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Finite Element analysis of a shape memory alloy actuator for a micropump

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ABSTRACT

This paper deals with a Finite Element (FE) behavior analysis of a shape memory alloy actuator for a micropump. It is composed of two membranes of NiTi shape memory alloy (SMA) in a martensitic state at room temperature. They have an initial flat shape and are bonded together with an intermediate spacer. The thermal loading allows the actuator to move up and down in the membrane normal direction. A detailed analysis of sensibility to material and geometric parameters of the SMA actuator is undertaken by FE method. The actuation capability and reliability are studied in order to lead to optimal parameters set providing a higher stroke (deflection) with a low heating temperature. The shape memory effect exhibited by these membranes is simulated by means of the phenomenological constitutive law based on Chemisky–Duval model [1,2], and implemented in the Abaqus® FE code. The obtained numerical results were detailed proving the ability of the proposed modeling to reproduce the actuator behavior under thermal loading. This analysis showed that it is possible to provide a large stroke for a minimal geometry of the actuator.

1. Introduction

Micromachining technology is a miniaturization technique which can be used to manufacture various devices and systems. This technique has opened a new thrusts and made the possibility to develop various devices and systems in small size with high functionality, precision and performance in various domains such as automotive, aerospace, communication, medical, civil engineering [3–7]. In fact, some microsystems require an effective actuator which could be suitable for highly sensitive applications. Smart materials as piezoelectric ceramics or shape memory alloys (SMAs) were often considered for the design of micro-components and/or micro-devices [8–17]. In fact, their coupled and multiphysic behaviors allow the conversion of an electric or thermal energy on a mechanical one for actuator applications and vice versa for sensor applications. The development of thin films elaboration processes for these smart materials combined by the using of etching techniques made possible the design of complex geometry micro-components and micro-devices (micro-actuators, micro-valves, micro-sensors, stents, etc.) based on theses thin films [18–25].

SMA actuators are ones of the most used micro-devices to achieve such applications. In fact, SMAs can exhibit high forces or large strains, which could be converted to high pressures or large strokes (deflection). For this reason, SMA actuators have been considered for micropump actuations [26–29] where the stroke of the actuator determines the pumped volume per cycle. The actuator converts the input electric or thermal energy into mechanical work output inducing system motion. A wide range of SMA actuators for micropumps and microvalves were proposed in the literature [14,21,30–37]. They were

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etched in an SMA thin films (generally in NiTi) and they consider the shape memory effect property. During a heating, the actuator exhibits a displacement induced by the reverse martensitic transformation. This displacement is recovered during the cooling process leading to the forward martensitic transformation. This cooling process is generally very low (A fan can provide compressive convection for fast cooling [38]). For that reason, an actuator composed of two NiTi SMA membranes etched in a thin film and separated by a silicon spacer was proposed [30,31]. These two membranes are working in an antagonist way and the actuation is always obtained by heating. The heating of one membrane gives an actuation displacement in one way (fluid input) where the heating of the other membrane allows the opposite actuation displacement (fluid output). During the heating of any membrane, the other one is freely cooled. Thanks to the spacer inserted between membranes, the forward and reverse transformations are occurring under bending stress. This induces the activation and disappearance of oriented martensite variants leading to a significant transformation strain.

To analyze the behavior of such actuators, it is interesting to turn ones attention to many experimental investigations [32,30,39–41] and numerical studies [28,29,42,43] on various considered technologies in the case of micropumps. They are based on various experimental and/or numerical (FE simulation) tools in order to optimise their performance. In the present work, a numerical approach based on a finite element method (FEM) was considered. Most commercial codes based on FEM have a standard constitutive models database well adapted to conventional materials with elastic, viscoelastic, elasticplastic, elasticviscoplastic, etc. behaviors. However, these codes have very few or no constitutive models that describes all the specificities of an SMA thermomechanical behavior. As an example the FEM based Abaqus code has a superelastic constitutive law based on the Auricchio's model [44,45]. In order to analyse by FEM the shape memory effect behavior of such actuators, the only solution was to consider a user constitutive model which can be implemented in commercial FEM based code via a user subroutine (as an example one can use the User MATerial (UMAT) subroutine for Abaqus). The LEMTA's and the LEM3's (affiliated to Université de Lorraine, Arts et Mtiers ParisTech and CNRS) research groups have, in collaboration, developed and implemented in Abaqus a thermomechanical constitutive law covering all the specificities of the SMA behavior (superelasticity, shape memory effect, internal loop behavior, difference between tension compression, saturation and hysteresis effects, etc.) [1,46]. In this model the inelastic strain induced by forward and reverse transformations is characterised by four internal variables. Two are scalar and correspond, respectively, to the volume fraction of all the martensite and the twinned part. The two other internal variables are tensorial and correspond respectively to the mean transformation and the mean twinning strains. The constitutive equations of this model were derived from an assumed expressions of the Gibbs free-energy and the dissipation function. The driving forces corresponding to internal and control variables were derived and compared to the corresponding yield forces in order to determine active mechanisms. Additional developments allowed to take into account the asymmetry between tension and compression, the management of internal loop and the saturation behaviors. This FE analysis considered the 2D version of this constitutive model corresponding to the plane stress assumption.

An analysis of the influence of the various material and geometric parameters was discussed. The aim is to highlight factors in relation with the actuator stroke. Finally, an optimal configuration was suggested able to provide a high stroke with minimal geometry. The optimization objective function was the actuation capability and reliability of the actuator. In some cases, the optimization and a higher heating temperature can lead to a higher actuator stroke. On the other hand, this leads to a higher stress level and an important transformation strain in the NiTi actuator. In that case, the actuator becomes unreliable to operate if the stress and transformation strain is beyond material strength. In order to ensure both high stroke and reliability, a corresponding criterion was defined. The obtained results allowed designing the configuration of the proposed actuator with an optimized stroke.

This paper is organized into five sections including the introduction and the conclusion. In the second section, the description of the SMA actuator properties was detailed. The studied material is a NiTi SMA in the martensitic state with a self-accommodate martensite variants at room temperature. The third section deals with the adopted constitutive model and the numerical simulation of the SMA actuator behavior based on a FEM. Finally, the sensitivity to material and geometrical parameters on the stroke of the actuator was discussed. The FE analysis gave a significant results of the actuator behavior under a thermal loading. Results allowed defining a set of geometrical parameters for the actuator providing an important stroke with a minimal size.

2. Description of the studied SMA actuator

The actuator adopted design was initially proposed by Benard et al. [30,31]. It considers two NiTi membranes at the martensitic state with a self-accommodate martensite variants at room temperature as shown in Fig. 1a. They have an initial flat shape and are bonded together with a crown in the exterior contour (exterior spacer), and with an intermediate spacer in silicon material. This assembly induces a bending stress field on membranes leading to an orientated martensite and a strain state recoverable by thermal loading. When the top membrane is heated, it becomes austenitic and recovers the deformation, thus the actuator moves downwards, resulting a further deflection in the other membrane. The cooling allows it to return to a martensitic state. When the bottom membrane is heated, it becomes austenitic and causes the deformation, so the actuator moves in the other direction. The principle of the actuator is shown in Fig. 1. There are several possible actuation methods for such SMA actuator: