4D PRINTING OF NITINOL SHAPE-MEMORY COMPONENT MADE BY SLM ADDITIVE MANUFACTURING

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ABSTRACT

The concept of 4D printing comes from associating the design possibilities allowed by 3D printing, and a smart material. It involves the additive manufacturing of a material capable of changing its geometry, functions or properties under the effect of an external stimulus after its production.
Using the shape memory alloy (SMA) technology, this study aims to manufacture an SMA with a reversible martensitic transformation and design innovative space actuators in nitinol (NiTi) alloy. The selective laser melting (SLM) technology based on a powder bed fusion enables to produce complex components in metallic material.

INTRODUCTION

Shape memory alloys are well known for their particular thermomechanical properties: superplasticity and shape memory effect. These unusual properties for metallic materials are possible due to the austenite-martensite phase transformation. Nitinol is the most commonly used alloy due to its ease of forming by conventional manufacturing processes. It is used in many fields of industry such as medical, aerospace or automotive. Since the beginning of the 2010 decade, NiTi has been used in additive manufacturing [1]. This process allows the production of parts with complex geometry, especially since NiTi is a difficult material to be machined. Today, the control of the process has increased and homogeneous and dense materials are obtained with mechanical properties close to a conventional NiTi [2].
In partnership with LEM3 laboratory, Thales Aliena Space and CNES, a development program funded by ESA and led by Nimesis Technology is underway. The objective of this project is the development of optimized NiTi alloy shape memory components for aerospace applications.

POWDER STRATEGIES

The austenite-martensite phase transformation of NiTi occurs at defined temperatures, i.e. the activation temperatures of the alloy. These temperatures are directly linked to the chemical composition of the alloy. Figure 1 shows the evolution of the martensitic transformation temperature as a function of the Ni content. These temperatures are extremely sensitive and difficult to control: 0.1 at% difference in composition corresponds to about a 10°C shift in transformation temperatures.

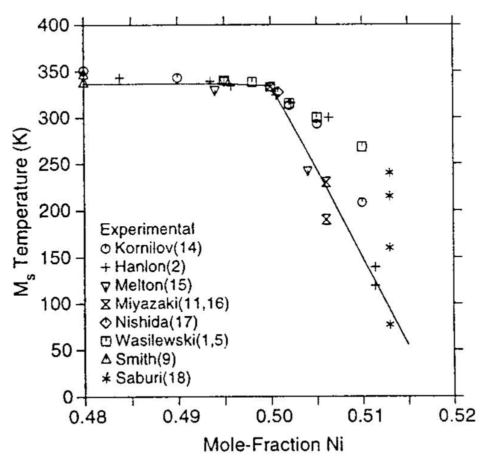

Figure 1. Martensitic transformation temperature vs. Ni content.

To have an additional advantage on the control of the alloy, two different powder strategies have been tested: pre-alloyed powder and powder mixing. The advantage of the mixture compared to the pre-alloyed powder is the possibility to control the composition of the alloy by adjusting the amount of Ni or Ti powder in the mixture. In this case, the alloy is made in situ during manufacturing. In the case of pre-alloyed powder, the composition is fixed but additive manufacturing only involves remelting the alloy. The following presents results with a pre-alloyed powder.

ADDITIVE MANUFACTURING MATERIAL DEVELOPMENT

A pre-alloyed NiTi powder, with a near equi-atomic composition and a particle size between 15 and 45 µm was used. An experimental design was conducted on a SLM 280HL machine. The manufacturing was carried out under controlled atmosphere with an oxygen level lower than 300 ppm.

The experimental plan was performed varying the standard parameters of the SLM process (power, speed of the laser and distance between two laser passes). In the case of SMA alloy development, an additional criterion in the material development phase concerns its martensitic transformation capacity, also known as transformation enthalpy. It is measured by differential scanning calorimetry (DSC).

Several optimal fabrication parameters result in transformation enthalpies between 15 and 20 J/g, comparable to a standard NiTi alloy. Figure 1 shows the DSC for a selected set of manufacturing parameters for as-build NiTi alloy, with a transformation enthalpy of 17 J/g. The results are also compared with the solution heat treated alloy. The As activation temperature is 35°C for the as-build material and 31°C after heat treatment. After heat treatment, the enthalpy of transformation is similar but the width of the peak is smaller, indicating a faster and better controlled transformation, when heating the material.

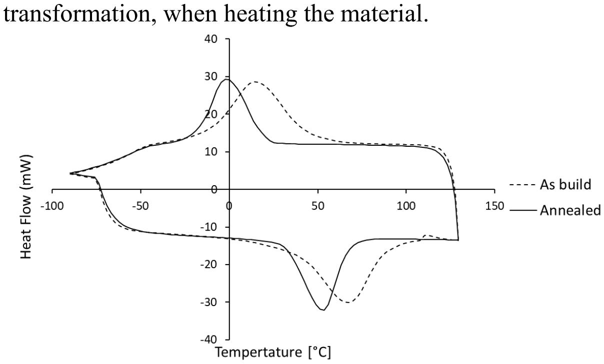

Figure 2. DSC results showing the phase transformation behaviour of NiTi alloy manufactured by selective laser melting process.

