Project 17: Development of Advanced Nickel-Titanium-Hafnium Alloys for Tribology Applications

Spring 2018 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
April 11-12, 2018

Student: Sean Mills (CSM)
Faculty: Prof. Aaron P. Stebner (CSM)
Industrial Mentor: Dr. Christopher Dellacorte (NASA GRC)
Industrial Mentor: Dr. Ronald D. Noebe (NASA GRC)

Project 17: Characterization of Microstructure Evolution in Nickel-Titanium-Hafnium Intermetallics

- Student: Sean Mills (Mines)
- Advisor(s): Aaron Stebner (Mines)

Project Duration

PhD: August 2015 to August 2019

Problem: Ni-Ti alloys experience high residual stress due to rapid quenching processes. The result is cracking and machining distortion. Not quenching leads to low hardness.

Objective: Elucidate the effect of Hf ternary alloying on metallurgy and bearing element performances.

Benefit: Hf-alloying could lead to reduction in residual stress by eliminating the need for rapid cooling while retaining high strength and hardness levels of quenched binary Ni-Ti.

Recent Progress

- Rolling contact fatigue (RCF) tests on $Ni_{54}Ti_{45}Hf_1$ and $Ni_{54}Ti_{43}Hf_3$ alloy specimens
- TEM characterization of microstructure evolution in 56at.% Ni alloys
- Continued Time/Temperature/Transformation (TTT) research

Metrics

Description	% Complete	Status
1. Residual stress and hardness testing on $Ni_{55}Ti_{45}$ & $Ni_{54}Ti_{45}Hf_1$ (NASA)	80%	●
2. Literature review	80%	●
3. Rolling contact fatigue characterization of $Ni_{54}Ti_{45}Hf_1$ alloy	70%	●
4. Time/Temperature/Transformation of $Ni_{54}Ti_{45}Hf_1$ alloy	30%	●
5. Alloy optimization – vary nickel and hafnium contents by 1-8 at%	20%	●

Industrial Relevance

Nitinol shape-memory alloy with added hafnium resists both wear and corrosion

January 09, 2016

Source: ASM International

Puris LLC, Bruceton Mills, W. Va., recently signed a limited (partially) exclusive, term license agreement with NASA Glenn Research Center to produce a high-performance, hafnium-enhanced shape-memory powder metallurgy alloy that provides resistance to both wear and corrosion.

Marketed under the brand name SM-103, the 60NiTi(Hf) alloy demonstrates a lower residual stress than other 60 nitinol alloys, resulting in improved response to heat treatment and easier processing. It delivers resistance to both wear and corrosion, traditionally considered to be mutually exclusive, in addition to favorable load-bearing properties. These attributes make it well suited to industrial bearings and precision bearing applications.

<www.asminternational.org/web/smst/news/industry/results/-/journal_content/56/10180/26098479/NEWS>

C. DellaCorte, M. K. Stanford, R. A. Manco, and F. Thomas, "Design Considerations for Resilient Rolling Element Bearings Made From Low Modulus Superelastic Materials," in *ASME/STLE 2011 International Joint Tribology Conference*, 2011, pp. 223–224.

Overview

Introduction

Why do we want to optimize Ni-Ti-Hf for space age bearings?

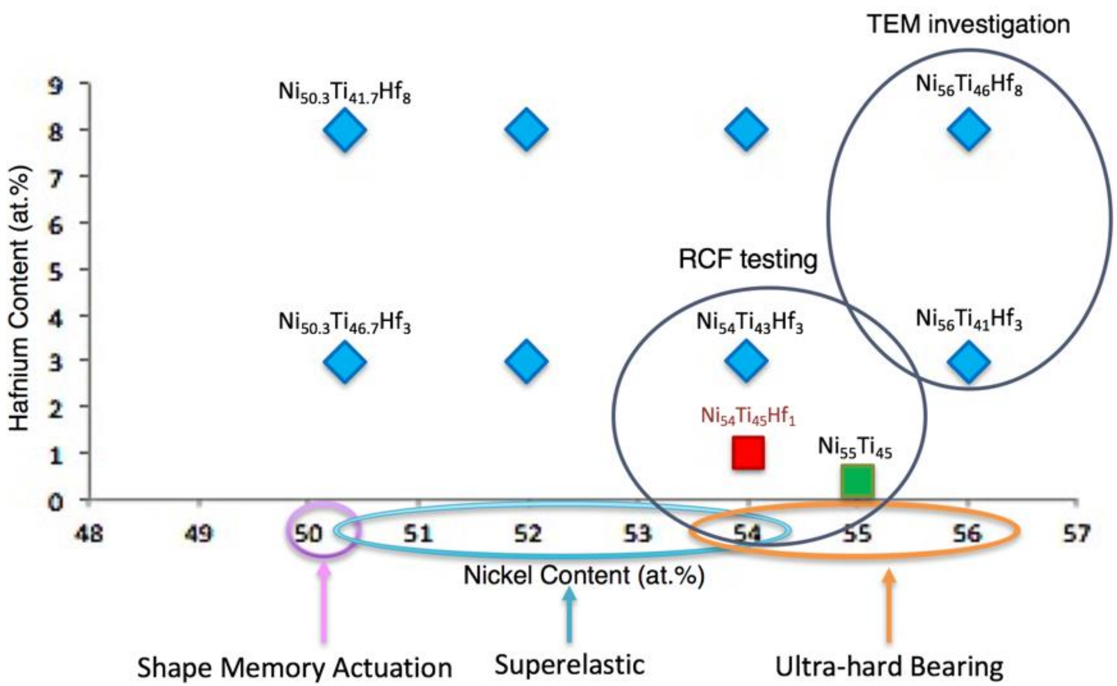
Results

Rolling contact fatigue (RCF) testing

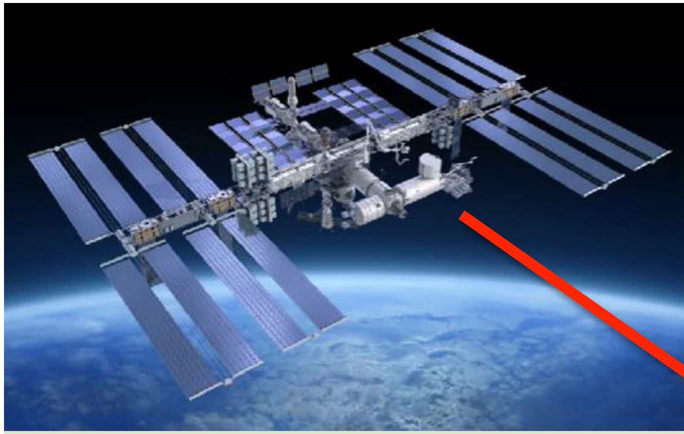
TEM microstructure analysis

Conclusions

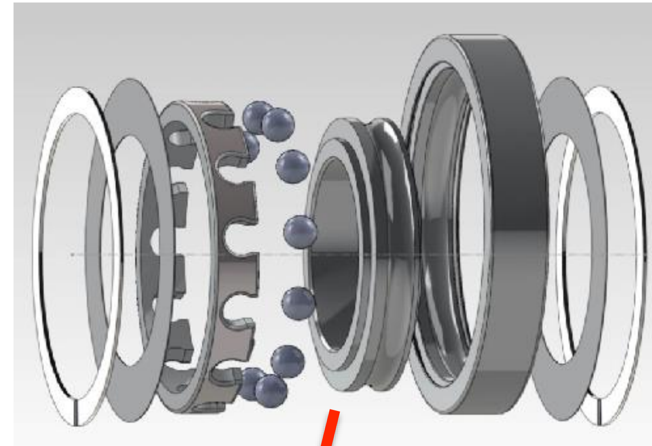
Optimized microstructure for best tribology properties.



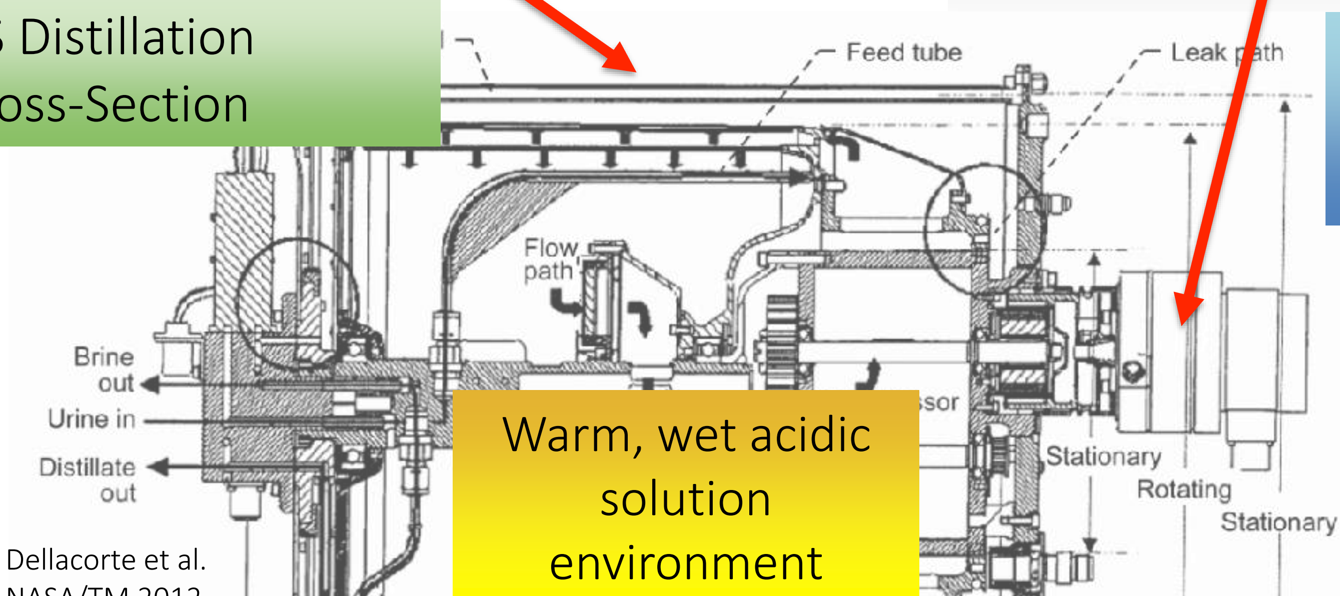
Application: Water recycling system on International Space Station



