National Aeronautics and Space Administration

4D Printing of Shape Memory Alloys for Solid-State Staged Deployment of Structures

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Program: FY21 SURP **Strategic Focus Area: Additive Manufacturing, Multifunctional Systems**

Objectives

Design heat treatments for the controlled transformation response of additively manufactured shape memory alloys. Towards this goal:

1. Develop a physics-based model capable of predicting precipitation behavior in AM NiTi .
2. Verify the accuracy of the model through experimental work.
3. Use machine-learning on data generated by the model to predict the thermal history necessary to induce a desired precipitation response.
4. Design additive manufacturing processes capable of producing this target thermal history.

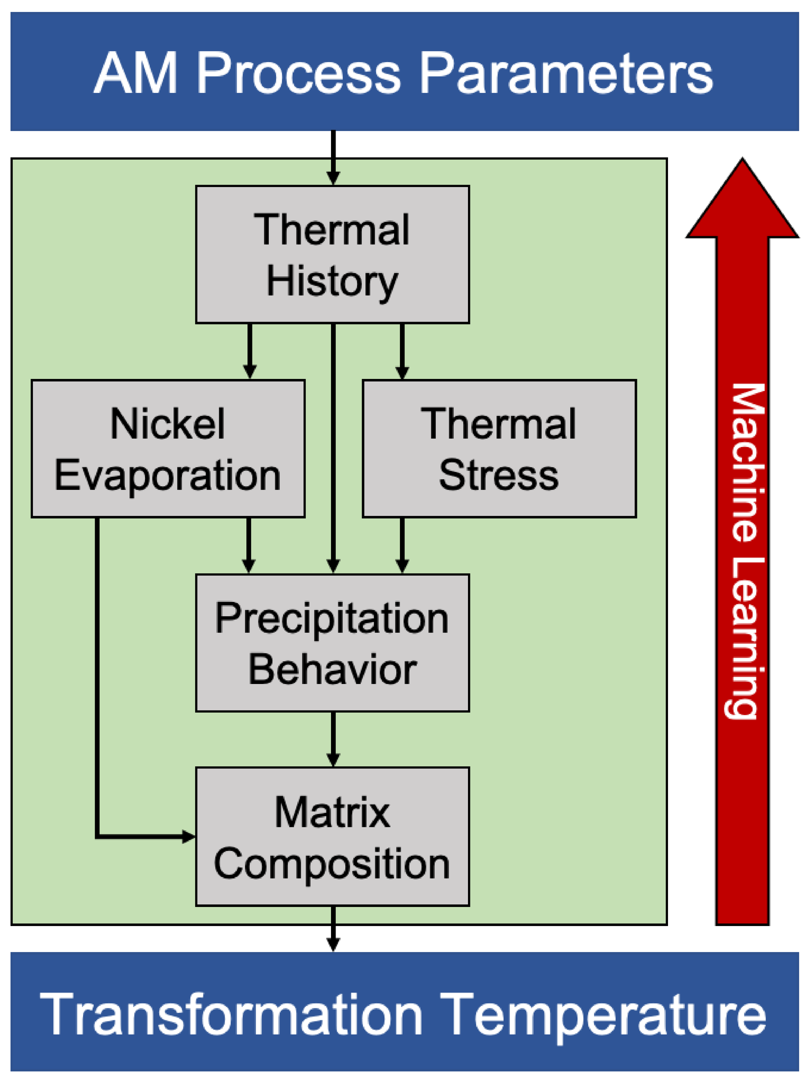

Figure 1: Target process description

Background

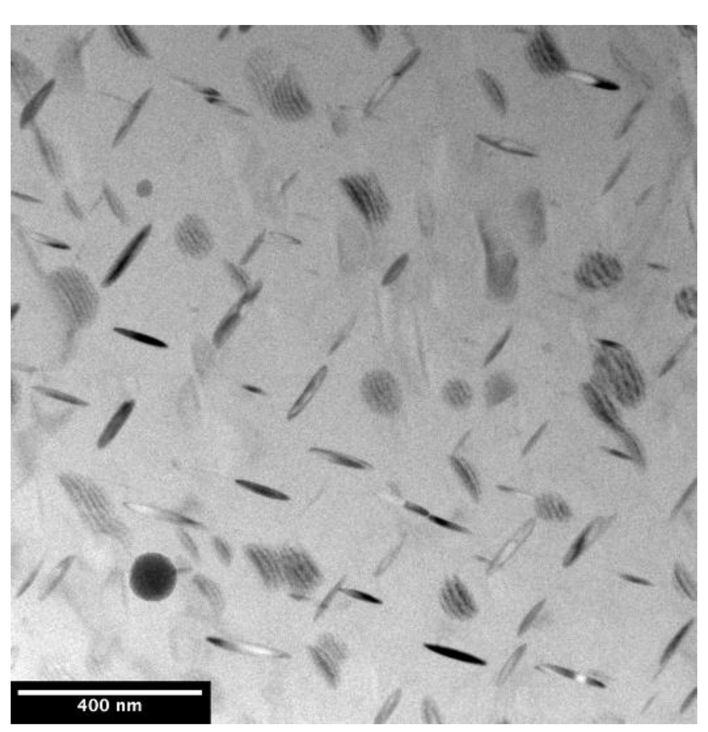

Figure 2: TEM of Ni_4Ti_3 Precipitates

The shape-memory behavior of NiTi is highly tunable via heat treatment due to the formation of nickel-rich precipitates. A depletion of 1% Ni in the matrix can increase the transformation temperature by as much as 160° C.

