Cold Spray Additive Manufacturing with Shape Memory Alloys for NASA Aerospace Applications

Eva Piazza, Matthew Gleason, Kiran Judd, Ashton Lyon, Danielle Cote
Worcester Polytechnic Institute (WPI), Worcester, MA

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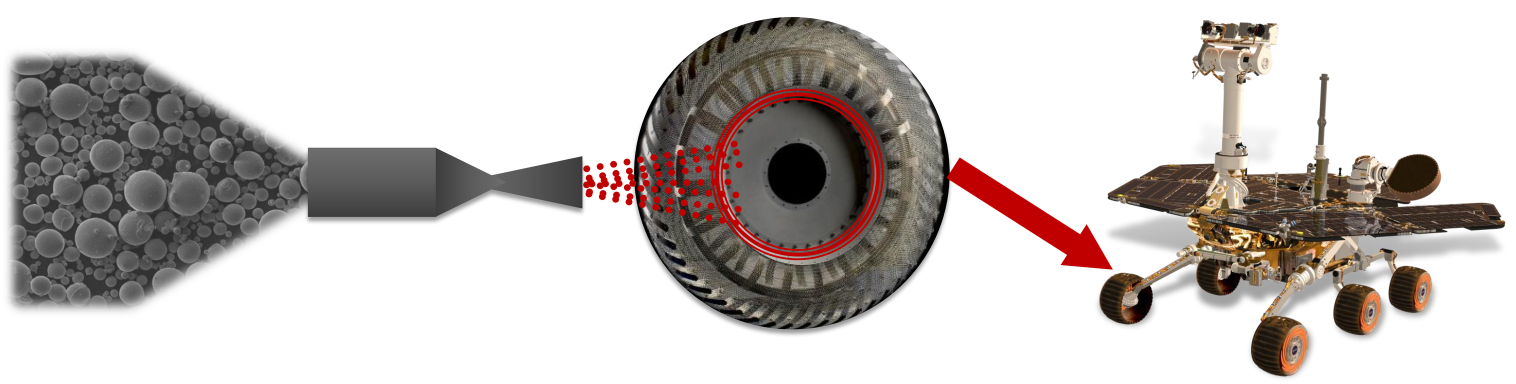
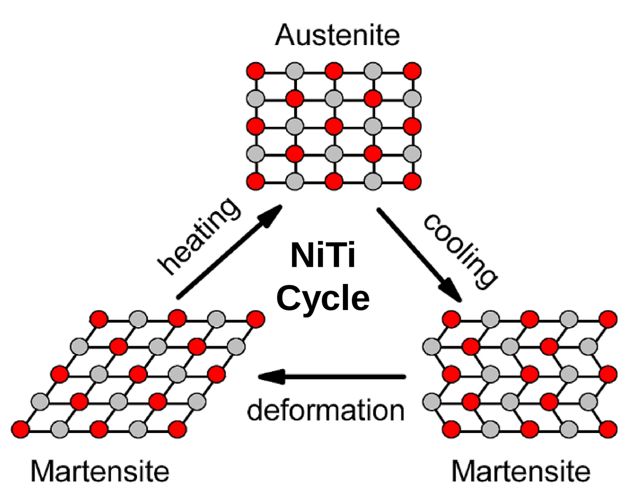
MOTIVATION

Problem: Shape Memory Alloys (SMA) have valuable, unique properties but are difficult to join with traditional methods.