ISS Distillation Cross-Section



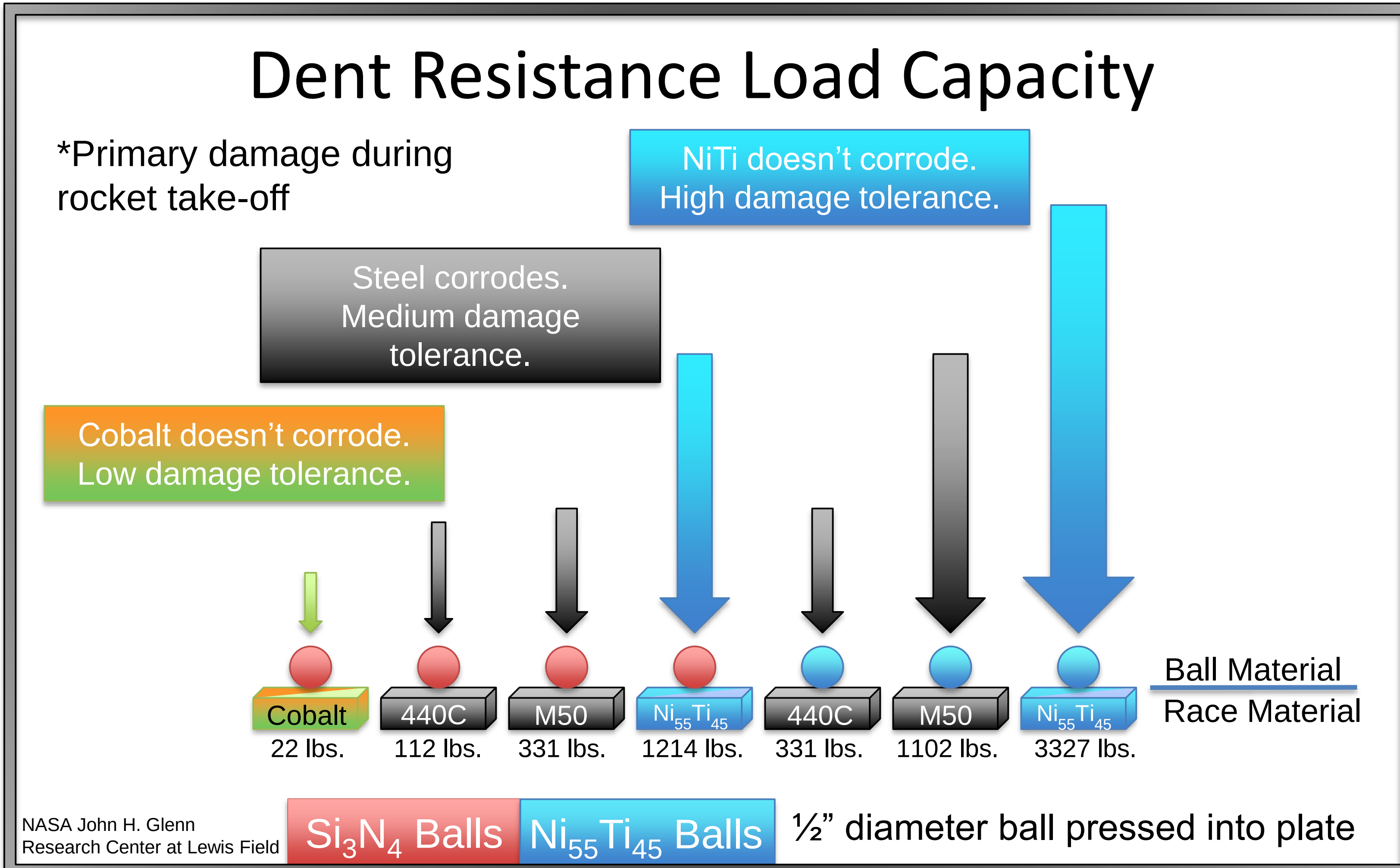
Rotating Centrifuge Bearing



Warm, wet acidic solution environment

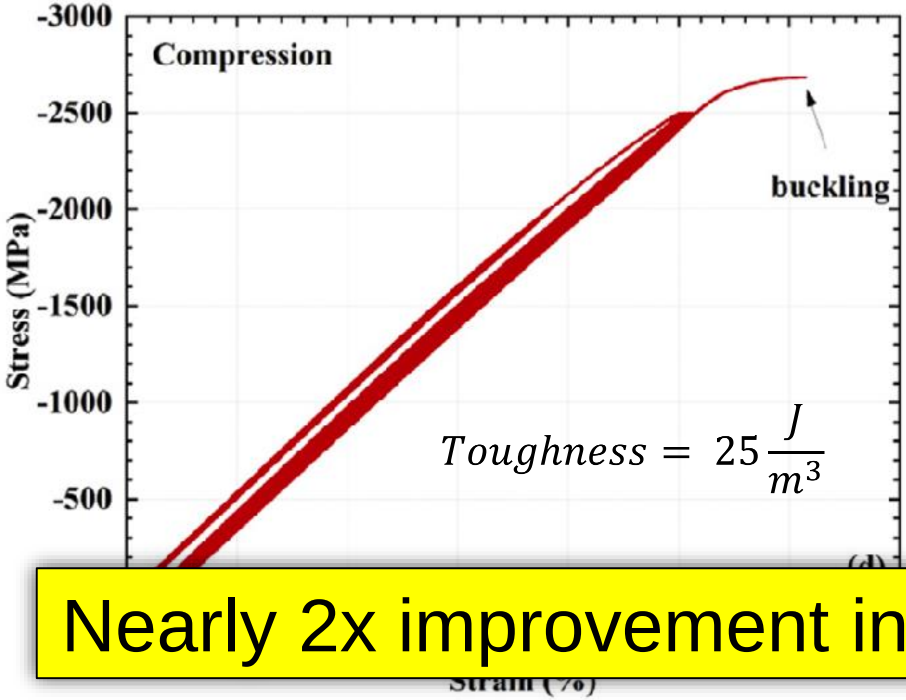
Dellacorte et al. NASA/TM 2012

Nickel-rich Ni-Ti alloys show superior damage resistance



Ni-Ti-Hf alloys show higher toughness exhibit large superelasticity

55at% NiTi in compression

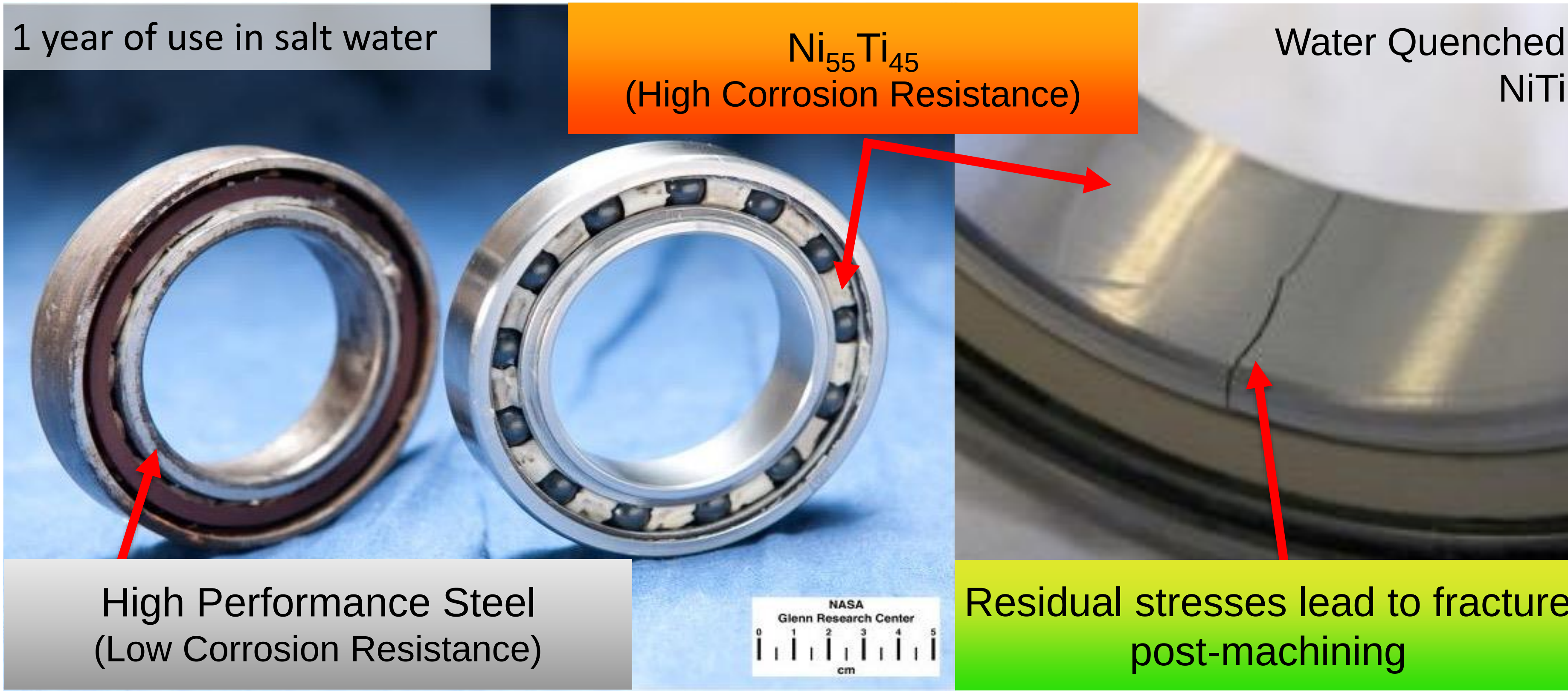


Nearly 2x improvement in damage impact resistance!

Benafan et al. Intermetallics 2017

Casalena et al. Advanced Engineering Materials 2017

Ni-Ti has better corrosion resistance than steel, but susceptible to untimely failures



Small Hf substitution can lower solvus temp
➔ reduction of residual stress

Hf atoms substitute Ti atoms
➔ slow kinetics while retaining hardness!

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
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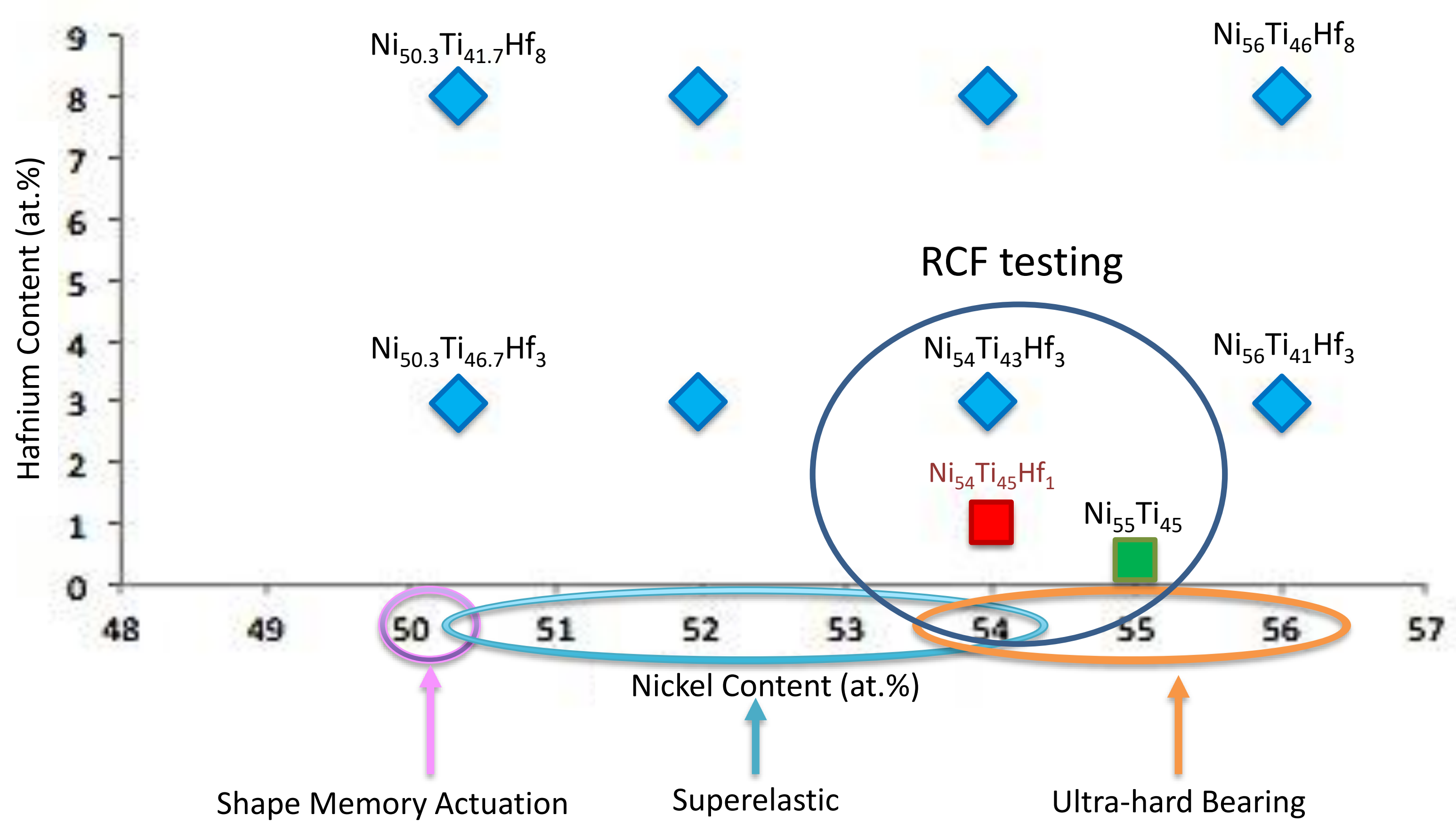
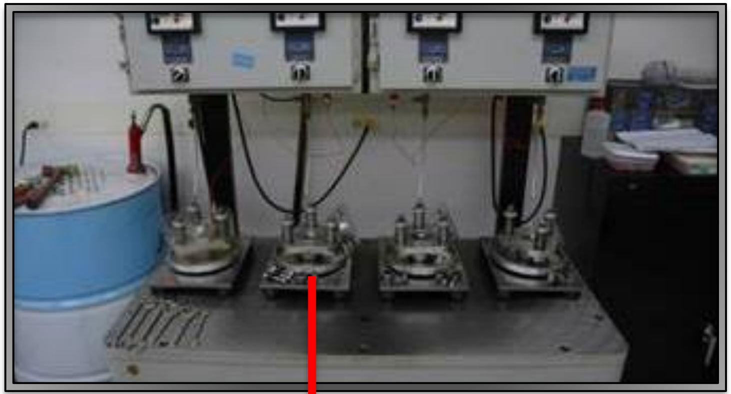
Optimized design space of Ni-Ti-Hf alloys

