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Modeling of shape-memory alloys in scramjet engine applications

Modelagem de aplicação de ligas de memória de forma em motores scramjet

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ABSTRACT

This work consists of a theoretical-analytical modeling using applications of intelligent materials, called shape-memory alloy (SMA), in scramjet engines varying the speed from Mach 7 to 14. Through the shockwave relationships, the angles, the Mach number and the recoil distance at the leading edge of the cowl were found out, to select the SMA that has the best deformation recovery. After using the theoretical Auricchio model, the superelastic behavior of the alloys was observed for different elastic properties in the austenite and martensite phases to perform a computational simulation, using the finite element method in Solver ANSYS, in order to represent the performance of the material in a simpler way.

KEYWORDS: Shape-memory alloy, Scramjet, Auricchio model.

RESUMO

Este trabalho consiste em uma modelagem teórico-analítica utilizando aplicações de materiais inteligentes, denominados de liga de memória de forma (LMF), em motores scramjet variando a velocidade de Mach de 7 a 14. Por meio das relações de ondas de choque, foram encontrados os ângulos, o número de Mach e a distância de recuo no bordo de ataque da carenagem para selecionar a LMF que apresenta melhor recuperação de deformação. Após utilizar o modelo teórico Auricchio, foi observado o comportamento superelástico das ligas para diferentes propriedades elásticas nas fases austenita e martensita para a realização de uma simulação computacional, utilizando o método dos elementos finitos no Solver ANSYS, que representa de forma mais simplificada o desempenho do material.

PALAVRAS-CHAVE: Liga de memória de forma, Scramjet, modelo Auricchio.

INTRODUCTION

Because of the advancement of aerospace technology, engineers and technicians observed problems in the materials that made up the vehicle's airframe, due to its aerodynamic heating and shockwave interactions, resulting in high temperatures in the aerodynamic structure that causes thermal stresses and ablation[1].

In the mid-1960s, Buehler and colleagues at the U.S. Naval Ordnance Laboratory discovered the shape-memory effect (SME) of a nickel-titanium (Ni-Ti) equiatomic alloy that came to be known as nitinol. This alloy presents a pseudoelastic behavior, when exposed to tension or heating. The term shape-memory alloys (SMA) belongs to the group of metallic materials that demonstrate the ability to return to their previously defined shape or size, when exposed to an appropriate thermomechanical procedure[2]. Given this fact, the first application in the aeronautical industry occurred.

Hypersonic aerospace vehicles equipped with supersonic combustion technology, called scramjet engines, use the principle of the hypersonic airbreathing propulsion to produce maximum thrust. In ideal operation, the oblique shockwave generated during the hypersonic flight should focus on the leading edge of the engine's cowl, causing the flow deflection in the combustion chamber entry of the scramjet engine. However, as the vehicle accelerates during the flight, the shock layer tends to become less thick and more attached to the vehicle body. This fact causes the incidence of the oblique shockwave generated at the compression ramp's leading edge to occur outside the design point, affecting several different points of the engine cowl, as shown in Fig. 1.

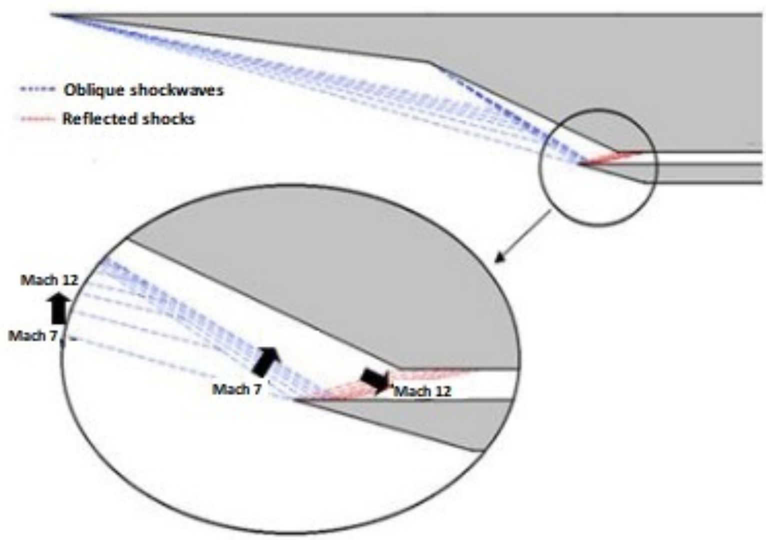

Figure 1: Incidence of the oblique shockwave in the engine cowl ranging from Mach 7 to Mach 12.