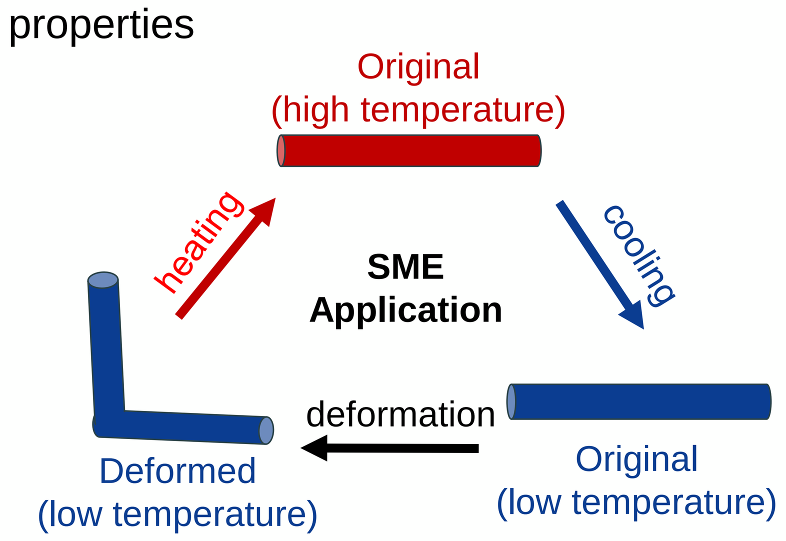
Shape Memory Alloys (SMA) are metal alloys with ability to ***change shape based on stimuli*** such as temperature, voltage, stress, magnetism, etc. Current uses of SMA include *biomedical devices, consumer goods, actuators, and aerospace parts*. SMAs are ***used in Mars Rover wheels, deployment mechanisms***, and has future use in ***self-healing shelters on Mars***. However, SMA are sensitive to traditional manufacturing processes and can ***lose valuable properties at high processing temperatures.***

BACKGROUND: Shape Memory Alloys (SMA)



Pseudoplastic NiTi	Pseudoelastic NiTi
54.7 wt% Ni	55.3 wt% Ni
Martensitic	Austenitic
SMA	Superelastic

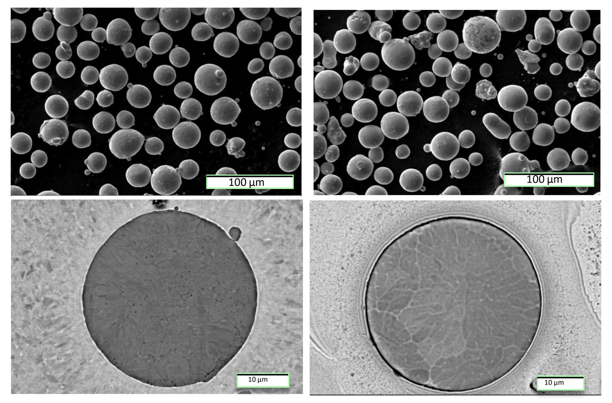
Nitinol (NiTi)
- Binary composition of nickel and titanium
- Austenitic to martensitic transformation allows for superelastic/pseudoelastic properties



METHODS

Two types of NiTi powders were obtained from Fort Wayne Metals – NiTi 5 (pseudoplastic/SMA) and NiTi 9 (pseudoelastic/superelastic). These powders were **characterized for mechanical and chemical properties** to determine feasibility in cold spray applications. Additionally, **non-SMA powders, Al 6061, 316 Stainless Steel, CP Ti, and Ti-6Al-4V** were selected for application in aerospace structures and subsequently characterized prior to spraying.

Powder Morphology Characterization	Mechanical/ Chemical Characterization
Particle Size Distribution	Differential Scanning Calorimetry
Sphericity/Uniformity	Particle Compression
Flowability	Nanohardness
External structural features	Chemical composition



(Top Row) SEM images of loose NiTi 5 powder (left) and NiTi 9 powder (right). (Bottom Row) SEM sectioned and polished NiTi 5 powder (left) and NiTi 9 powder (right).

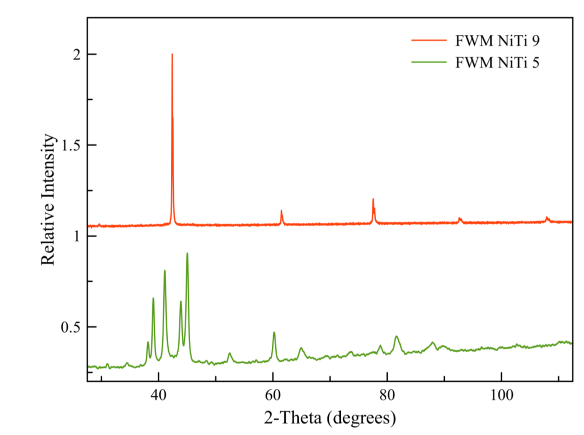
RESULTS: NiTi Powder Characterization

Goal: Determine efficacy of using cold spray to join NiTi powder to various substrates while retaining Shape Memory Effect.

