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Austenite–martensite phase transformation of biomedical Nitinol by ball burnishing

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ABSTRACT

Nitinol has received considerable attention for biomedical and aerospace applications due to its shape memory and superelastic properties. Shape memory and superelasticity are induced in Nitinol by transforming austenite into martensite. Austenite can transform to martensite by applying stress or heat. One promising method to initiate a stress induced phase transformation is ball burnishing. In this study, phase transformation of Nitinol ($Ni_{50.8}Ti_{49.2}$) (at.%) by ball burnishing at various forces was investigated. Burnishing tracks were characterized and microstructures in the subsurface were investigated. Also, a corresponding burnishing simulation was performed to gain insight into the phase transformation mechanism of Nitinol by burnishing.

1. Introduction

Nitinol is a nickel–titanium alloy of near equiatomic composition with shape memory as well as superelastic properties. Shape memory corresponds to a process in which Nitinol will return to a previously defined shape when heated to its transition temperature. Superelasticity refers to the wide elastic range (nearly 8%) compared to conventional materials such as stainless steel. These two features combined with outstanding biocompatibility have made Nitinol a promising material in the biomedical field. The most well-known use of Nitinol in the medical field is for cardiovascular stents. A stent is defined as a cylindrical medical device used to widen a narrowed or stenosed lumen in order to maintain the patency of the lumen. Currently, stents are being increasingly used in blood vessels, gastrointestinal tracts, and renal and biliary tracts (Chun et al., 2010).

Nitinol typically exhibits two phases: austenite and martensite. Austenite has a body center cubic structure and is stable at higher temperatures. Martensite is a monoclinic crystal which is stable at lower temperatures (Fischer et al., 2002). Phase transformation can be induced by a temperature change or applied stress (Duerig et al., 1999). Table 1 shows material properties of martensite and austenite.

The austenite to martensite transformation is shown in Fig. 1. In the superelasticity region of Fig. 1, Nitinol is initially in an austenitic state at the origin point O. With an applied stress, Nitinol is loaded along path O → E, where a phase transformation from austenite to martensite and detwinning of martensite simultaneously occur. A large elastic strain up to 8% can be achieved. Upon unloading along path E → O, the material transforms back to austenite, and the superelastic deformation is recovered and thus demonstrates a hysteresis loop in the stress–strain diagram.

In the thermal shape memory region of Fig. 1 (Guo et al., 2013), when Nitinol is cooled down below the martensite finish temperature (M_f) along path O → A, complete austenite to martensite (twinned) transformation occurs. The material is plastically deformed through reorientation and detwinning of martensite along path A → B. Next, elastic unloading occurs from B → C and leads to reoriented detwinned martensite. After heating above the austenite finish temperature (A_f), the material transforms from martensite to austenite and recovers the pseudoplastic deformation, thus remembering its previously defined shape.

Since Nitinol has been widely used in biomedical field, it is critical that the material has superior resistance to corrosion and fatigue. Burnishing is a promising surface treatment technique to tailor the surface integrity. By altering the surface integrity, the corrosion and fatigue resistance can be improved.

Phase transformation from martensite to austenite by burnishing will alter the mechanical properties on the surface. The objective of this study is to investigate the fundamental phase

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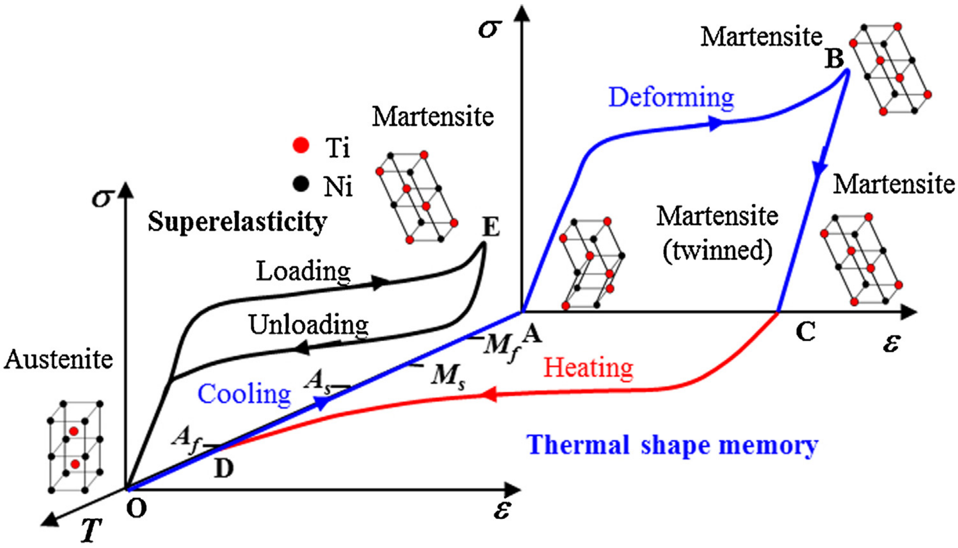

Fig. 1. Stress–strain–temperature diagram of Nitinol (Guo et al., 2013).