Currently, several aerospace research centers have been developing new propulsion technologies, aimed at a new generation of space exploration vehicles with reduced cost and just as safe as conventional propulsion technology. According to Costa[3], hypersonic airbreathing propulsion systems use a supersonic combustion ramjet (scramjet) that has greater potential, meeting the basic requirements of extremely high speed, reliability, safety and cost, consuming hydrogen as fuel and oxygen from the atmosphere as oxidizer. This system uses the oblique shockwave during hypersonic flight to promote compression and deceleration of freestream at the scramjet inlet, obtaining adequate conditions at supersonic speeds into the combustion chamber.

A proposed alternative is the application of smart materials, such as SMA, allowing the scramjet engine to adapt to different operational environments during its hypersonic flight.

Once the properties of the material to be used are known, it is possible to make an analysis of its behavior using the ANSYS software and the Auricchio[4] modeling, which aims to study the superelastic behavior of alloys with shape memory.

THEORY

Shape-memory alloy

SMA demonstrate the ability to return to a previously defined size or shape, when exposed to a thermomechanical process. They have two important characteristics: SME and superelasticity effect. SME is the ability to recover a large amount of inelastic deformation after heating at a certain temperature. This is observed in the material's microstructure. Superelasticity is the thermomechanical property of the material that allows the initial recovery, when removing the load that it is exposed[5].

For the SME occurrence, it is necessary to have prior knowledge of the present distinct crystallographic phases, called martensite and austenite. In martensite, a diffusionless transformation occurs. In the other hand, there is no atomic diffusion, only the coordinated movement of the atoms by the shear mechanism. It is the phase known for presenting low temperatures and monoclinic crystalline structure. Due to a loading or temperature variation, the internal microscopy structure is altered presenting an accommodation by twinned, that is, the characterization by the stacking failures, not showing the rupture of chemical bonds, turning the alloy reversible. Austenite has a high temperature phase, a cubic crystalline structure and it is crystallographically more ordered offering greater resistance to possible deformations, which is known as the mother phase. From the microscopic and macroscopic view, the structure remains unchanged when exposed to mechanical loading[6]. It can be said that it is an elastic phase.

One of the main consequences of the phase stabilization is the change in the transformation temperature: start martensite (Ms), final martensite (Mf), start austenite (As), final austenite (Af). If the temperature increasing is verified, there is stabilization in the martensitic phase; if there is decreasing, there is stability in the austenitic phase, as shown in Figs. 2 and 3.

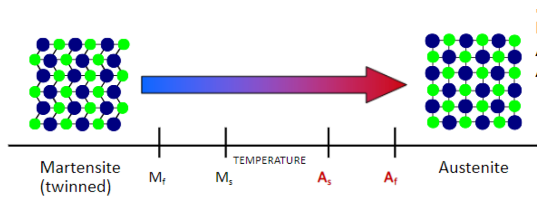

Figure 2: Transformation from twinned martensite to austenite.

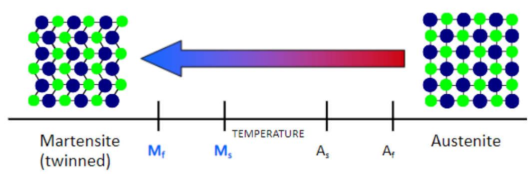

Figure 3: Transformation from austenite to twinned martensite.

The cooling/heating cycle of the alloy shows a thermal hysteresis, in which the material or the system tends to preserve its properties as soon as the load or temperature that generated them ceases. However, a phase transformation can occur, when a mechanical load is applied to the material in the twinned martensite phase. When it continues to be loaded, it reaches a limit in which the molecular structure undergoes a new change, called as detwinned martensite phase. In the scheme presented by Fig. 4, it is possible to verify the alternating of phases with the variation of temperature versus stress in an alloy with SME.

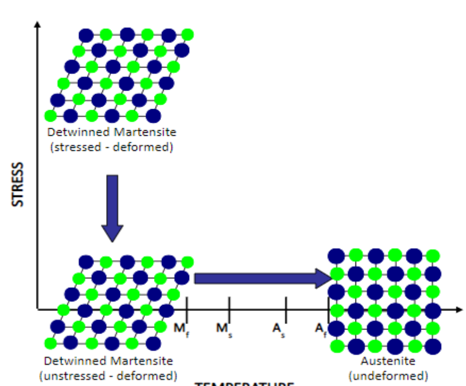

Figure 4: Temperature variation versus load application in the phase transformations.

Since the SMA considerations were made, a bibliographic review of the existing alloys with such effect was conducted, such as nickel-titanium (Ni-Ti) alloy, copper-aluminum-nickel (Co-Al-Ni) alloy, nickel-titanium-hafnium (Ti-Ni-Hf) alloy and titanium-nickel-zirconium (Ti-Ni-Zr) alloy, which allowed the best choice of the material that fits in this research and presented in the discussion section.