Powder Type	M_f	M_p	M_s	A_s	A_p	A_f
NiTi 9	-80.25	-44.41	10.83	-82.98	5.44	**37.25**
NiTi 5	5.82	35.66	81.88	44.08	69.07	**109.43**

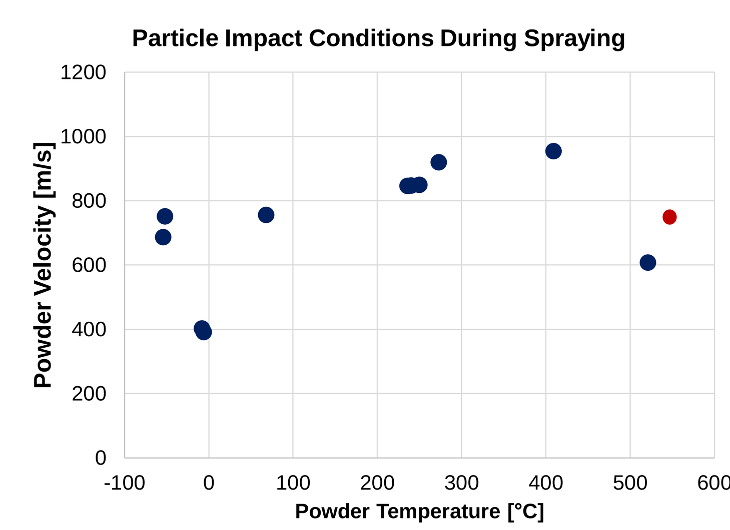
Transition temperatures of NiTi define behavior and application; temperatures determined through Differential Scanning Calorimetry.

Powder Characterization Summary
- High sphericity; high powder flow rates
- Internal microstructures and phases similar to traditionally wrought NiTi
- Transition temperatures consistent with chemical composition
- Nanoindentation and particle compression are difficult to compare, as models based on non-SMA plasticity



XRD of NiTi 5 vs NiTi 9 powder, showing austenitic peaks in NiTi 9 and primarily martensitic peaks in NiTi 5.

RESULTS: Model-Guided NiTi to NiTi Joining



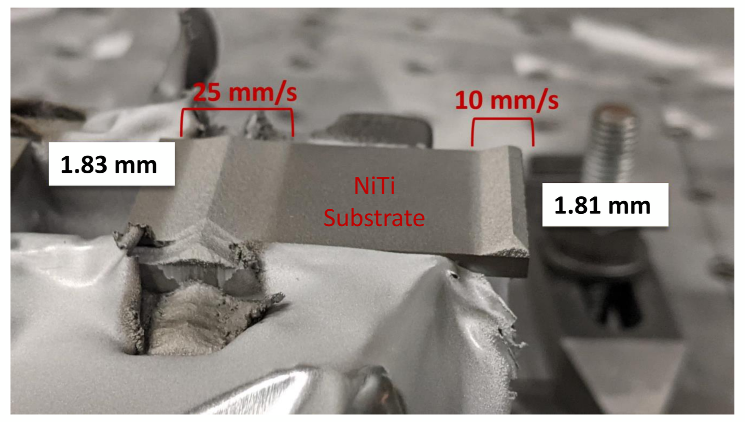
Modeling with Kinetic Spray Solutions
Traditional methods of parameter variation were not effective as NiTi behaves differently from non-SMA powders
- KSS was used to model *particle velocity (m/s)* against *particle temperature (°C)* using cold spray parameters
- Targeted higher temperatures right around M_d (**Martensitic deformation temperature**; above which NiTi will behave plastically rather than superelastically)

Raster Speed Effects

Raster Speed	10 Mm/s	25 mm/s	50 mm/s	100 mm/s	200 mm/s	500 mm/s
Number of Passes	**20**	**40**	**40**	**80**	**150**	**400**
Deposition Thickness (mm)	**1.81**	**1.83**	**0.83**	**0.96**	**0.56**	**1.34**

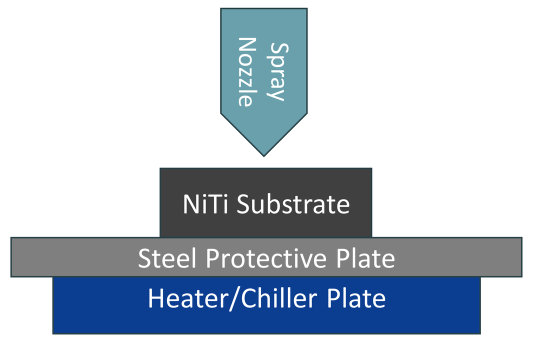
Constant Parameters

Gas Type	Gas Temperature (°C)	Gas Pressure (psi)	Powder Feeder Rate (rpm)
N_2	700	900	6