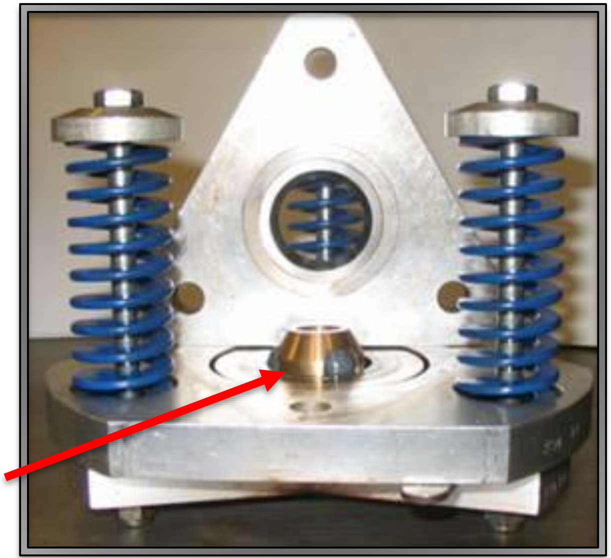


Rolling contact fatigue testing of $Ni_{55}Ti_{45}$, $Ni_{54}Ti_{45}Hf_1$ and $Ni_{54}Ti_{43}Hf_3$

Test rig

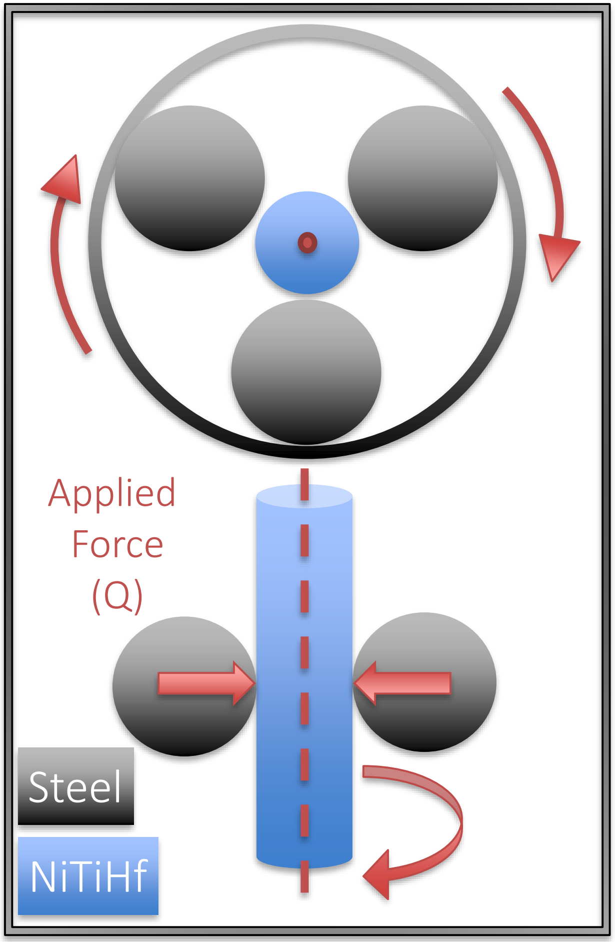


Spring loaded test head



Ball bearing retainer

Three ball-on-rod RCF test configuration



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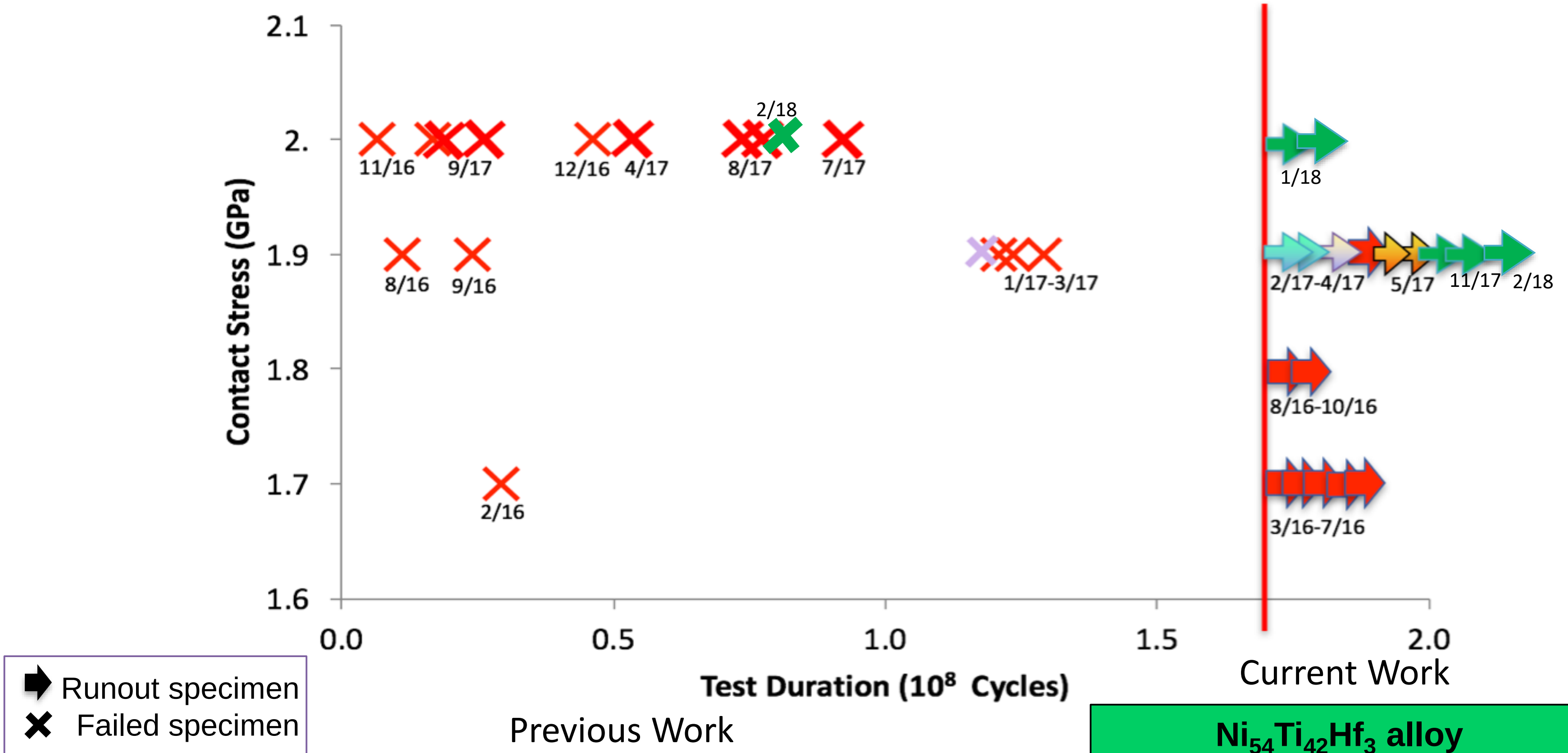
RCF Tests: Composition and secondary processing → better performance



$Ni_{54}Ti_{45}Hf_1$ 1000ºC$_{AC}$+400ºC Age
Failures ranging from $10^7 – 10^8$ cycles at 2.0 GPa

$Ni_{54}Ti_{45}Hf_1$ 900ºC$_{WQ}$+400ºC Age
2 run outs at 1.9 GPa

$Ni_{55}Ti_{45}$ 900ºC$_{WQ}$+400ºC Age
2 runouts at 1.9 GPa

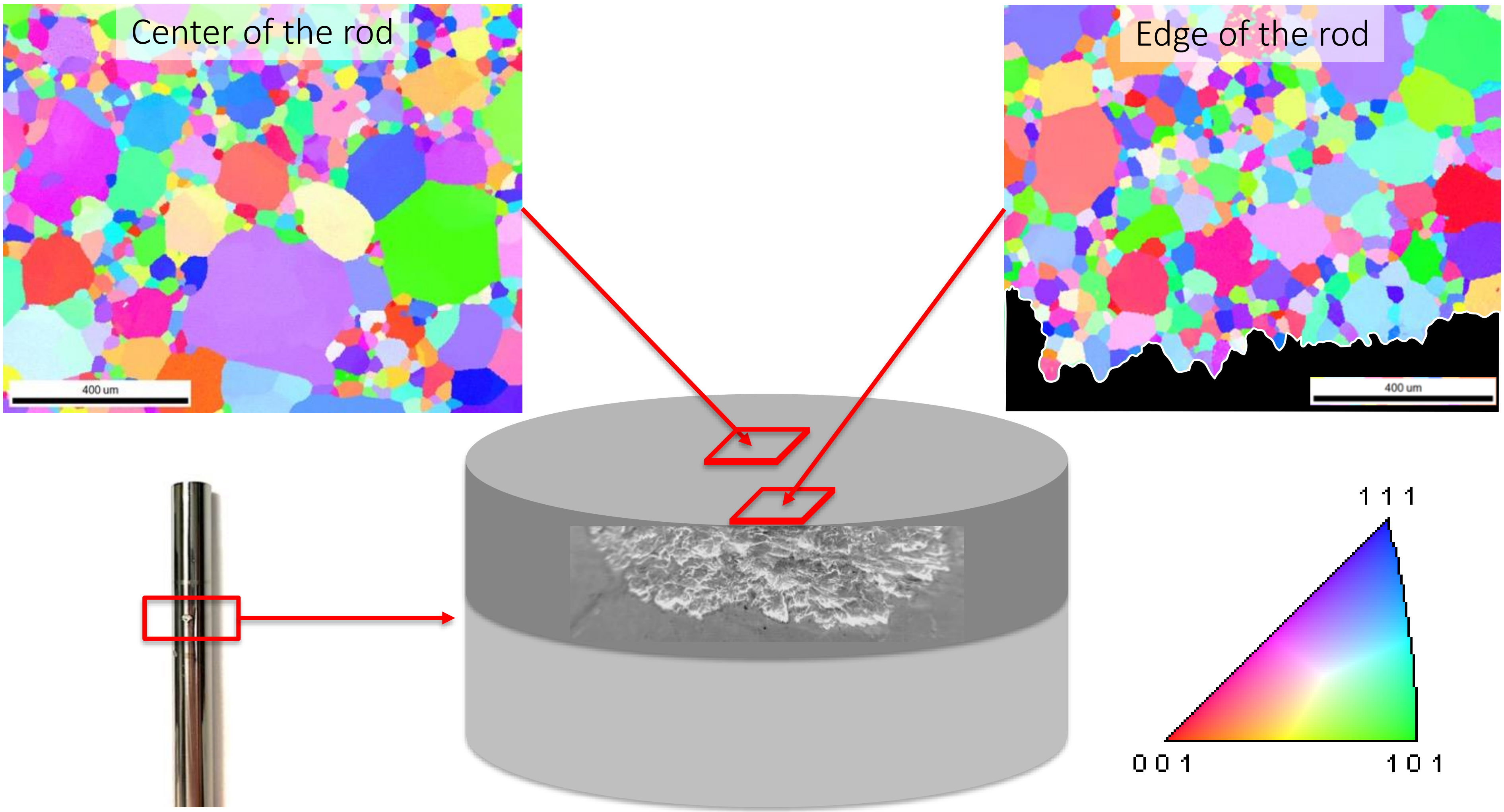
$Ni_{54}Ti_{45}Hf_1$ 900ºC$_{AC}$+400ºC Age
1 runout and 1 failed prior to 800hrs runout time at 1.9 GPa

$Ni_{54}Ti_{42}Hf_3$ alloy
1000ºC$_{WQ}$+ 300ºC(12hrs)$_{AC}$
3 runouts at 1.9GPa
2 runouts at 2.0GPa
1 failed specimen at 2.0GPa