Auricchio model

Computational simulations were carried out using ANSYS solver and based in the Auriccho model[4]. This model proposes to study the superelastic behavior of alloys with SME for the different properties in the martensite and austenite phases. The Auricchio model is characterized by being relatively simple and close to the experimental results. The ANSYS solver is based on this model to represent the model's behavior in a simplified way. There is the definition for each ANSYS required parameter, as shown in Table 1.

Table 1: Auricchio model.

Density (ρ)		Shape-memory alloy (SMA) density
Isotropic elasticity	Young's modulus E_A	The Young's modulus of austenite.
	Poisson's ratio *v*	The Poisson's ratio of austenite.
Shape-memory effect	Hardening parameter H	The slope of the stress-strain curve during martensitic transformation.
	Reference temperature T_{ref}	The temperature at which the SMA properties are measured.
	Elastic limit σ_s^{AM+}	The start stress for austenite to martensite transformation.
	Temperature scaling parameter C	The slope of band transformation considered the same for the twice sense of transformation: austenite to martensite and martensite to austenite.
	Maximum transformation strain ε_{tr}^{max}	The maximum strain due to martensitic transformation.
	Martensite modulus Em	The Young's modulus of martensite.
	Lode dependency parameter β	A parameter that measures asymmetric behavior of SMA under compression and tensile loadings. In the case of symmetric behavior β=0.

After studying the mechanical properties, it is possible to see the graphs of the Auricchio model in Figs. 5 and 6. Figure 5 is related to the Tab. 1, in which one can see the phase diagram and stress-strain curve parameters. In Fig. 6, path 1 (black line) shows that the material is in a totally austenitic state. When reaching path 2 (blue line), the material goes through the transition phase. The percentage coefficient grows up to the maximum limit, which reaches the martensitic phase. However, it relates its constitutive laws to stress (σ), deformation (ε) and the martensitic phase fraction (ξ)[7].

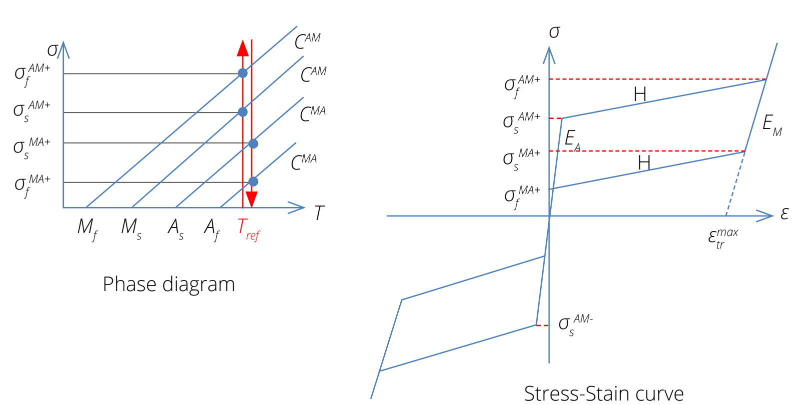

Figure 5: Phase diagram and stress-strain curve.

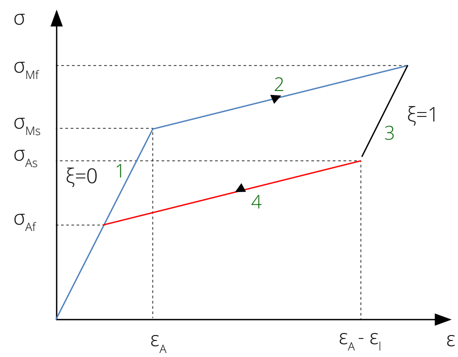

Figure 6: Martensitic percentage in shape-memory alloys.

RESULTS AND DISCUSSION

Based on previous work[2], it is determined that, during a flight, the hypersonic vehicle is subjected to critical conditions. Therefore, the SMA applied to the scramjet cowl must have good physical and mechanical properties, such as high resistance to corrosion and oxidation and high melting point, resulting in greater efficiency in the scramjet engine. It is possible to see that the alloys that showed the best mechanical properties were Ti-Ni-Zr and Ti-Ni-Hf, because they presented a higher phase transformation temperature, which is a requirement to be obeyed during a hypersonic flight.

From a theoretical analysis, it was possible to know the shockwave angles of incidence in the cowl of the scramjet engine, varying from Mach 7 to 14 (Fig. 7), and also to observe the variation in deformation that the material will assume. In this circumstance, the SME will suit the engine's requirement without compromising the thermo-structural requirements, maximizing the results during its operation.