The numerous processing parameters of AM have opened the door to "4D-printed" functionally graded materials with location-specific heat treatments, precipitate structures, and transformation temperatures. Such a material would be able to execute complex 3D movements solely in response to thermal stimuli.

Fine control of transformation temperatures requires the development of a physics-based model able to predict the behavior of Ni_4Ti_3 precipitates under AM conditions.

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Approach and Results

Precipitation in near-equiatomic NiTi SMAs occurs via a complex process involving two metastable intermediates and an unusual highly-oriented relationship between the matrix and the precipitate.

The Kampmann-Wagner Numerical (KWN) model offers a flexible and computationally efficient means of abstracting decades of computational and experimental descriptions of these interconnected processes into a single model.

A Python implementation of the KWN model called Kawin was developed.

- The particle size distribution (PSD) is modelled using fixed size classes
- Nucleation is modelled according to Classical Nucleation Theory
- Fluxes between size classes are determined by the growth rate of the class
- Thermodynamic and kinetic calculations use JPL's PyCalphad software

The complexity of Ni_4Ti_3 precipitation has required additional behavior to be studied, characterized, and adapted for use within Kawin.

- Coherent precipitation of Ni_4Ti_3 introduces significant elastic strain into the matrix
  → A model for the elastic behavior of these precipitates has been developed
- Ni_4Ti_3 can only form and grow as disks along the {111} plane of the matrix.
  → Thermodynamic and kinetic correction factors have been calculated
- Nucleation behavior changes from homogenous to heterogenous within the composition range of interest.
  → A framework for heterogeneous nucleation and grain boundary effects has been created.
- Nucleation and growth is highly sensitive to applied stresses, which can resolve or exacerbate the strain introduced by the precipitate. The rapid thermal cycling of AM produces thermal strains that simulate this effect.
  → Accounted for through simulation of the additional energy of the stressed lattice and a model of aspect ratio as a function of stress.