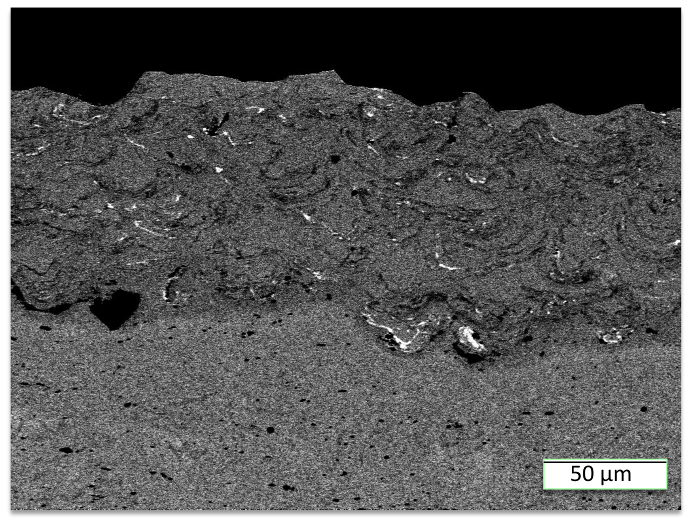
Deposition of SMA NiTi powder on SMA NiTi using slower raster speeds of 25 mm/s and 10 mm/s.

FUTURE WORK: NiTi to NiTi Joining



Hot Plate Heating Substrate
- Higher temperature substrate above M_d temperature to remove any superelasticity

Chiller Plate Cooling Substrate
- Keep SMA substrate in martensitic phase and reduce thermal buildup during spray



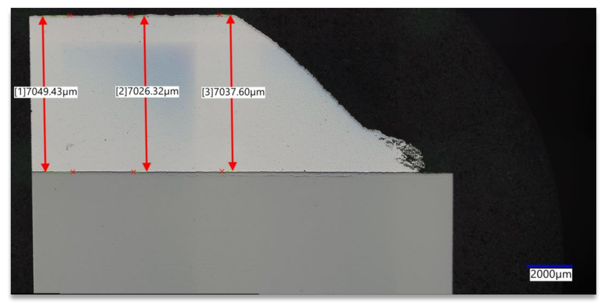
Initial deposit of SMA NiTi onto SMA NiTi using a hot plate to hold substrate at roughly 400 °C during spraying.

RESULTS: Non-SMA to NiTi Joining

Goal: Optimize Non-SMA powder deposits onto SMA NiTi for use as structural aerospace components.

Powder Type	Gas Type	Gas Temperature (°C)	Gas Pressure (psi)	Deposition Thickness (mm)
Al 6061	**He**	**450**	**580**	**3.96**
Ti64	He	480	580	1.37
Cp Ti	He	475	580	1.82
316 SS	N_2	650	900	2.41

Non-SMA Powders on SMA NiTi
- Deposited on as-received SMA NiTi substrates
- Easily deposited onto NiTi substrates with coatings comparable to non-SMA substrates



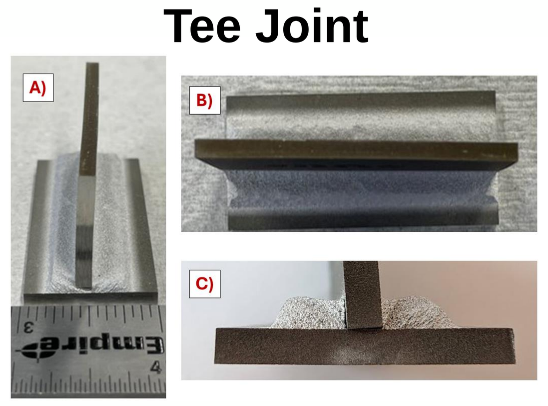
Cross sectioned deposit of Al 6061 deposited onto pseudoelastic NiTi substrate shows consistent, non-porous coating.

Lug shear sample of Al 6061 deposited onto SMA NiTi substrate.