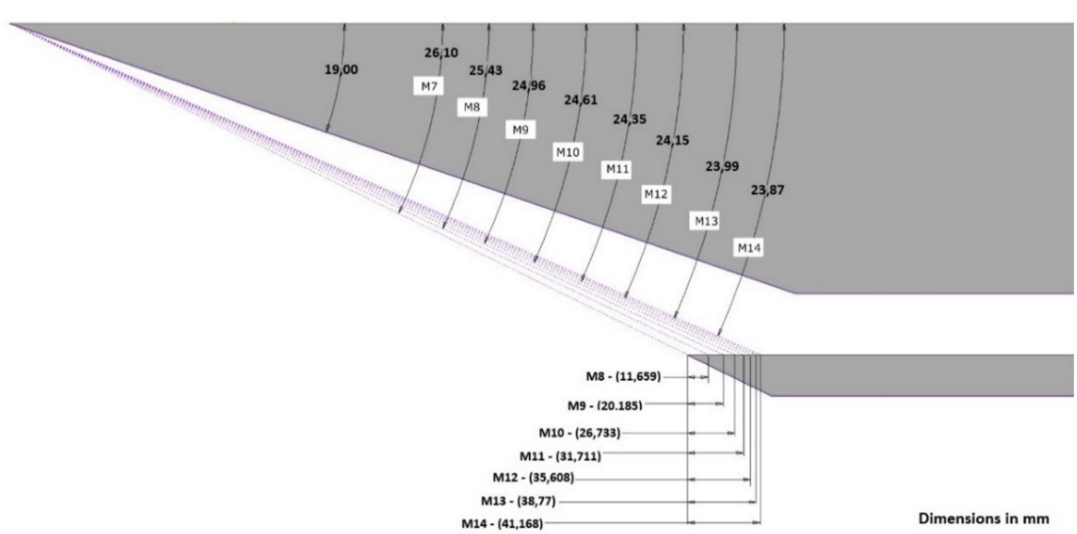

Figure 7: Shockwave system focusing on the leading edge of the cowl.

Referenced in Firstov et al.'s work[8], as it is related to shape recovery percentage, one can see that, in comparison to the deformation when subjected to temperature variation, the Ti-Ni-Zr alloy has a higher shape recovery percentage (3.7%) than the Ti-Ni-Hf alloy, which presents a shape recovery percentage of 3.4%, seen in Fig. 8.

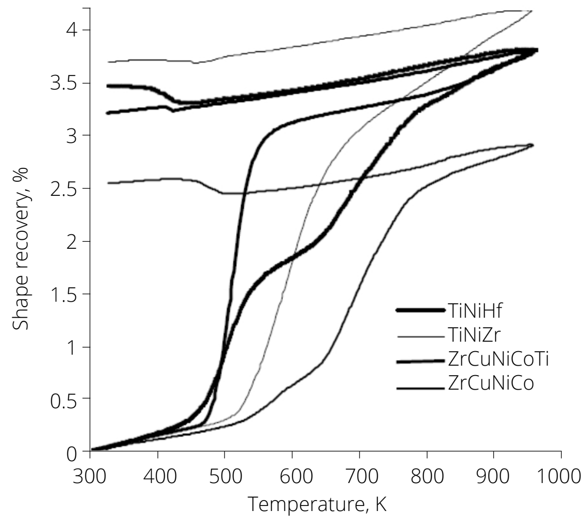

Figure 8: Shape recovery on heating after compression.

CONCLUSION

It is concluded that, considering the SMA studied so far, the Ti-Ni-Zr alloy was chosen to be applied to the scramjet engine cowl, because it presents a better recovered deformation (εR), due to its low deformation percentage (ε), when submitted to stress or heating. The main suggestion for future works is to realize structural analysis via numerical simulation, due to the aerodynamic behavior caused during the hypersonic flight using a scramjet engine endowed with SMA.

AUTHORS' CONTRIBUTION

Conceptualization: Brito AARB; **Formal Analysis:** Passaro A, Costa FJ, Lima MSF; **Investigation:** Brito AARB; **Methodology:** Brito AARB, Passaro A, Costa FJ, Lima MSF; **Project Administration:** Costa FJ; R**esources:** Passaro A, Costa FJ; **Software:** Passaro A; **Supervision:** Passaro A, Costa FJ, Lima MSF; **Validation:** Brito AARB; **Visualization:** Brito AARB, Costa FJ; **Writing – Original Draft Preparation:** Brito AARB; **Writing – Review & Editing:** Passaro A, Costa FJ, Lima MSF.

DATA AVAILABILITY STATEMENT

Data will be available upon request

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Not applicable.

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