FRACTURE MECHANICS OF SHAPE MEMORY ALLOYS: MODELING AND EXPERIMENTAL APPROACHES

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ABSTRACT

Shape memory alloys (SMAs) exhibit unusual fatigue and fracture response with respect to common engineering metals, due to stress- or thermally-induced phase transition phenomena. In fact, these mechanisms significantly affect the crack formation and propagation either under static or fatigue loading. As a consequence, standard solid mechanics approaches cannot be directedly applied to SMAs. Within this context, novel strategies for material testing and modeling are critically assessed. In particular, near crack-tip fields are analyzed by the Digital Image Correlation (DIC) method. DIC data are also used to to estimate the effective Stress Intensity Factor (SIF), by a numerical fitting with the William’s expansion series. Results are systematically compared with the predictions of a recent analytical model. Experimental and analytical results revealed that testing temperature plays an important role on both fracture and fatigue crack propagation. It has been demonstrated that these effects are correctly captured by the analytical model and, consequently, it can be actually used to define fracture and crack propagation criteria.

KEYWORDS: SHAPE MEMORY ALLOYS, FRACTURE MECHANICS, CRACK PROPAGATION.

INTRODUCTION

Nickel-Titanium based (NiTi) shape memory alloys (SMAs) have been becoming more and more attractive in recent years, due to their interesting functional properties, namely shape memory effect (SME) and pseudoelastic effect (PE). These properties are due to reversible phase transformations between a parent austenite phase (B2) and a product martensite one (B19′), which can be activated either by temperature variations (TIM) or applied stresses (SIM). However, despite the increasing interest and the extensive researches carried out in last decades, many aspects related to crack formation and propagation mechanisms, are still unknown. As a consequence, some research activities have been carried out in recent years with the aim of studying the effects of stress and/or thermally induced transformations on fatigue [Kang, 2015] and fracture properties of SMAs [Maletta, 2016]. For this purpose, special methods have been recently applied to analyze near crack tip transformations, such as X-Ray micro-Diffraction (XRD) [Robertson, 2007, Gollerthan, 2009a], Infrared thermography (IR) [Gollerthan, 2009b, Maletta, 2014], Digital Image Correlation (DIC) [Daly, 2007, Wu, 2015, Sgambitterra, 2015a] and instrumented nano-indentation [Sgambitterra, 2015b]. Furthermore, *ad-hoc* analytical models have been developed recently [Maletta, 2010, Lexcellant, 2012, Baxevanis, 2011] to analyze the effects of crack tip transformations.

Within this context, systematic experiments and theoretical studies have been carried out in this investigation with the aim of capturing the actual stress-strain distribution at the crack tip during both static and fatigue loading. The effects of temperature on crack propagation mechanisms of SMAs have been studied. The DIC method has been applied to capture the near crack tip fields as well as to estimate the effective SIF, by a fitting with the William’s expansion series. The results have been systematically compared with the predictions of a recent analytical model [Maletta, 2016].

MATERIALS AND METHODS

A commercial pseudoelastic NiTi alloy (50.8 at.% Ni–49.2 at.% Ti), has been analyzed. Figure 1 illustrates the isothermal (T = 298 K) stress-strain response of the alloy together with the main thermo-mechanical parameters.

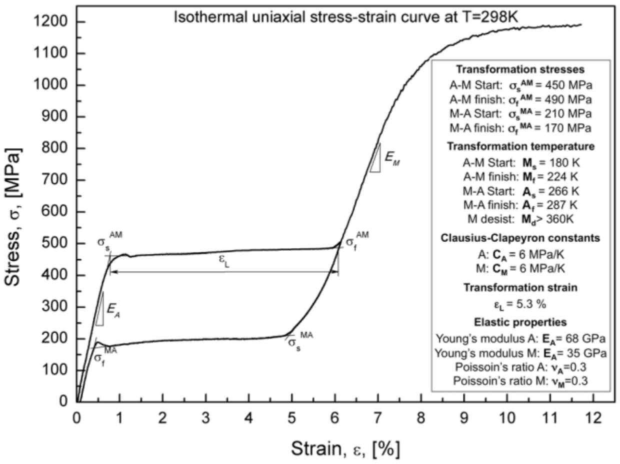

Figure 1. Isothermal stress-strain curve of the alloy (T = 298 K) together with the main thermo- mechanical parameters.