Table 1
Nominal properties of $Ni_{50.8}Ti_{49.2}$ (at.%) martensite and austenite (NDC, 2012; Fort Wayne Metals).

Material property	Nitinol martensite	Nitinol austenite
Melting point (°C)	1310	1310
Density (kg/m^3)	6500	6500
Elastic modulus (GPa)	40	75
Thermal expansion (10^{-6}/°C)	6.6	11
Thermal conductivity (W/m °C)	18	18

transformation process of $Ni_{50.8}Ti_{49.2}$ (at.%) under different burnishing loads using the experiment and numerical methods.

2. Literature review

Burnishing uses a hydraulically floating free rolling ball pressed against a workpiece's surface to induce plastic deformation. Burnishing is well-known to impart deep compressive residual stress in the subsurface that is beneficial to fatigue performance (Seemikeri et al., 2008). Moreover, burnishing is a cold-working process that enhances surface integrity features such as roughness and hardness while providing corrosion resistance and wear resistance (El-Khabeery and El-Axir, 2001). What makes burnishing unique is that it employs a small amount of cold work, usually less than 5%, to produce deep compressive residual stress (Zhuang and Wicks, 2002).

A conventional CNC milling machine can be used to implement the process and the motion of the burnishing ball with respect to the workpiece can be precisely controlled. The pressurized oil applies a normal force to the burnishing ball while the overflow oil forms a hydrostatic film between the ball and workpiece that acts as lubricant and coolant. A schematic representation of the burnishing process can be found in Fig. 2.

Extensive studies have been conducted to explore the effect of burnishing on surface integrity of various materials. Rao et al. (2008) conducted a systematic study of the effects of ball burnishing parameters on the surface hardness of HSLA dual-phase steel specimens through factorial design. Results from the statistical analysis showed that burnishing speed, feed, lubricant, and ball diameter significantly affect workpiece surface hardness.

De Lacalle et al. (2007) studied ball burnishing on Inconel 718. Samples were milled and then burnished using a 6 mm diameter burnishing ball under different pressures. Results showed that roughness after burnishing in all cases were lower than that of just milled surfaces. The lowest roughness was achieved using intermediate pressures from 10 MPa to 15 MPa when burnishing was applied perpendicular to the milling direction. It was found that at higher pressures, roughness increased as a consequence of the burnishing ball making grooves on the surface. No evidence of material damage was found.

Palka et al. (2006) reported that burnishing of X5CrNi18-9 stainless steel had led to an increase in number of slip bands, density of dislocations, and twinning deformations in the burnished surfaces. This resulted in an increase in the yield stress from 230 MPa to 450 MPa. It was also stated that excessive burnishing can lead to subsurface cracks which cause spalling, i.e. a phenomenon where the upper layer of a surface flakes off of the bulk material.

The improved surface integrity characteristics will sequentially affect the product corrosion and fatigue performance. Seemikeri et al. (2008) investigated the effect of burnishing on surface integrity and fatigue life of AISI 1045. It was found that the parameters that have greater influence on the surface roughness and fatigue life in decreasing order of importance were pressure, speed, ball diameter, and number of passes. For surface hardness, the parameters that had greater influence in order of importance were speed, pressure, ball diameter, and number of passes. No single

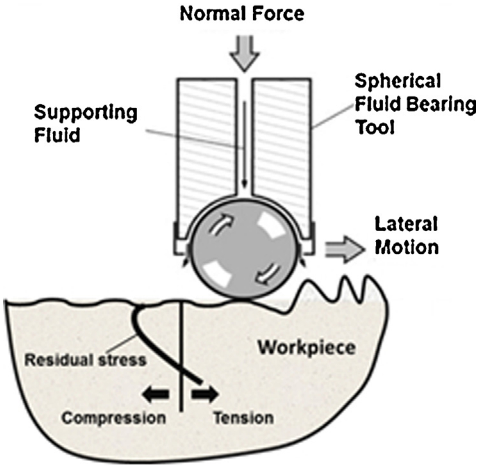

Fig. 2. Schematic representation of the burnishing process (Fu et al., 2012).