Grain refinement shows no significant reduction of grain size at edge of spall

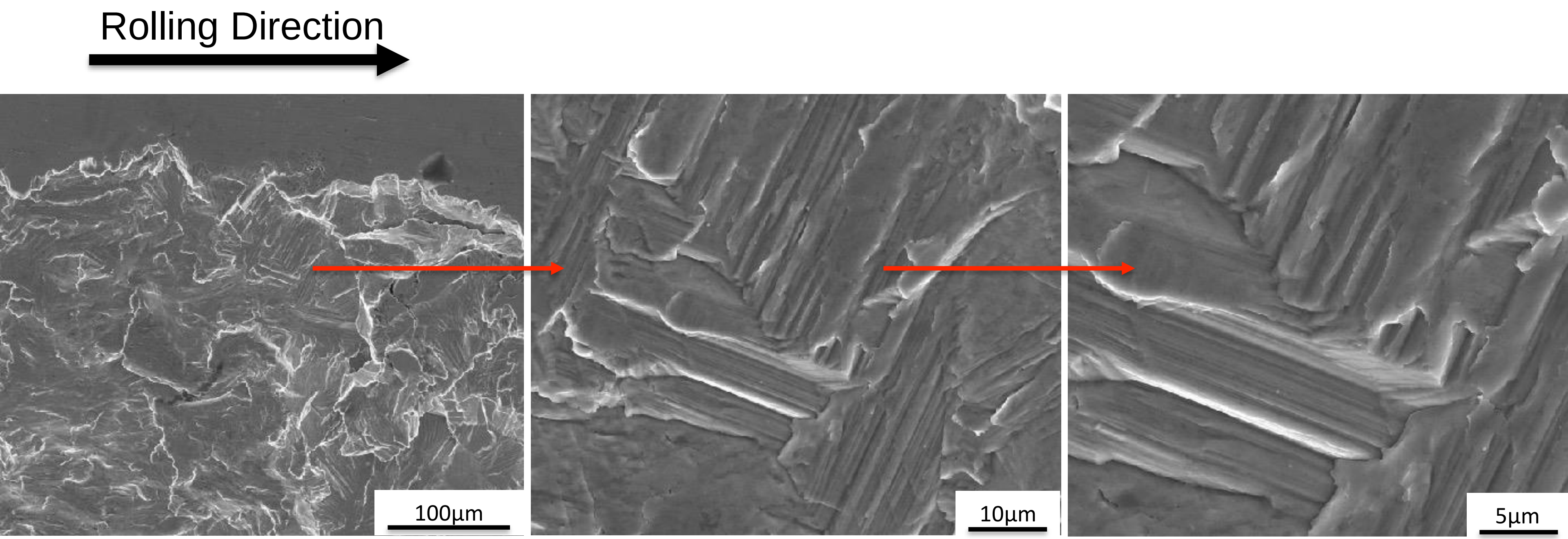
Used Ni-Ti-Hf test rod

Grain refinement shows no significant reduction of grain size at edge of spall

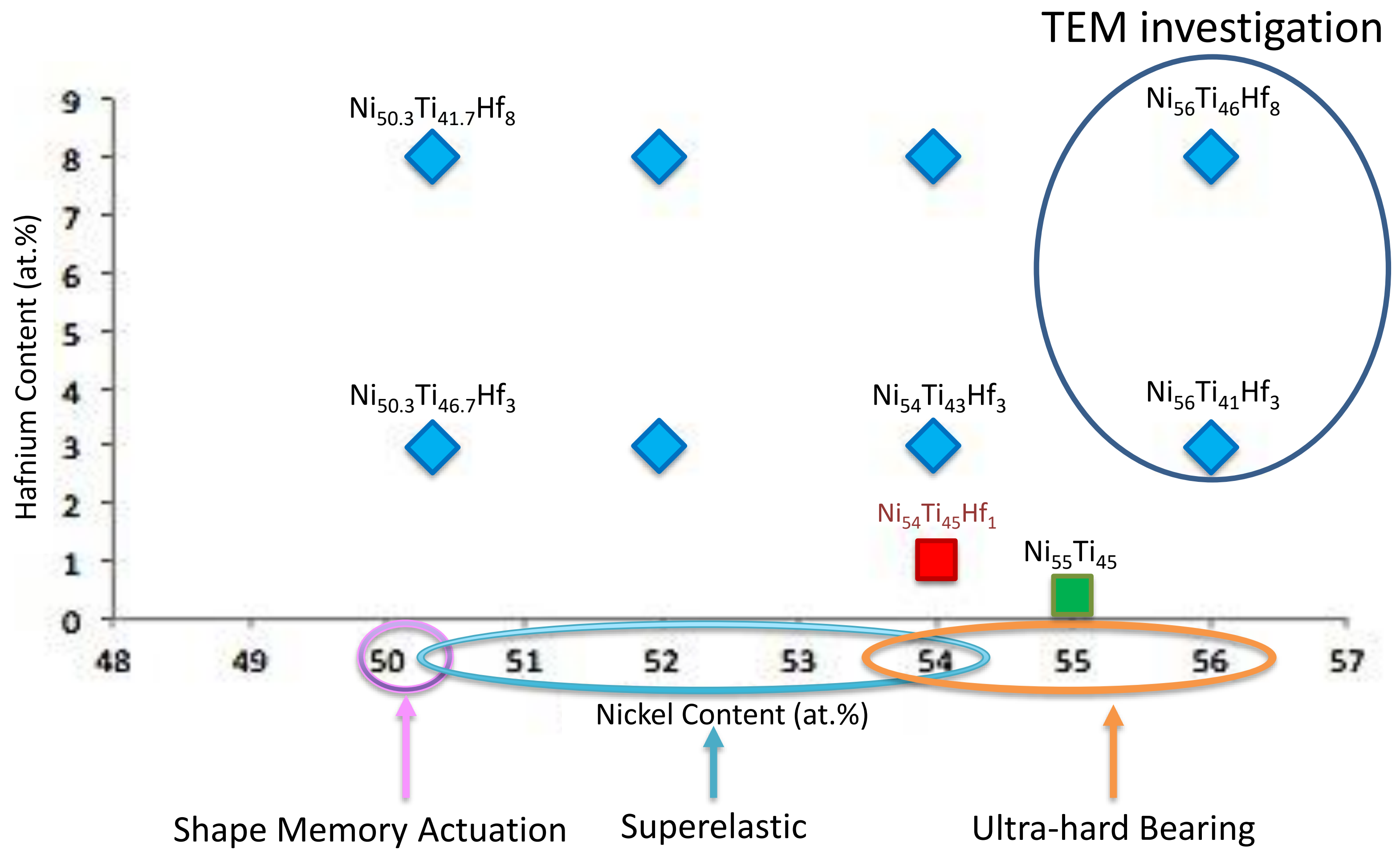


B. Aminahmadi, unpublished

Fast fracture facets on edge of spall



Optimized design space of Ni-Ti-Hf alloys



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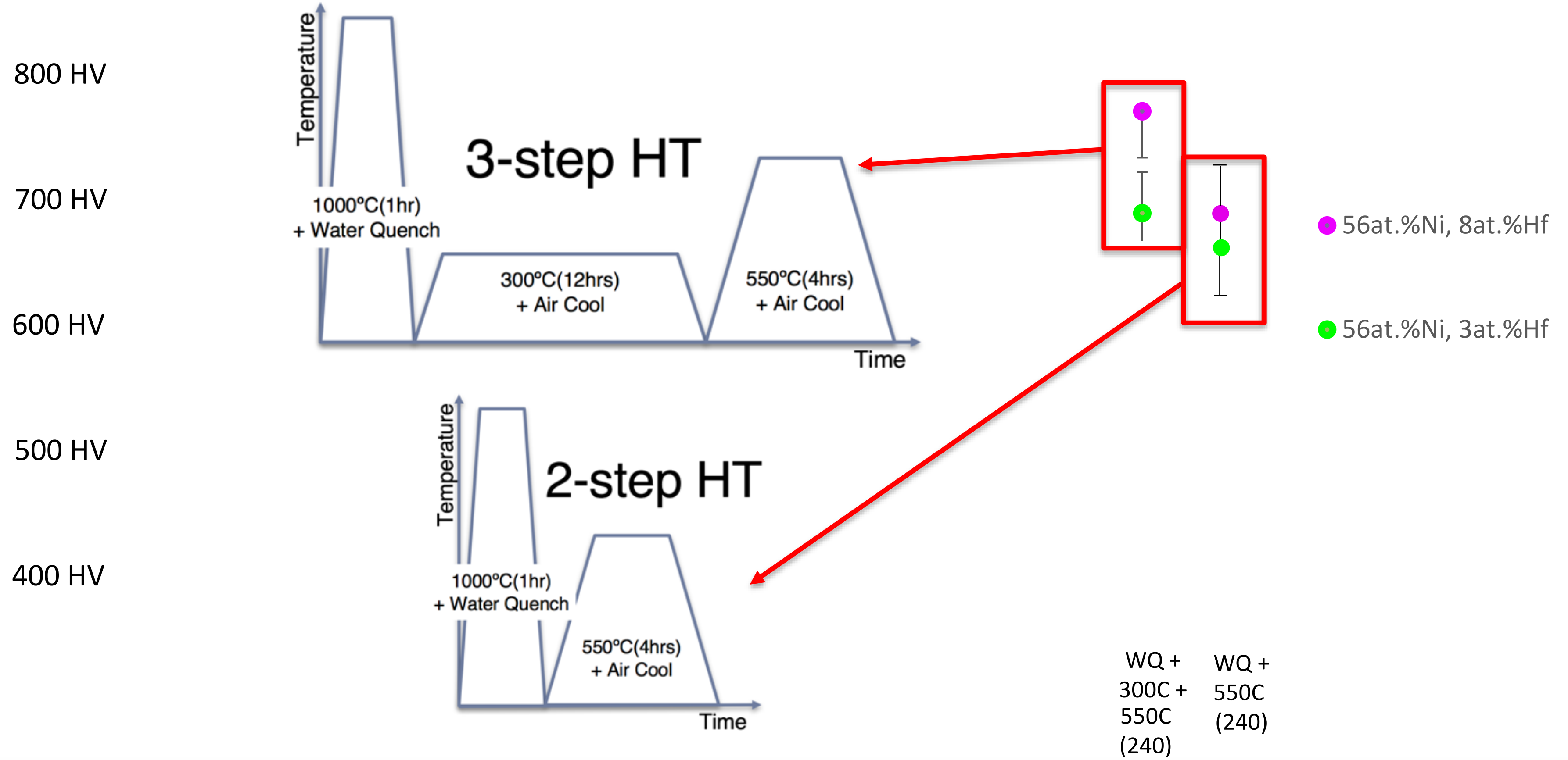
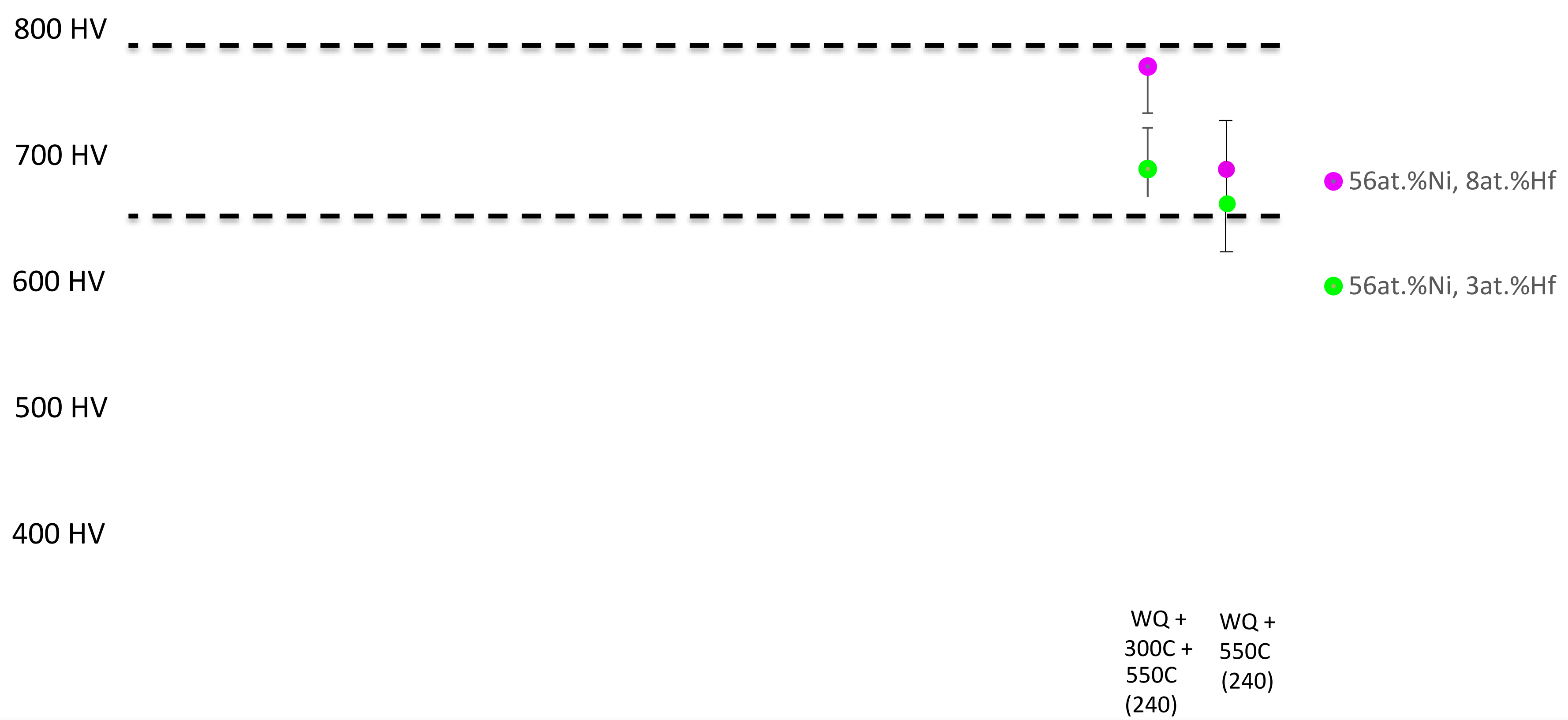
More Hafnium rich compositions showed higher hardness



Microscopy focus on $Ni_{56}Ti_{41}Hf_3$ and $Ni_{56}Ti_{36}Hf_8$.

