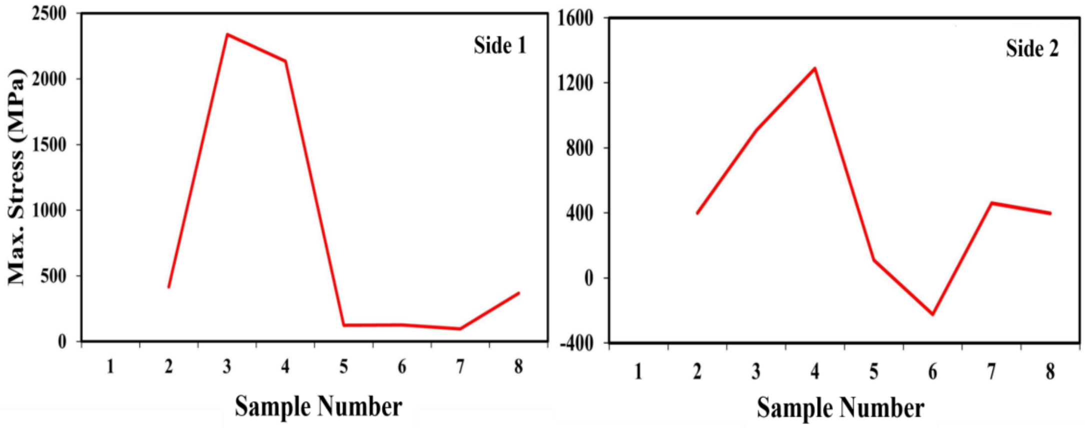


Figure 2: Ansys predicted stresses on the two sides of the samples

Conclusion

An innovative method for predicting residual stresses in additively manufactured NiTi beams was explored. The deflection observed after removing support structures was used to estimate the relaxation of stresses which can be related to the amount of residual stresses present in the samples after additive manufacturing. The samples were treated as cantilever beams, and a combination of beam mechanics equations along with finite element modeling using Ansys software was utilized to predict the stress levels within the samples. This study is aimed at helping the research community in estimating residual stress levels in additively manufactured NiTi in a convenient and cost-effective way. Accurate assessment of residual stresses has the potential to enhance the production of high-quality NiTi components crucial in biomedical applications (e.g., stents) and aerospace industries (e.g., actuators).

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