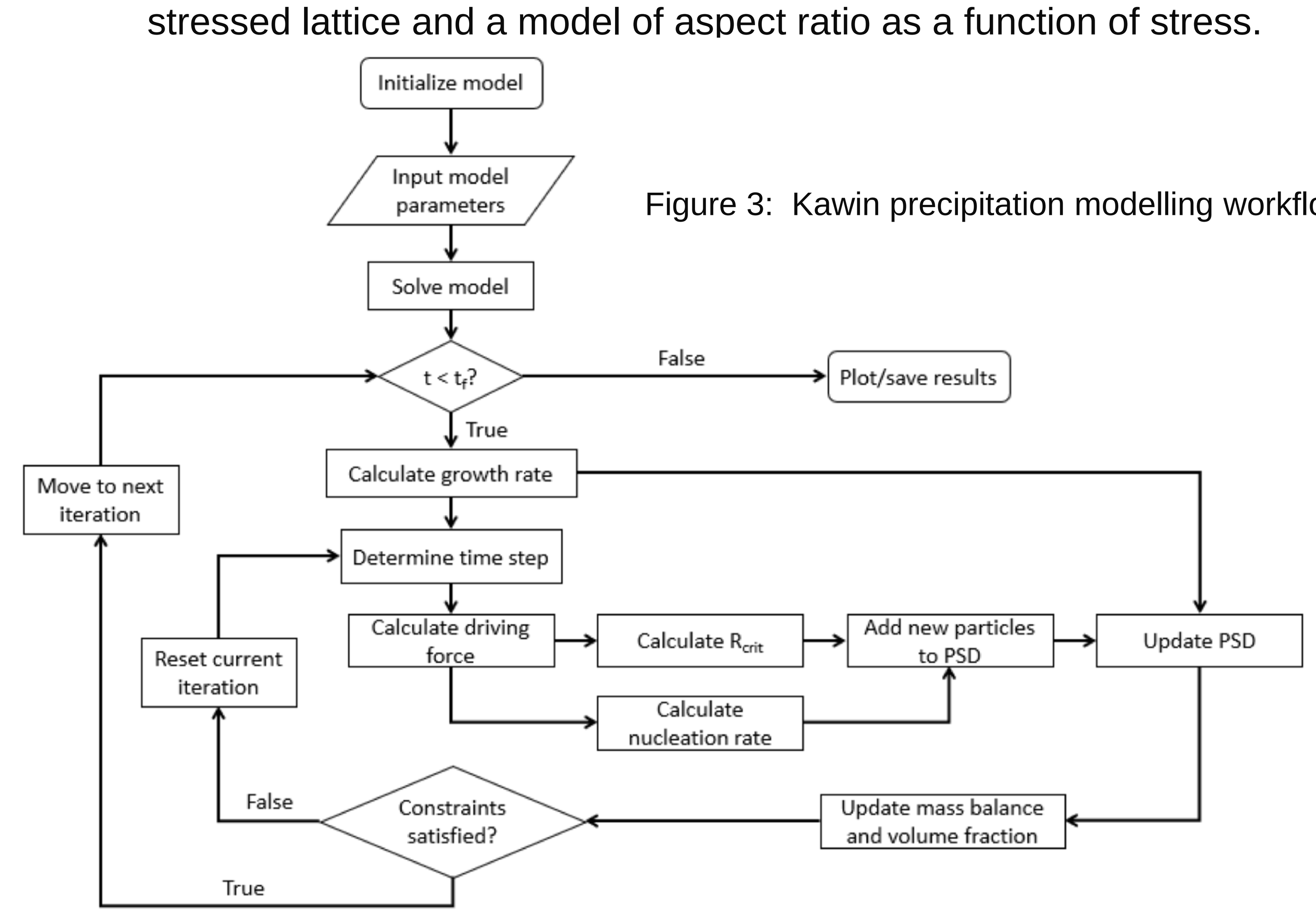

Figure 3: Kawin precipitation modelling workflow.

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Significance/Benefits to JPL and NASA

The development of finely controllable SMA based actuators will allow for a significant reduction in the mass and volume required for deployable structures such as solar panels and communications arrays.

NiTi based SMA actuators

- Have a work density as much as 25x that of electric motors
- Are capable of lifting up to 100x their weight.
- Can actuate in 3 dimensions and simultaneously bend, twist, and extend
- Possess minimal moving parts, mechanical complexity, or failure potential.

Origami-based mechanisms for deployable structures utilizing these properties of SMAs have already been designed.

- A key barrier to their implementation is the ability to more precisely control mechanical properties and transformation temperatures, which this project seeks to address.

While the overall goals of this project only required implementation of nucleation and growth models for the Ni-Ti system, the implementation of the KWN model was generalized to support arbitrary multi-component systems.

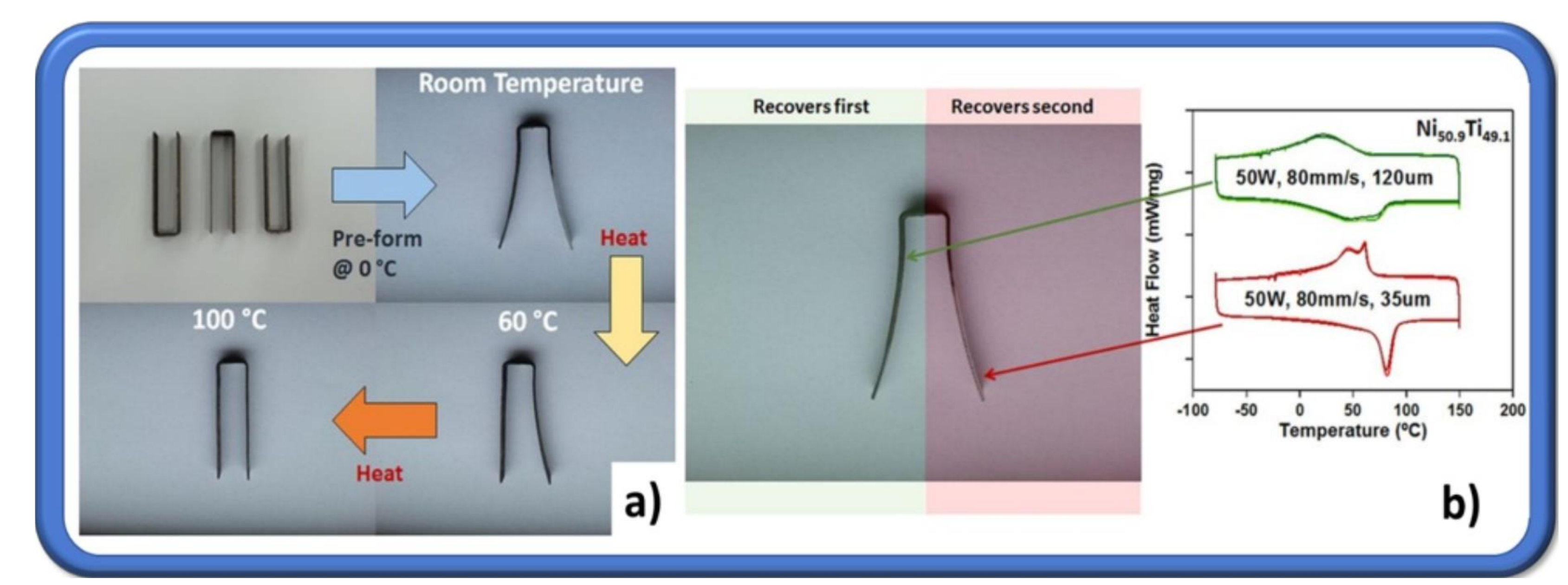

Figure 4: Example of location dependent shape-memory behavior

Publications

A New Technology Report (No. 52029) was generated for the creation of the Kawin software, and the software has been approved for release as open source.

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