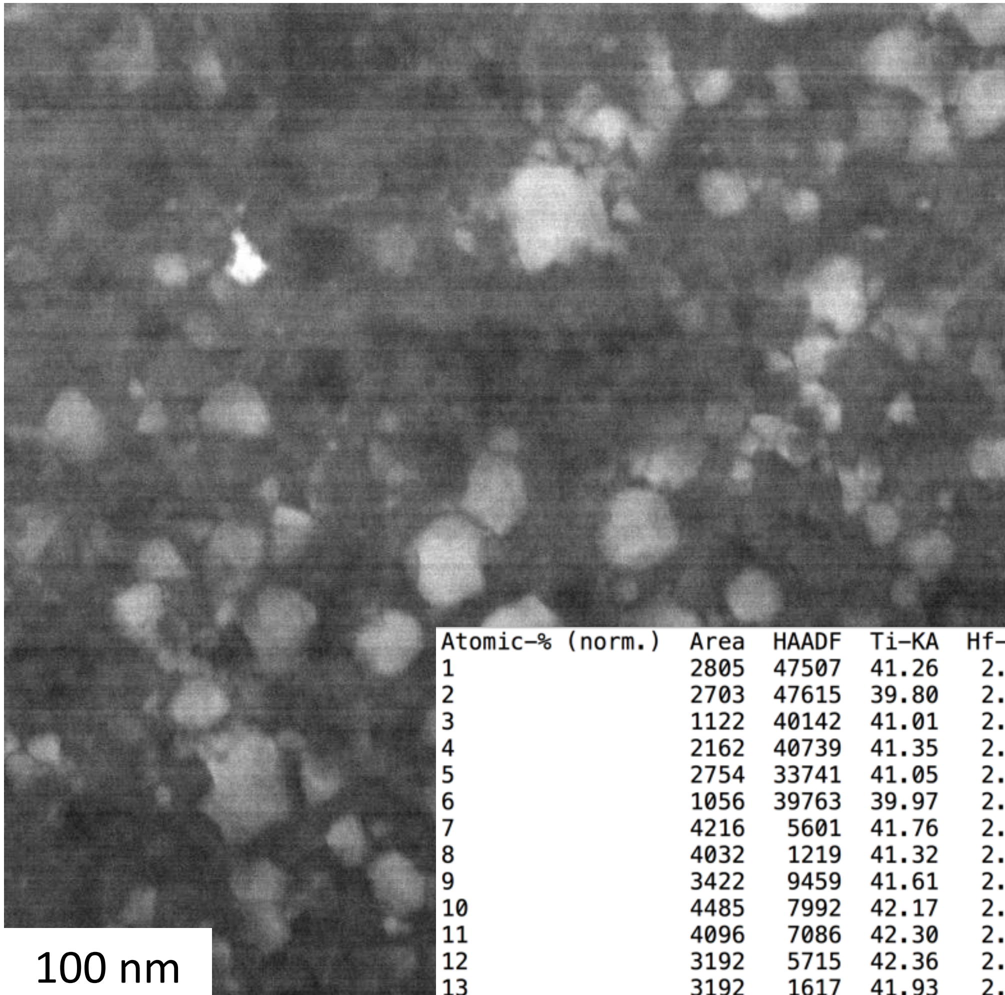
Pre-aged specimens have higher hardness than non-pre-aged specimens.

More Hafnium rich compositions showed higher hardness



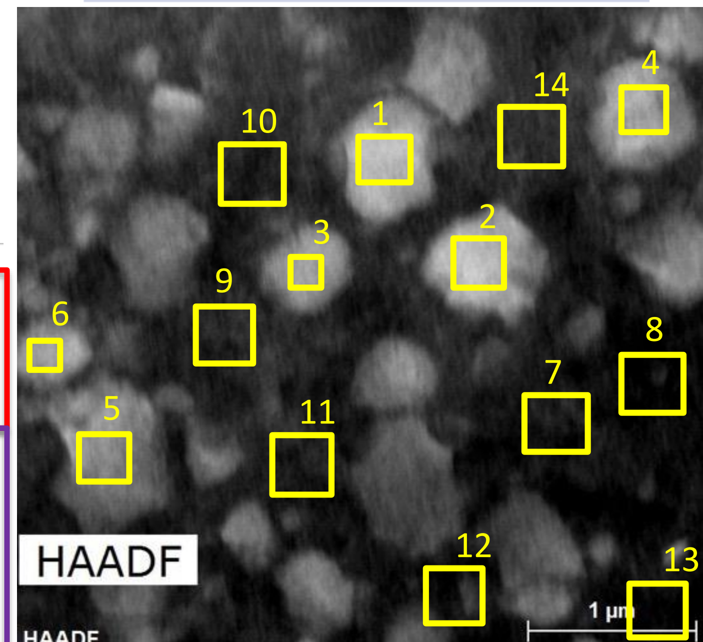
Microscopy focus on $Ni_{56}Ti_{41}Hf_3$ and $Ni_{56}Ti_{36}Hf_8$.
Pre-aged specimens have higher hardness than non-pre-aged specimens.

EDS of light vs. dark regions in $Ni_{56}Ti_{41}Hf_3$ SHT_{WQ}

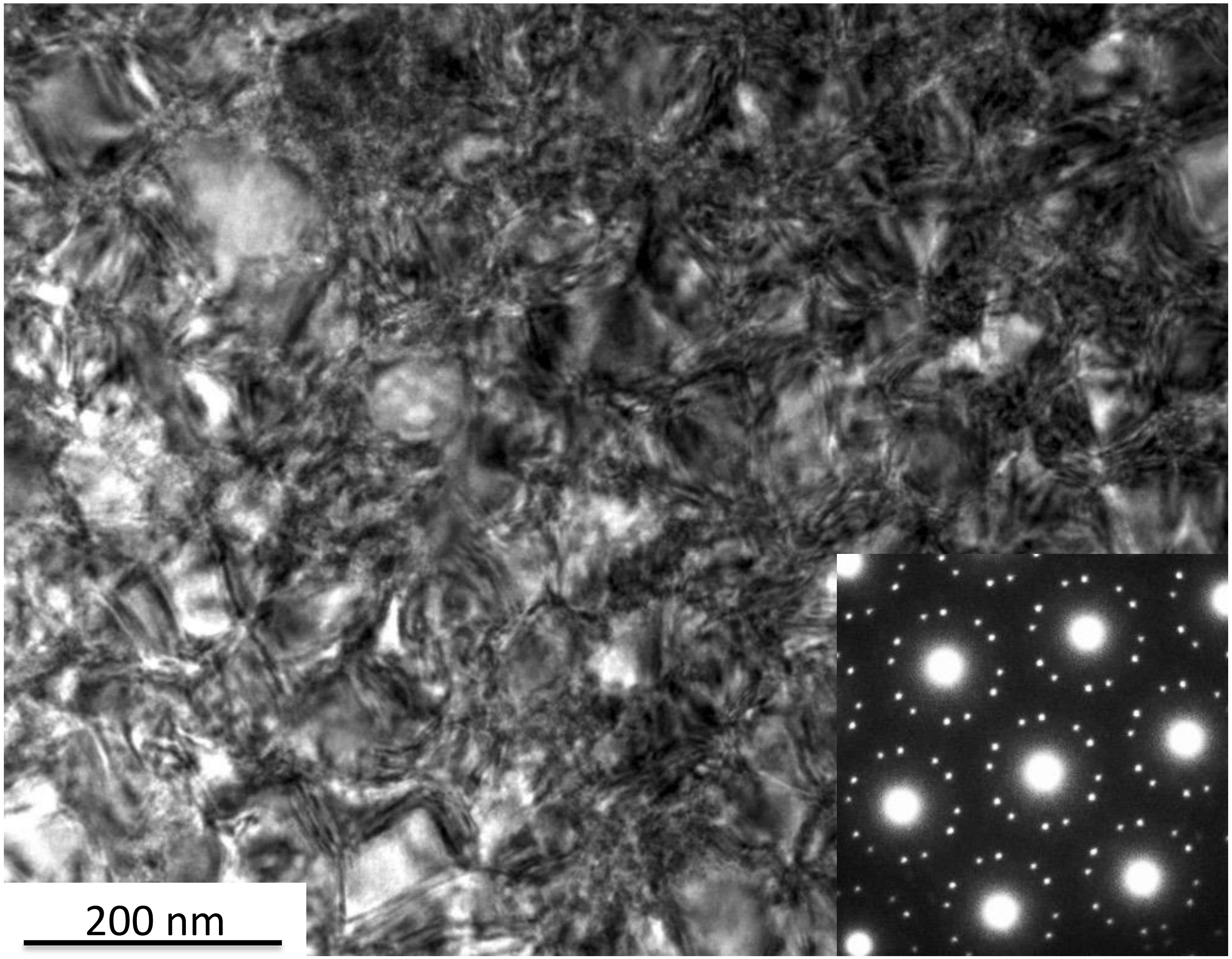


Composition
Ni-Ti (Xat.%Ni, 1-Xat.%Ti)
Ni_4Ti_3 (57.1at.%Ni, 42.9at.%Ti)
Ni_3Ti_2 (60at.%Ni, 40at.%Ti)
Ni_3Ti (75at.%Ni, 25at.%Ti)
Ti_2Ni (66at.%Ni, 33at.%Ti)

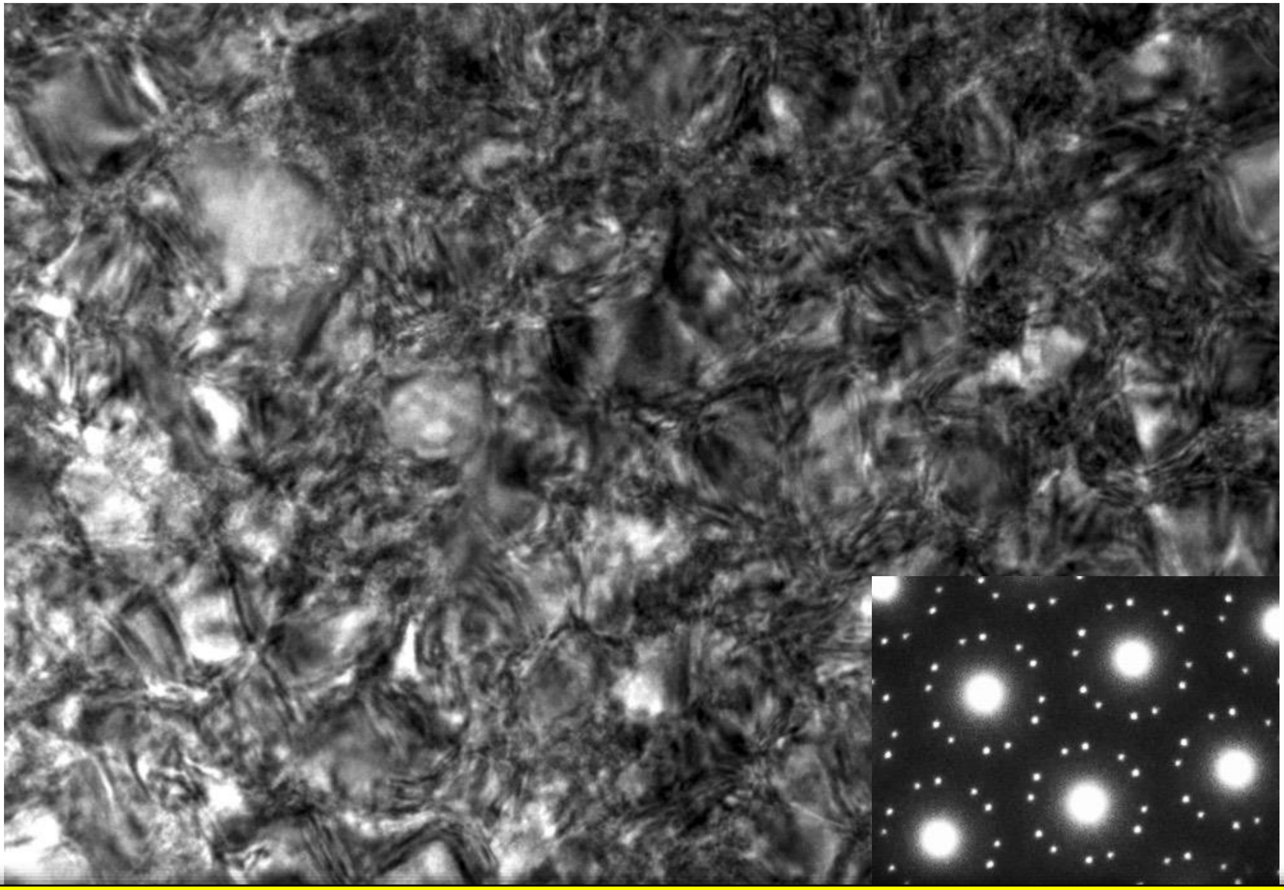
Atomic-% (norm.)	Area	HAADF	Ti-KA	Hf-LA	Ni-KA
1	2805	47507	41.26	2.21	56.52
2	2703	47615	39.80	2.44	57.75
3	1122	40142	41.01	2.55	56.44
4	2162	40739	41.35	2.21	56.44
5	2754	33741	41.05	2.27	56.67
6	1056	39763	39.97	2.57	57.46
7	4216	5601	41.76	2.34	55.90
8	4032	1219	41.32	2.26	56.42
9	3422	9459	41.61	2.45	55.95
10	4485	7992	42.17	2.28	55.55
11	4096	7086	42.30	2.42	55.28
12	3192	5715	42.36	2.26	55.38
13	3192	1617	41.93	2.37	55.71
14	4092	11877	41.72	2.09	56.20