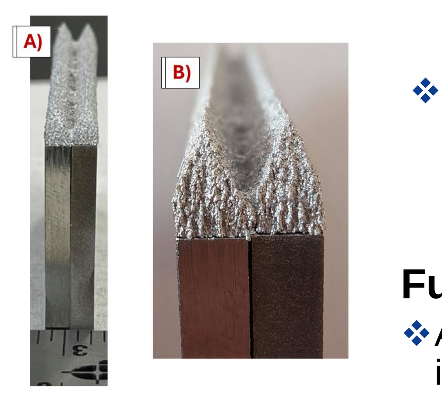
Lug Shear Testing
- Al 6061 selected for further joining based on application and deposition quality
- Al 6061 deposits formed on SMA NiTi substrates large enough for lug shear testing

RESULTS: Non-SMA Joint Creation

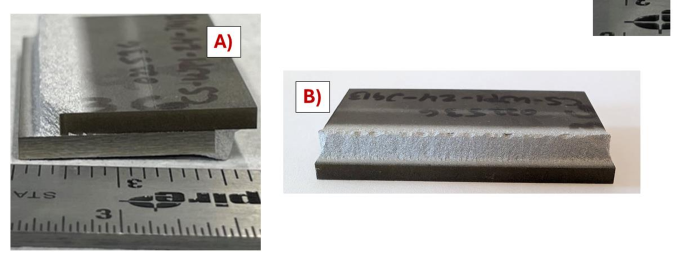
Tee Joint



Edge Joint



Lap Joint



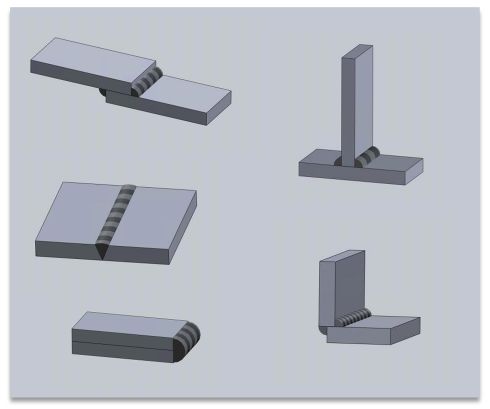
Tee, edge, and lap joints were successfully created with Al 6061 powder and SMA NiTi substrates.

Al 6061 on SMA NiTi Substrates
- Al 6061 powder used to "weld" SMA NiTi substrates together
- Joint geometries prioritized based on application purposes

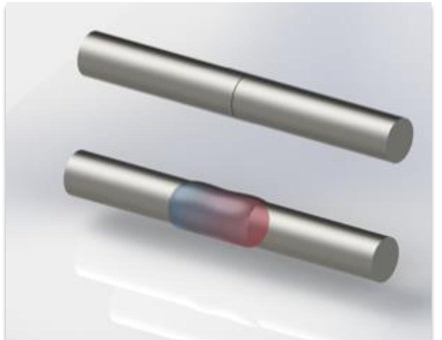
Future Improvements
- Al 6061 deposits onto SMA NiTi inform spray optimized spray parameters
- Joint mounts will hold NiTi substrates in specific configurations during sprays
- Strength tests will be performed to compare CSAM joints to traditionally welded joints

FUTURE WORK: Complex Geometries

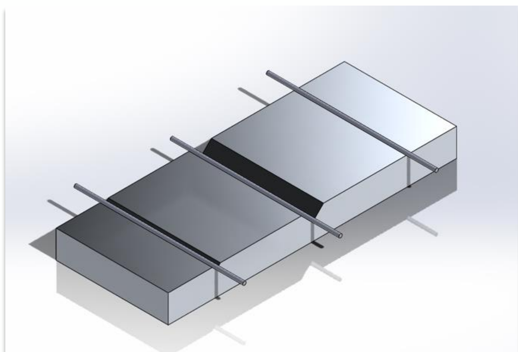
With the **success of joint creation with non-SMA powders to SMA NiTi substrates**, more complicated geometries with direct aerospace applications can be created.



More joints can be created such as dovetail and corner joints.



SMA NiTi tubes can be joined with 316 SS powder for gradient actuators.



SMA NiTi wires can be "welded" to Al 6061 frames to test feasibility for Mars Rover wheel frames.