National Aeronautics and Space Administration

FY23 Strategic University Research Partnership (SURP)

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

**Principal Investigator:** Richard Otis (357); **Co-Investigators:** Ryan Watkins (357), Christine Gebara (355), Raymundo Arroyave (Texas A&M University), Ibrahim Karaman (Texas A&M University)

## Objectives:

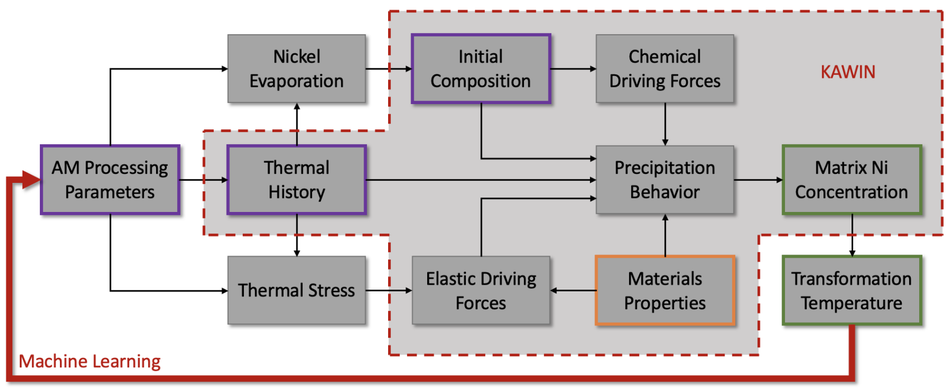



*Figure 1: Process map of the end-goal project workflow.*

1. Develop a physics-based model capable of predicting precipitation behavior in additively manufactured NiTi shape-memory alloys .

2. Use machine-learning on data generated by the model to predict the thermal history necessary to induce a desired precipitation response.

3. Design additive manufacturing processes capable of producing this target thermal history, allowing for NiTi parts with tailored transformation temperatures.

## Background:

The shape-memory behavior of NiTi is extremely sensitive to matrix Ni concentration. Heat treatment of NiTi can result in the formation of Ni-rich $Ni_4Ti_3$ precipitates.

AM processes can be designed to selectively induce precipitation and locally control transformation temperature