$Ni_{56}Ti_{41}Hf_3$ SHT_{WQ} + $300(12hrs)_{AC}$

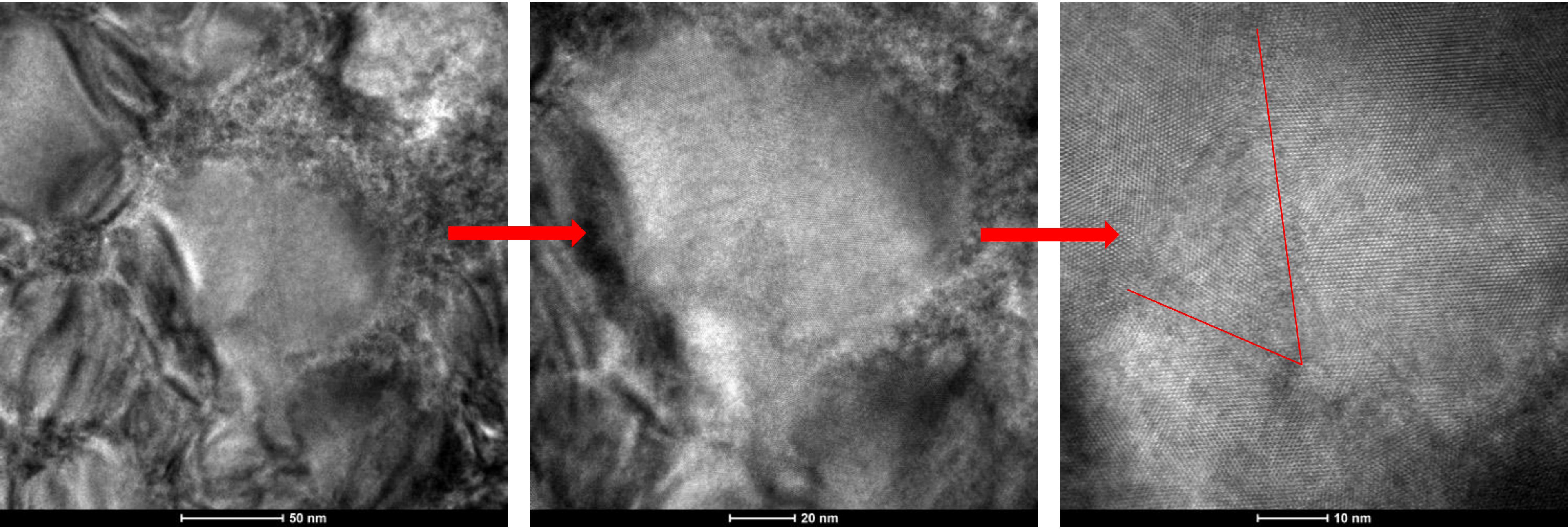


$Ni_{56}Ti_{41}Hf_3$ SHT_{WQ} + $300(12hrs)_{AC}$

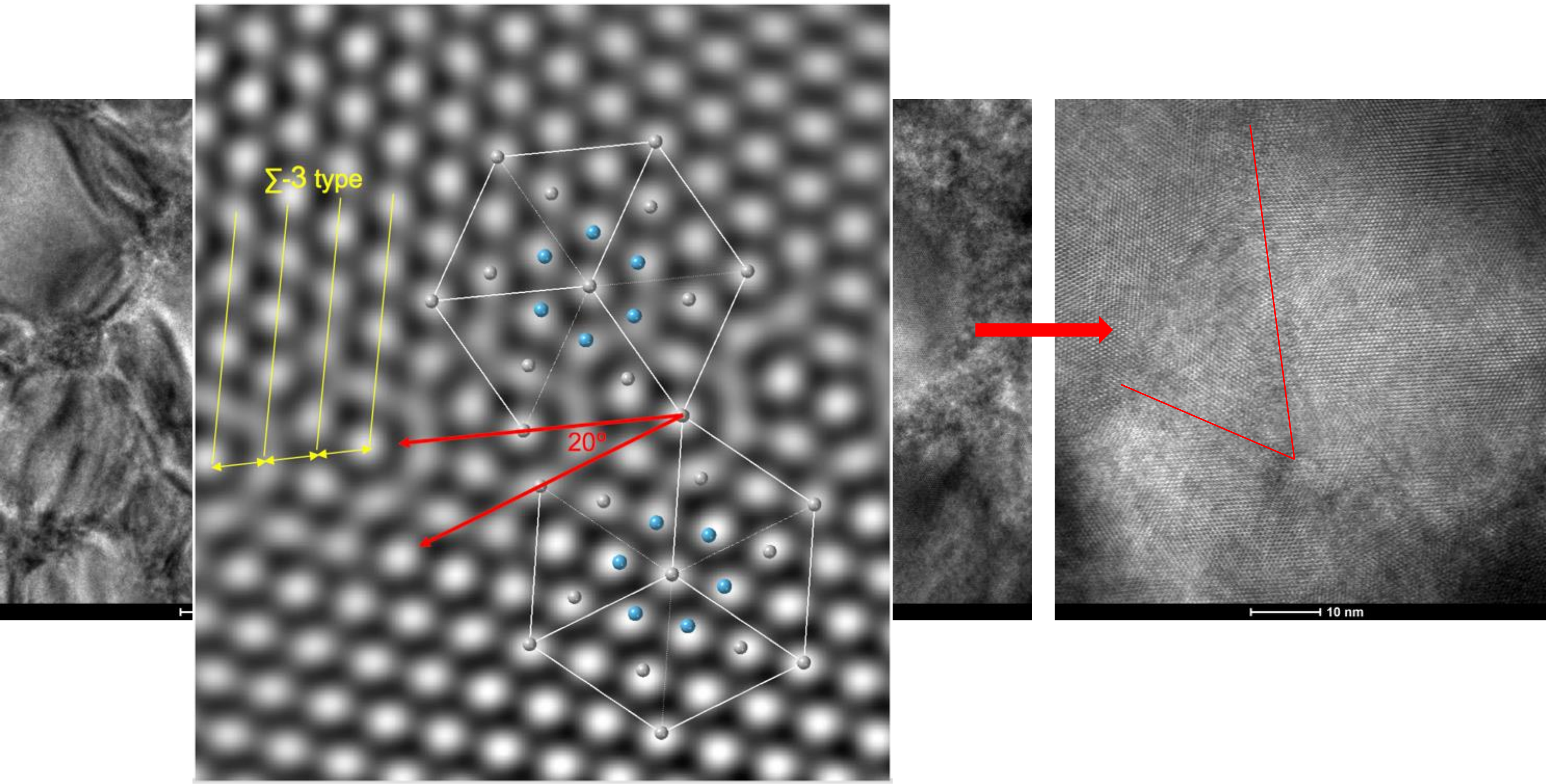


Coarsening of Ni_4Ti_3. Not a significant change in microstructure compared to SHT_{WQ} condition.

$Ni_{56}Ti_{41}Hf_{3}$ SHT_{WQ} + $300(12hrs)_{AC}$



$Ni_{56}Ti_{41}Hf_{3}$ SHT_{WQ} + $300(12hrs)_{AC}$



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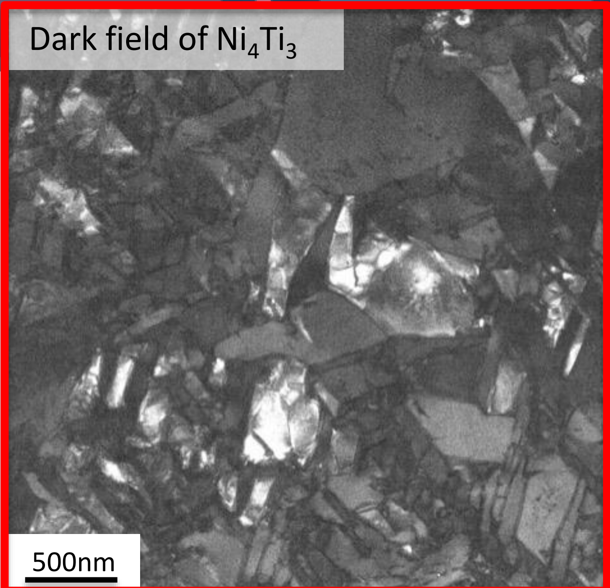
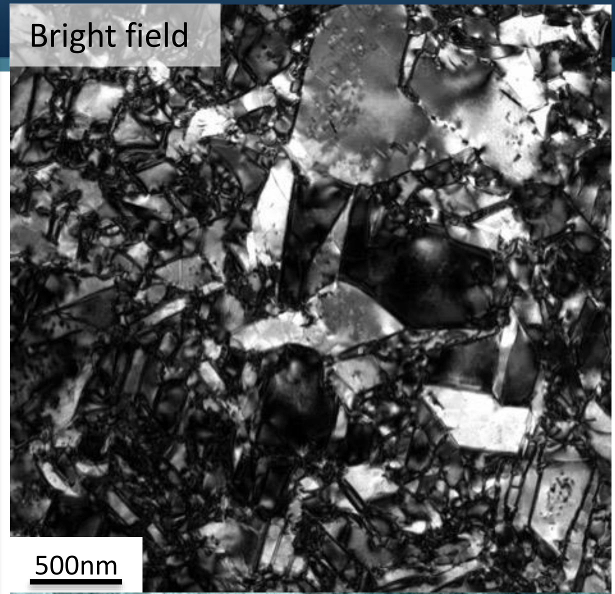
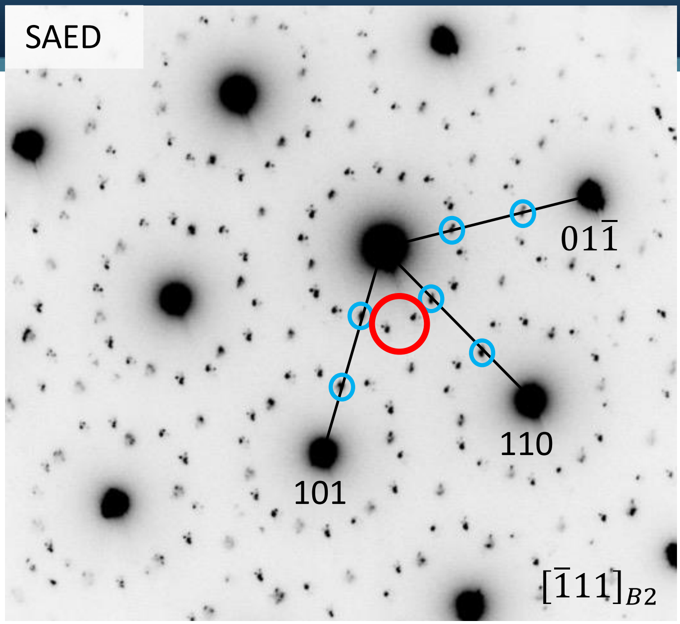
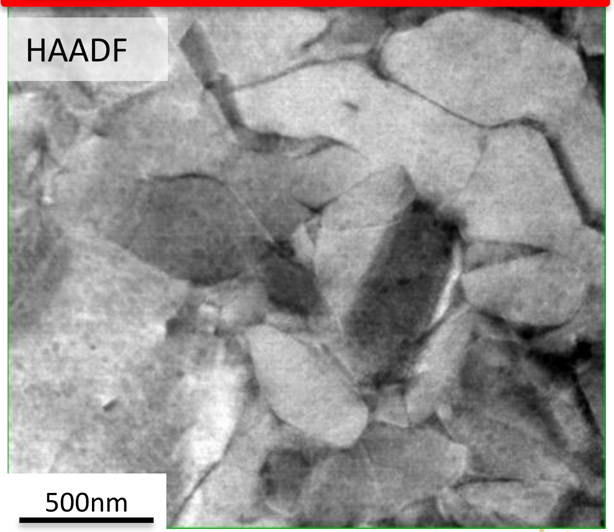
$Ni_{56}Ti_{41}Hf_3$ SHT_{WQ} + $300(12hrs)_{AC}$ + $550(1.5hrs)_{AC}$