Single edge crack specimens have been used for both fracture and fatigue crack propagation tests. Mode I isothermal tests were carried out at different temperatures within the pseudoelastic regime (20°C, 40°C and 60°C). Fracture tests have been carried out by means of a monotonic load to fracture while crack propagation tests have been executed under a fixed loading ratio ($R=\sigma_{min}/\ \sigma_{max}\sim0$). Crack evolution has been monitored by a CCD Camera and DIC has been performed, by using a commercial software. The experimental results have been critically analyzed by using a recent analytical model [Maletta, 2016]

RESULTS

Figure 2 reports the critical values of the SIF (K_{IC}) as a function of the temperature, obtained from fracture tests. The results disagree with the literature assumption that stress induced transformations represent a toughening effect. In fact K_{IC} calculated according to LEFM, increases with the temperature and, therefore, with decreasing the size of the transformation zone (Clausius-Clapeyron effect).

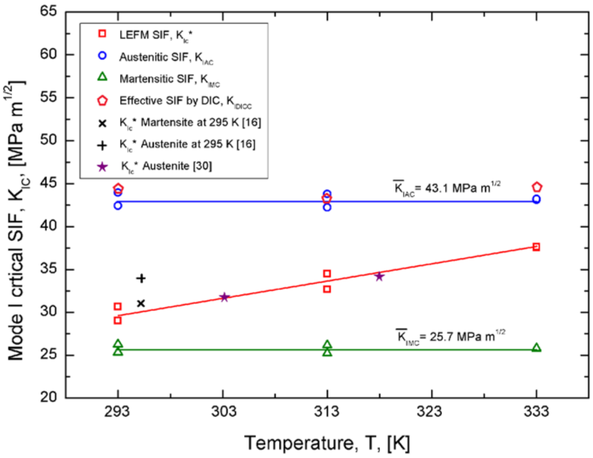

Figure 2. Critical values of the SIF vs temperature: comparison between LEFM, analytical and DIC results.

However, the increase of K_{IC}, based on LEFM is considered as an artifact, because this theory does not take into account the effects of temperature on SIF computation. In fact, the critical values of the austenitic SIF given by the analytical model ($K_{IA\ C}$) is temperature independent. This result is in agreement with the effective SIF estimated by DIC ($K_{IC\ DIC}$). Similar results have been obtained from crack propagation tests, as shown in Figure 3.

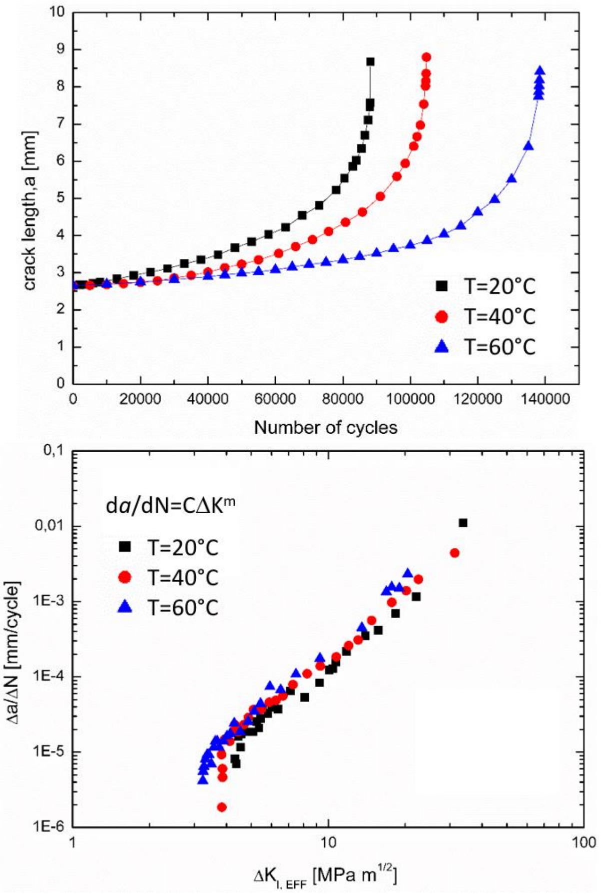

Figure 3. Crack propagation vs temperature: a) Crack length vs loading cycles; b) crack propagation rate vs effective SIF range

A marked increase of the crack propagation rate is observed when decreasing the temperature (Fig. 3.a), but it is actually attributed to the increase of the effective SIF. In fact, Fig. 3.b shows that the slope of the crack propagation curve (exponent m) becomes temperature independent when considering the effective SIF range.

CONCLUSION

A novel analytical method has been analysed by systematic comparison with data obtained from digital image correlation experiments. It is shown that the method is able to capture the marked temperature effects on the effective stress intensity factor and, therefore, it can be successfully applied to define fracture and fatigue crack propagation criteria for SMAs.

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