MECHANICAL CHARACTERIZATION

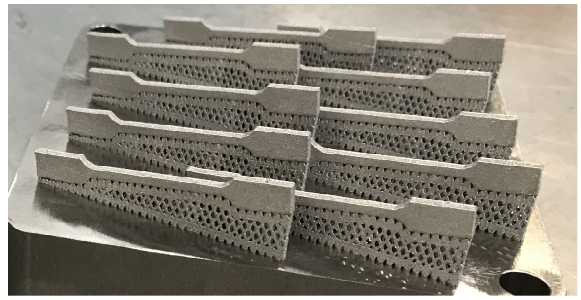

Figure 3. Additive manufacturing of tensile samples.

The material is then tested in tensile mode at room temperature. The stress-strain curve is presented in Figure 2 for the as-built material. The curve shows a standard response for a NiTi alloy, with a change in slope and a plateau due to stress-induced martensitic transformation (SIM) and reorientation (SIR). With an imposed strain of 4%, the residual strain is 3.1%. By heating, this deformation can be recovered to more than 90%.

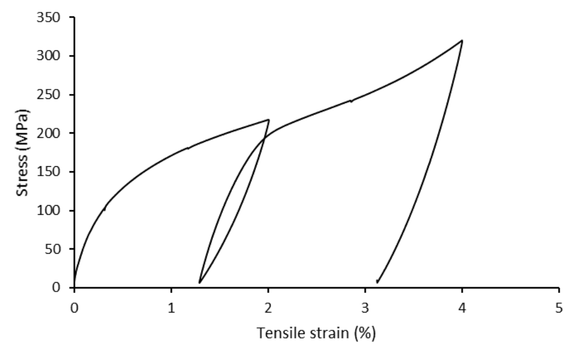

Figure 4. Tensile behaviour of as-build NiTi alloy fabricated by selective melting process.

PROOF OF CONCEPT

To perform a concept design, a 1x1 mm² square section hinge is proposed. It is realized in SLM additive manufacturing considering the identified manufacturing parameters used in the characterization tests presented in the previous sections.
A deformation corresponding to a 90° deployment of the hinge is imposed to the part. The deformed state is presented in Figure 3 (a). In a second step, the demonstrator is heated to trigger the phase transformation. The activated state is presented in Figure 2 (b), corresponding to the initial state before deformation of the hinge.

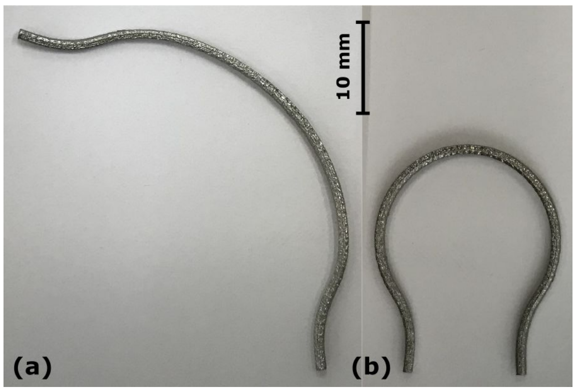

Figure 5. (a) Deformed state of the hinge before activation. (b) Activated state of the hinge after heating.

FUTUR WORK: ACTUATOR DESIGN

Applied to the design of space deployment actuators, several types of benefits can be obtained through additive manufacturing:

- Performance optimization
- Mass reduction
- Complex deployment dynamics
- Add functions: consider the SMA heater

The first type of component under development is a rotational deployment component for an actuator. Compared to the existing ones, the objective is to provide a torque and a degree of rotation defined while limiting the size of the actuator in length. The defined Specs are as follows:

- Maximum diameter: 60 mm
- Maximum length: 160 mm
- Minimum torque: 13 Nm
- Minimum rotation: 90°

CONCLUSION

The objective of this project is to develop NiTi by SLM additive manufacturing, called 4D printing. More specifically, the objective is to bring this technology from a TRL2 to a TRL4 at the end of the project.
The first step consisted in the development of NiTi by FA SLM by obtaining properties comparable to conventional NiTi, both in terms of martensitic transformation and in terms of mechanical properties.
The proof of concept being achieved, the current step is the design and dimensioning of innovative actuator concepts.

REFERENCES

[1] H. Meier, H., Haberland, C., Frenzel, J. & Zarnetta, R. (2009). Selective Laser Melting of NiTi shape memory components. *Innovative Developments in Design and Manufacturing.* 2010 Taylor & Francis Group, London, ISBN 978-0-415-87307-9.

[2] Wang, X. et al. (2020). Effect of process parameters on the phase transformation behavior and tensile properties of NiTi shape memory alloys fabricated by selective laser melting. *Addit. Manuf.* 36, 101545.