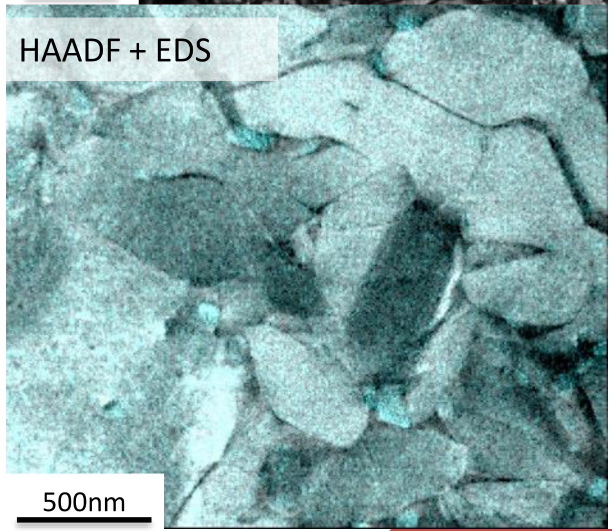
Low Hf with pre-age shows blocky Ni_4Ti_3 structure and H-phase









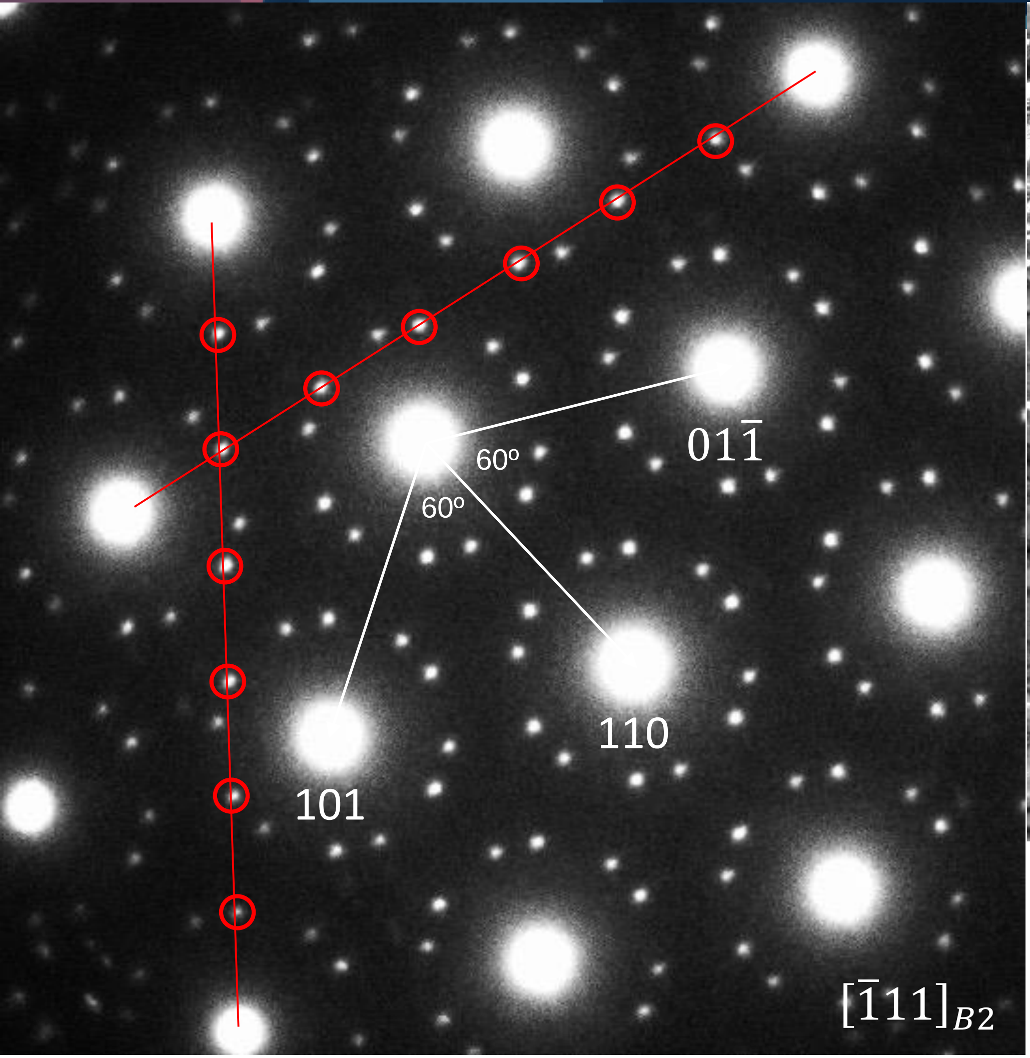


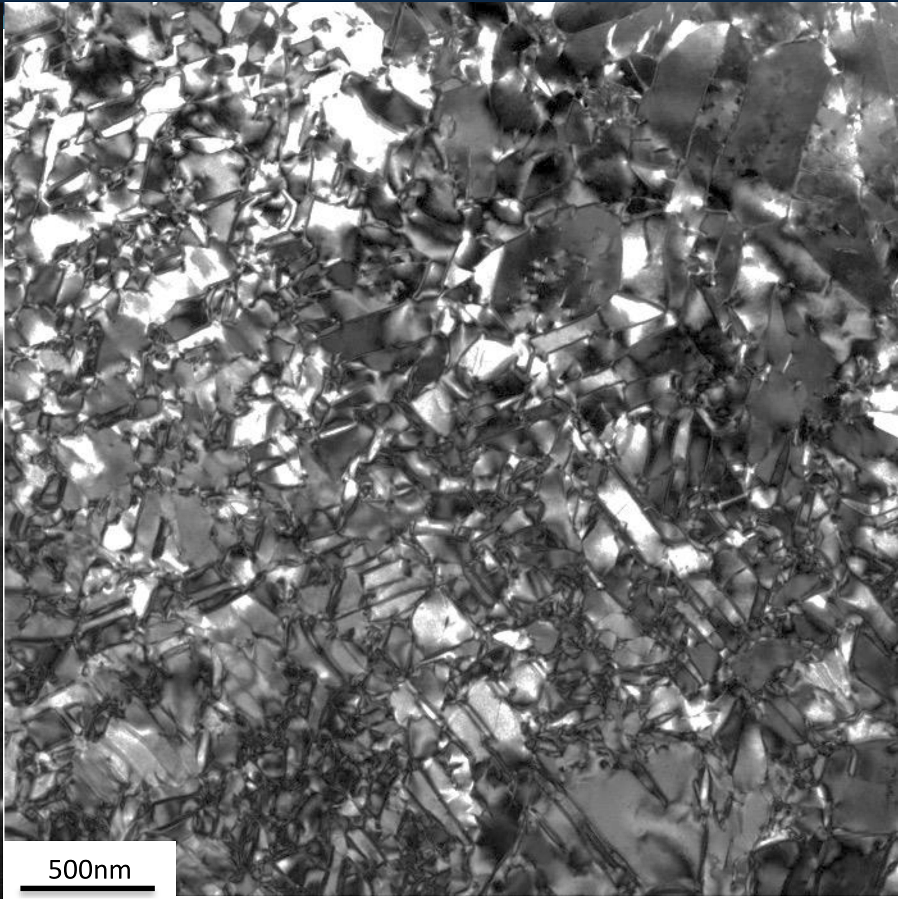
H-phase

Ni_4Ti_3

709 HV

$Ni_{56}Ti_{41}Hf_3$ SHT_{WQ} + 550(4hrs)$_{AC}$ Lower Hf without pre-age shows blocky Ni_4Ti_3



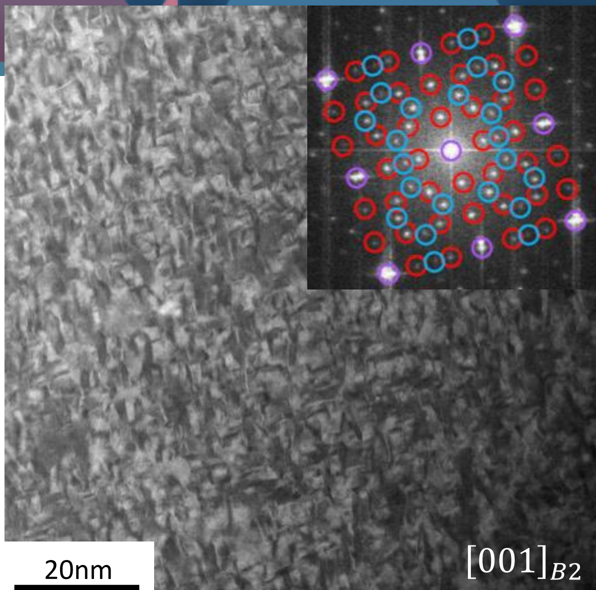


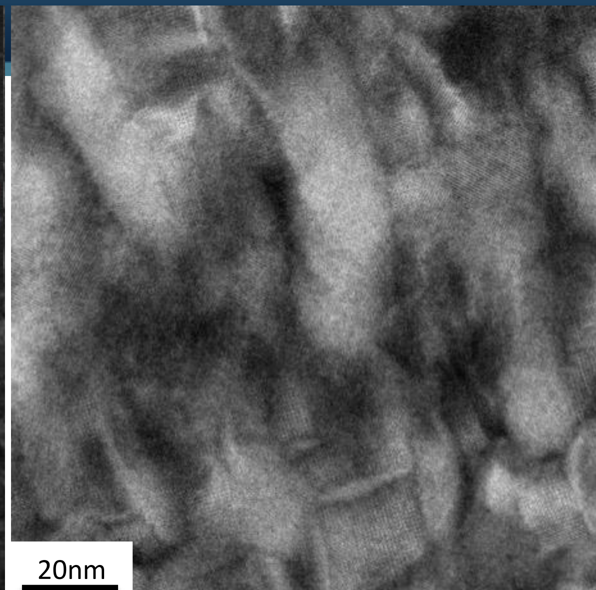
Ni_4Ti_3 super-reflections fall under $\frac{1}{7} < 321 >$

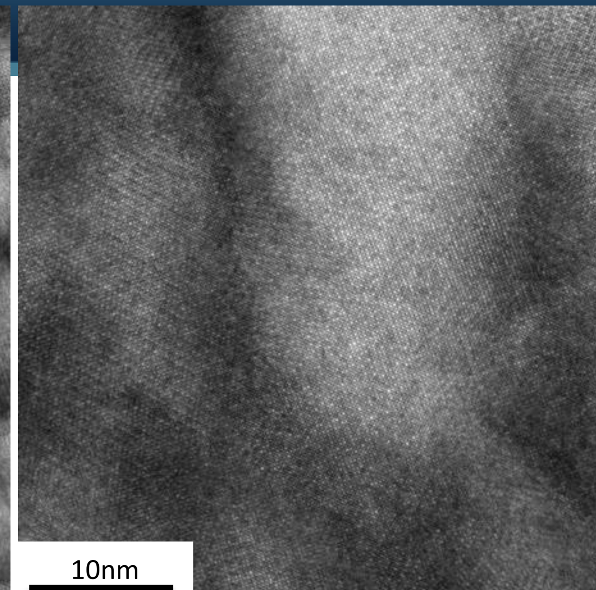
682 HV

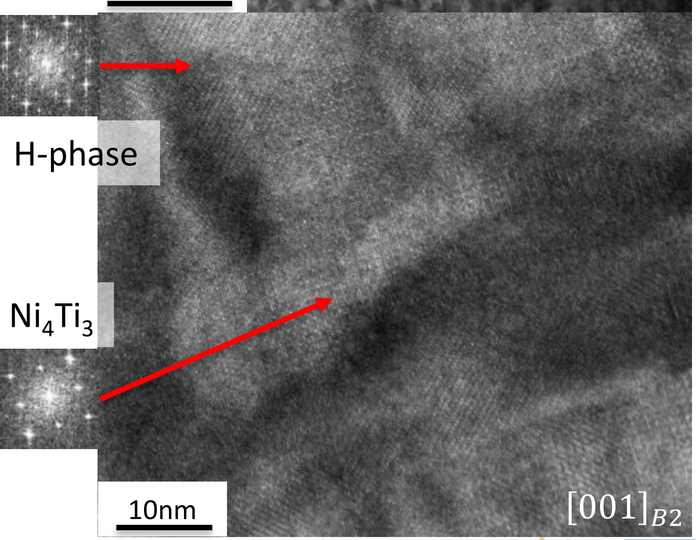
$Ni_{56}Ti_{36}Hf_8$ SHT_{WQ}+ $300(12hrs)_{AC}$ + $550(4hrs)_{AC}$