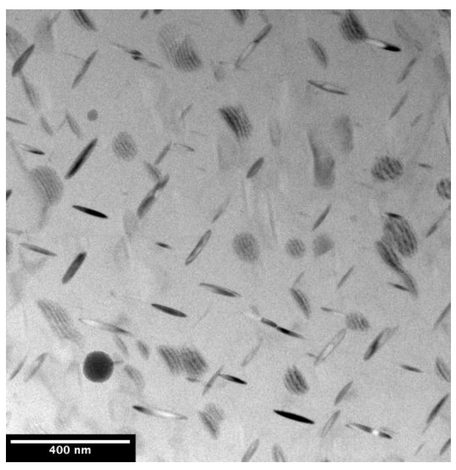



*Figure 2: Micrograph of $Ni_4Ti_3$ precipitates in $Ni_{50.8}Ti_{49.2}$*

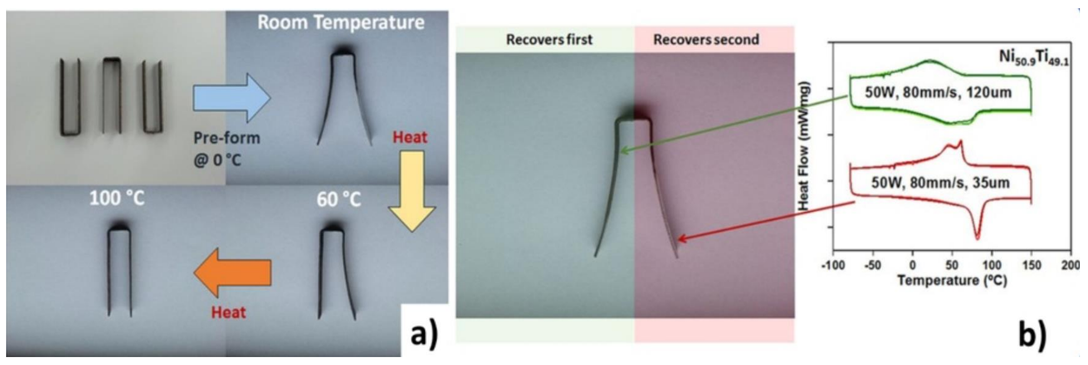



*Figure 3: Example of location-dependent transformation temperatures.*

## Approach and Results:

- Kawin, an open-source implementation of the KWN algorithm for precipitation modelling, has been developed and released.
- Kawin has been calibrated against experimental data to be able to reproduce the precipitation behavior of Ni4Ti3 in near-equiatomic NiTi SMA's.
- This has been coupled with models for differential evaporation and thermal history to model the impact of all factors controlling the transformation temperature of NiTi SMA's.
- Bayesian Optimization has been used in conjunction with this model to design composition/heat treatment combinations that produce a target transformation temperature.

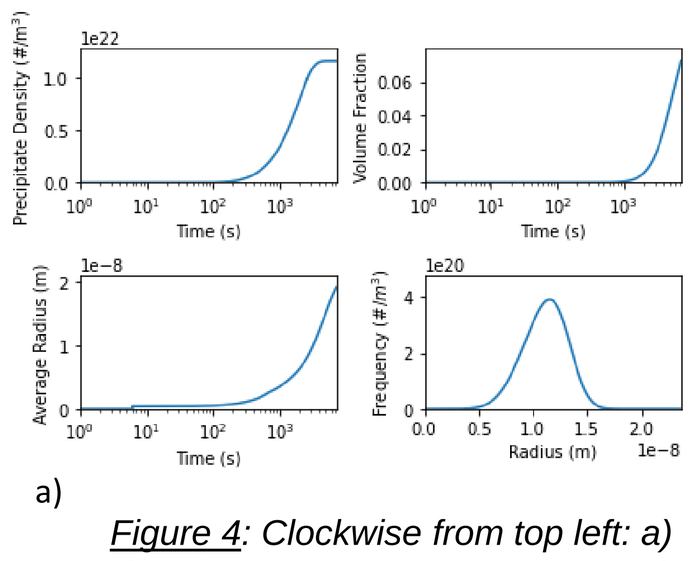
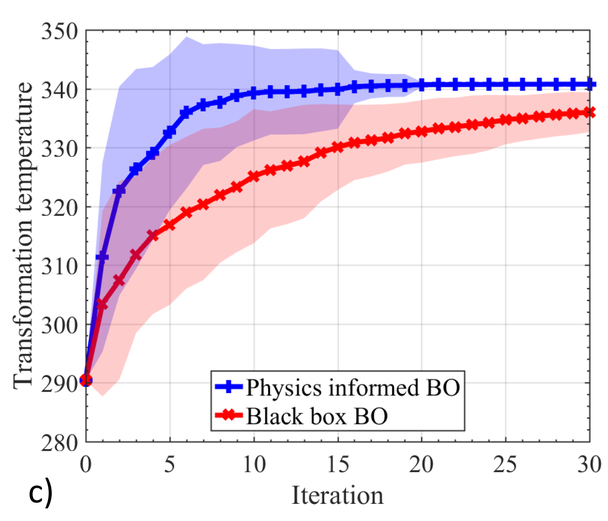



*Figure 4: Clockwise from top left: a) Simulated precipitation behavior of Ni4Ti3 for an isothermal heat treatment. b) Slice of a simulated thermal history produced during single-track 3D-printing of NiTi. Each point on this grid would has an associated precipitation simulation. c) Comparison of Physics-Informed Bayesian Optimization, showing the precipitation physics-aware kernels converged to a better solution more quickly than the black box BO model.*




## Significance/Benefits to JPL and NASA:

NiTi based SMA actuators can lift up to 100x their weight, simultaneously actuate in all 3 dimensions, and have little mechanical complexity or failure potential. 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.

**National Aeronautics and Space Administration**

**Jet Propulsion Laboratory**
California Institute of Technology
Pasadena, California

**www.nasa.gov**

Clearance Number: CL#23-5235
Poster Number: RPC#001


## Publications:

Nicholas Ury, Raymond Neuberger, Noah Sargent, Wei Xiong, Raymundo Arróyave, Richard Otis, "Kawin: An open source Kampmann–Wagner Numerical (KWN) phase precipitation and coarsening model," Acta Materialia, Volume 255, 2023.

## PI/Task Mgr. Contact Information:

Email: Richard.Otis@jpl.nasa.gov