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Elastocaloric effect vs fatigue life: Exploring the durability limits of Ni-Ti plates under pre-strain conditions for elastocaloric cooling

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ABSTRACT

Structural fatigue is the major obstacle that prevents practical applications of the elastocaloric effect (eCE) in cooling or heat-pumping devices. Here, the eCE and fatigue behaviour of Ni-Ti plates are systematically investigated in order to define the fatigue strain limit and the associated eCE. Initially, the eCE was evaluated by measuring adiabatic temperature changes at different strain amplitudes and different mean strains along the loading and unloading transformation plateaus. By comparing the eCE with and without pre-strain conditions, the advantages of cycling an elastocaloric material at the mean strain around the middle of the transformation plateau were demonstrated. In the second part of this work, we evaluated the fatigue life at the mean strain of 2.25% at the loading plateau and at the unloading plateau after initial pre-straining up to 6% and 10%, respectively. It is shown that on polished samples, durable operation of 10^5 cycles can be reached with a strain amplitude of 0.50% at the loading plateau, which corresponds to adiabatic temperature changes of approximately 5 K. At the unloading plateau (after initial pre-strain of 10%), durable operation was reached at a strain amplitude of 1.00%, corresponding to adiabatic temperature changes of approximately 8 K. The functional fatigue was analysed after the cycling and it is shown that once the sample has been stabilized there is no further degradation of the eCE, even after 10^5 cycles. These results present guidelines for the design and operation of efficient and durable elastocaloric devices in the future.
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1. Introduction

1.1. Background and motivation

Elastocaloric cooling based on the elastocaloric effect (eCE) in shape memory alloys (SMA) is emerging as one of the most promising alternatives to the widely used vapour-compression cooling technology [1], which is relatively inefficient and employs gaseous refrigerants with high Global Warming Potential that can leak and harm the environment. SMAs have been studied extensively over the past couple of decades due to their unique properties, such as the shape memory effect and superelasticity, associated with temperature-induced and stress-induced martensitic transformation, respectively. Nowadays, SMAs are widely applied in many biomedical and other engineering applications [2]. Recently, a significant focus has also been put on the eCE of SMAs, related with the latent heat of the stress-induced martensitic transformation (superelasticity). The eCE can be characterised as a positive temperature change or negative entropy change during the forward martensitic transformation when a superelastic SMA is loaded at its transformation plateau; and as a negative temperature change or positive entropy change during reverse martensitic transformation upon unloading [3]. Generally, all SMAs can be considered as potential elastocaloric materials when they undergo a stress-induced transformation, and their transformation temperatures are below the operating temperature for the desired application. The most commonly used SMA is binary Ni-Ti alloy (Nitinol), which was first reported in 1963 [4] and remains by far the most widely applied SMA due to its superior fatigue behaviour (over other SMAs) and biocompatibility [2]. Due to

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the prevalence of Ni-Ti alloys over other SMAs, the eCE is thus the most extensively studied in Ni-Ti alloys, where adiabatic temperature changes up to 25 K have been reported in several studies [5–10]. It was shown that doping Ni-Ti with Cu and Co or Fe may improve functional and structural fatigue, while retaining relatively high adiabatic temperature changes (up to 10 K) [11,12]. A comprehensive evaluation of transformation temperatures and latent heats of transformation of ternary and quaternary Ni-Ti-based alloys was performed by Frenzel et al. [13]. It was further shown that Ni-Ti-Cu-V alloys exhibit good functional stability, high latent heat and very low hysteresis width and are therefore a very promising candidate for elastocaloric cooling [14]. Recent comprehensive reviews on elastocaloric materials can be found in [15,16].

Theoretical studies based on experimental characterisation of elastocaloric materials show that elastocaloric cooling can be potentially significantly more efficient than vapour-compression technology [6,12,17–20] as well having a lower environmental impact. Recently, the first prototypes demonstrating a high potential of the eCE as a cooling or heat-pumping mechanism have been developed and tested [21–24]. The most promising results to date were obtained using a regenerative elastocaloric cycle based on a porous elastocaloric material composed of a stack of dog-bone shaped Ni-Ti plates working as an active elastocaloric regenerator loaded in tension [24]. In addition to the positive aspects of the reported prototype, such as high temperature span, high heating/cooling power and potentially high efficiency, limited durability with a fatigue life of only up to 6000 cycles was reported [25]. This is insufficient for any practical application where fatigue life well above ten million cycles is required [5]. The fatigue life can potentially be improved if the elastocaloric regenerator is loaded in compression [23]. It is known that the fatigue life during compression loading can be significantly better compared to tension loading, as cracks and defects in the material have limited potential to grow and propagate [26]. Longer fatigue life is a big advantage of compression loading for elastocaloric cooling, yet on the other hand, tension loading enables applications of thin elastocaloric elements (which would buckle under compression), that allows for efficient and rapid heat transfer between the elastocaloric material and heat sink/heat source, which is crucial for an efficient elastocaloric device.

Since it has been demonstrated that an elastocaloric regenerator loaded in tension can be very efficient with high specific cooling/heating power [24], the aim of this study is to define the maximum applied strain at which long-term, durable operation (above 10^5 cycles) is reached and to evaluate the associated eCE of commercial Ni-Ti plates loaded in tension at the fatigue strain limits. The results present guidelines for the design and operation of efficient and durable elastocaloric devices in the future.

1.2. Overview of SMA fatigue behaviour from an elastocaloric perspective

Despite numerous studies of the eCE in the last years, only minor attention has been put on evaluation of structural fatigue of the elastocaloric materials – despite being crucial for practical applications. Most of the studies (with few exceptions as discussed below) concentrated on the eCE at a very low number of cycles (below 1000). Therefore, there is a lack of systematic analysis of the fatigue strain limits and related eCE for durable operation of elastocaloric materials. However, Chluba et al. [12,27] demonstrated an ultra-low fatigue Ni-Ti-Cu-Co thin film made by sputtering deposition that can withstand 10 million loading cycles in tension with a strain up to 2.50% and adiabatic temperature changes up to 10 K. This highly encouraging result already meets the demands of practical applications, but the disadvantage is that the applied sputtering deposition technique is still too time-consuming for large-scale production of this material that would be required in practical cooling or heating applications. Engelbrecht et al. [28] compared fatigue life and eCE of Ni-Ti plates with different surface finishes and different stabilization methods loaded in tension. They showed that a better surface finish leads to longer fatigue life (as expected), but even polished samples failed prior to 5000 cycles when loaded up to 4%. Very recently, fatigue life and eCE of Ni-Ti, Ni-Ti-Cu, Cu-Zn-Al and Ni_2FeGa alloys during tension and compression loading were studied by Wu et al. [26]. They showed that when loaded in compression, all evaluated alloys reached runout (>10^4 cycles), while during tension loading this was the case only for the Ni_2FeGa alloy.

As the fatigue of SMAs is generally a major challenge for all its applications, it has been widely studied in the recent years. Following the pioneering work of Melton and Mercier [29], there are several state-of-the-art papers that address different crucial aspects of SMA's fatigue behaviour, such as surface finish [30], inclusions [31,32], pre-strain conditions [33–36], operating conditions (test temperature, frequency, strain-rate) [37–40], heat treatment during cycling (healing) [41], etc. Since the failure in these materials takes place shortly after the crack nucleation, the interest in the current state-of-the-art is mainly to control crack initiation that is usually caused by surface roughness and/or inclusions [42]. Surface finish is an extremely important parameter for greater fatigue life - polishing (electro-polishing or fine mechanical polishing) or etchings are thus highly recommended [28]. Launey et al. [31] demonstrated that a Ni-Ti alloy with a low inclusion rate showed a 5-fold improvement in fatigue resistance (with an impressive 10^7-cycle fatigue strain limit of 2.50%) compared with standard grade Ni-Ti. Urbano et al. [32] performed a comprehensive study on the impact of inclusions in Ni-Ti wires on their fatigue life. They showed that, in particular, large inclusions (above 20 μm) of carbide and/or oxide near the surface of the sample, which effectively act as cracks, can drastically reduce the fatigue life. It was further demonstrated that an applied pre-strain may also significantly influence the fatigue life of SMAs. As reported by Tolomeo et al. [33] and Pelton et al. [34], the fatigue life of Ni-Ti can be increased if the sample is loaded with a mean strain around the middle of the transformation plateau and the total applied strain remains within the plateau. It was shown that a fatigue limit of 10^7 cycles can be reached with a strain amplitude of 0.50% at a mean strain of 3% for tension loading [34]. On the other hand, Mahtabi and Shamsaei [35] demonstrated detrimental effects of applying tensile pre-strain on the fatigue behaviour of a superelastic Ni-Ti sample, despite findings from other studies [33,34] showing benefits. The impact and benefits of pre-strain on structural fatigue of Ni-Ti alloys are therefore not yet fully understood. Furthermore, Ong et al. [36] showed that if a Ni-Ti wire is initially pre-strained up to 11% and then cycled at the unload plateau, this can increase the fatigue strain limit (at 10^7 cycles) to a strain amplitude of 0.50% (compared to 0.12% at pre-strain up to 4%). They argued that large pre-straining generates compressive residual stresses around inclusions and reduces the stress state, which delays the crack initiation process. Interestingly, Wagner et al. [41] demonstrated that periodic annealing of the Ni-Ti samples well above the austenitic finish temperature (also called healing) retransforms the residual martensite accumulated during the superelastic cycling back to the austenitic phase and therefore enhances both structural and functional fatigue. This approach can be a promising method to increase the fatigue life of elastocaloric materials and, by retransforming the residual martensite, to improve the eCE during the cycling. Comprehensive reviews on the fatigue life of SMAs can be found in [42–45].

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