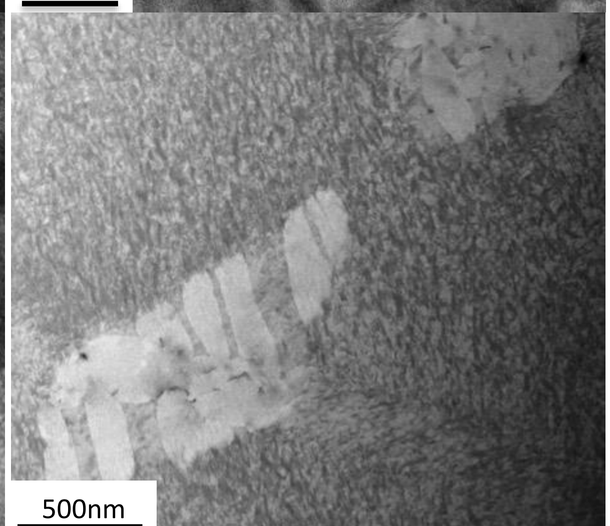
Higher Hf with pre-aged condition shows fine Ni_4Ti_3 and H-phase











B2

Ni_4Ti_3

H-phase

769 HV

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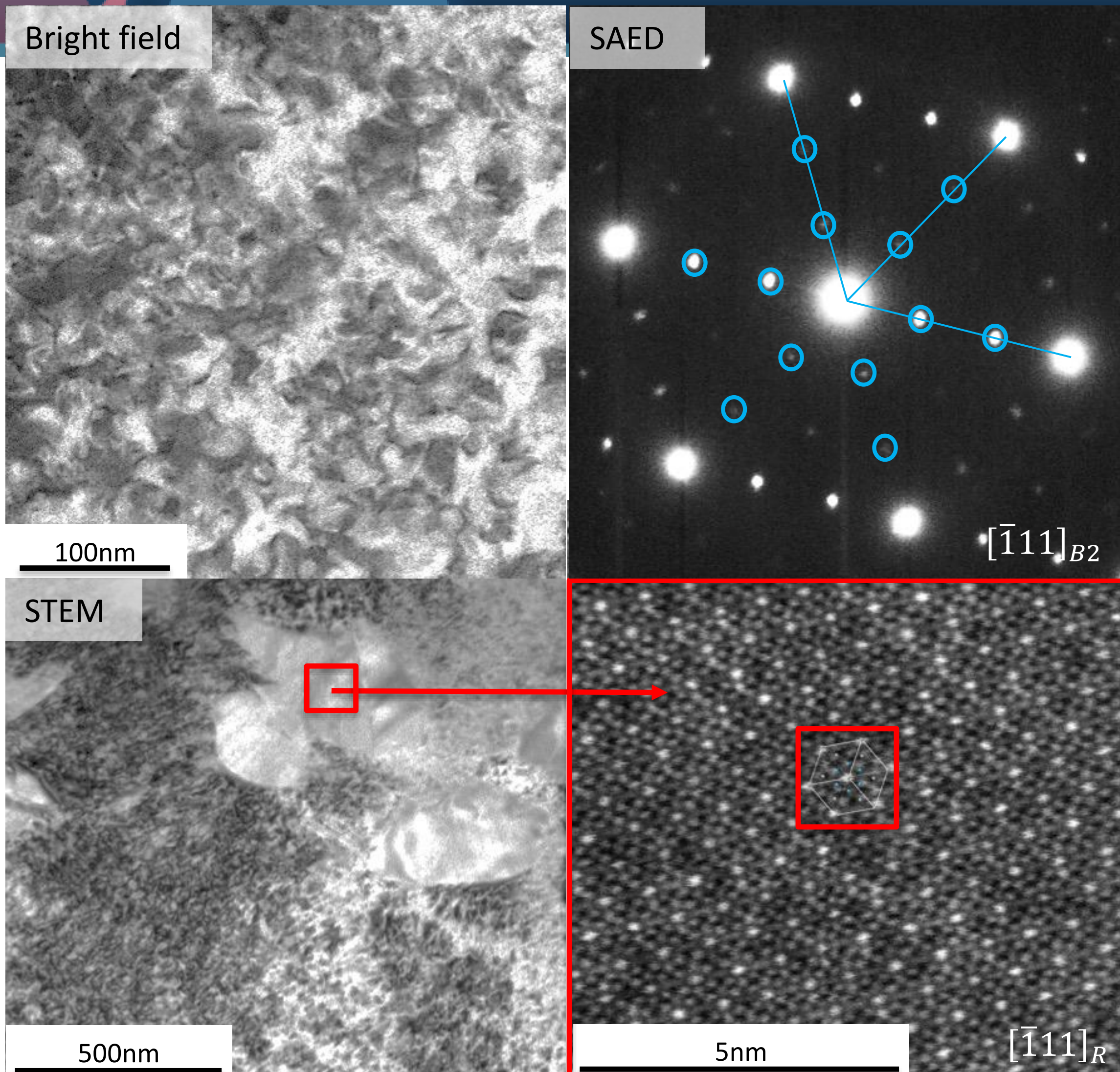
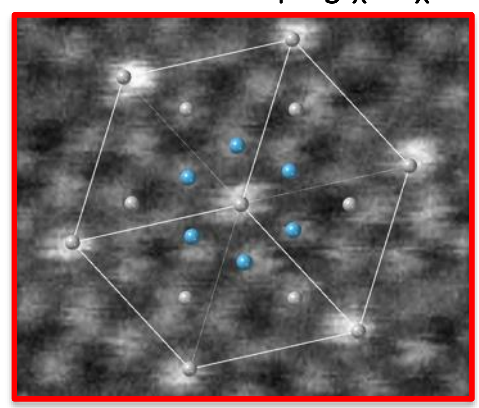
$Ni_{56}Ti_{36}Hf_8$ SHT_{WQ}+ 550(4hrs)$_{AC}$
Higher Hf without pre-age shows fine H-phase



H-phase diffraction spots fall under $\frac{1}{3} < 110 >$

700 HV

Sparse formation of large $Ni_4Ti_{3-x}Hf_x$



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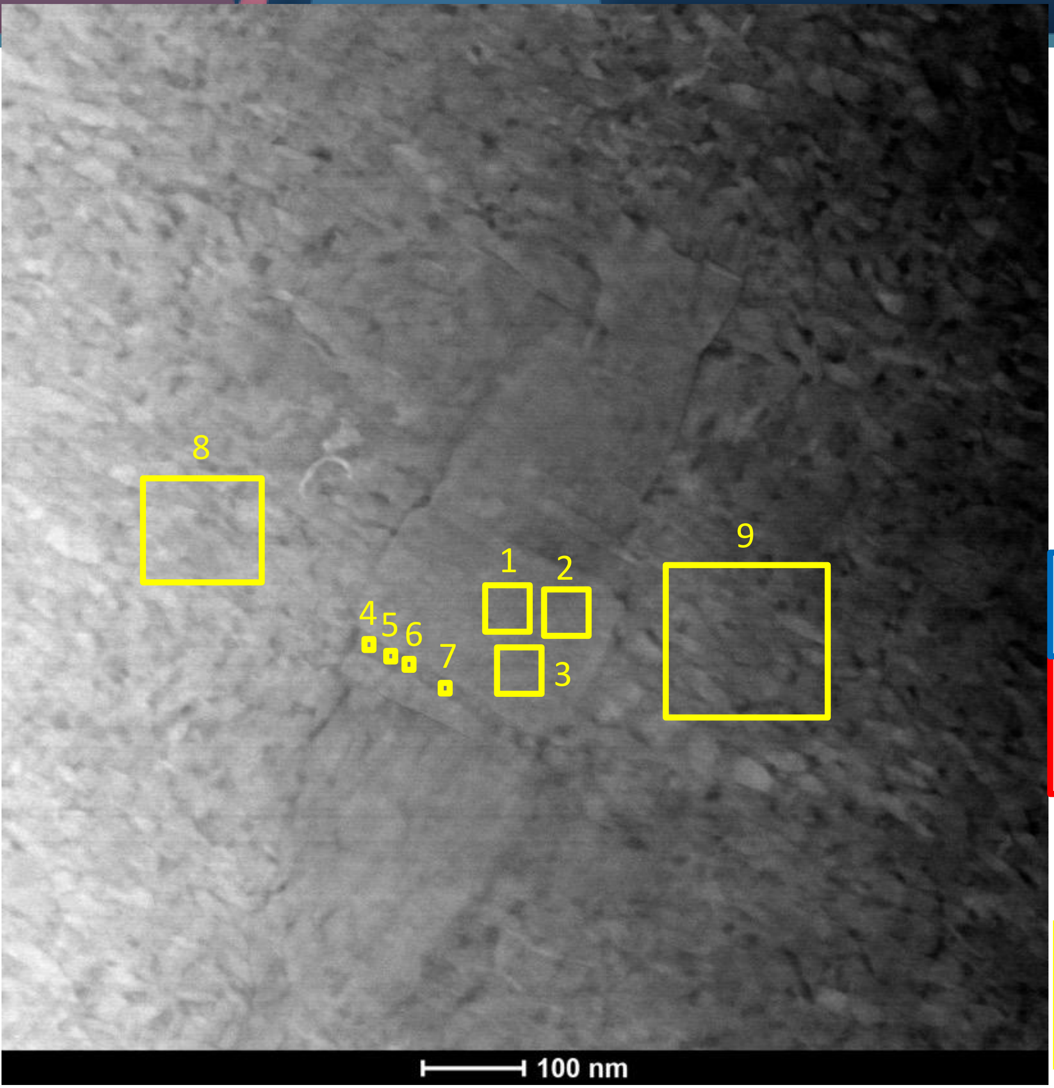
$Ni_{56}Ti_{36}Hf_8$ SHT_{WQ} + 300(12hrs)+550(4hrs)



Composition
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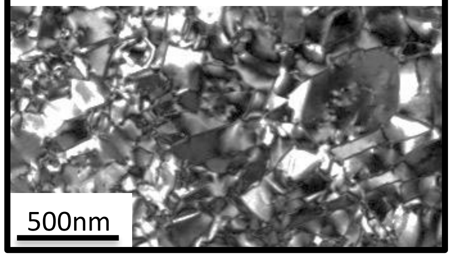
Ni_3Ti (75at.%Ni, 25at.%Ti)
Ti_2Ni (66at.%Ni, 33at.%Ti)

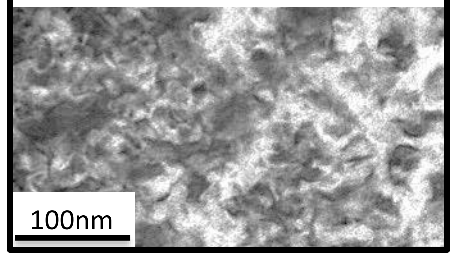
Atomic-% (norm.)	Area	HAADF	Ti-KA	Hf-LA	Ni-KA
1	1258	28892	35.87	6.64	57.49
2	2279	29435	34.53	7.58	57.88
3	1280	30939	36.03	6.26	57.71
4	110	35935	36.80	8.37	54.83
5	100	34864	40.65	6.12	53.22
6	81	32784	37.00	7.64	55.36
7	81	29335	41.97	5.44	52.59
8	20433	21043	36.60	7.79	55.61
9	10176	46072	36.71	7.35	55.94

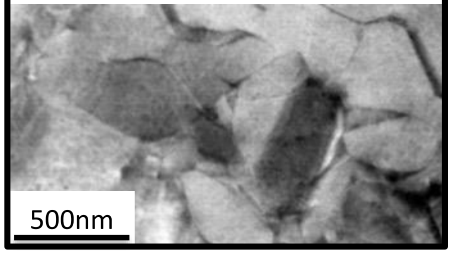
Large precipitate corresponds to Ni_4Ti_3 composition.

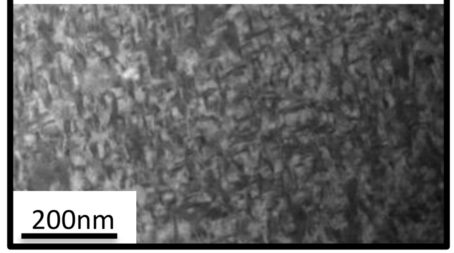
Secondary precipitation depends on composition and heat treatment

	$Ni_{56}Ti_{41}Hf_3$	$Ni_{56}Ti_{36}Hf_8$
Without 300C (12hrs)	<u>Blocky</u> Ni_4Ti_3 No H-phase	<u>Fine</u> H-phase No Ni_4Ti_3
With 300C (12hrs)	Blocky Ni_4Ti_3 <u>and</u> H-phase	Fine H-phase <u>and</u> Ni_4Ti_3



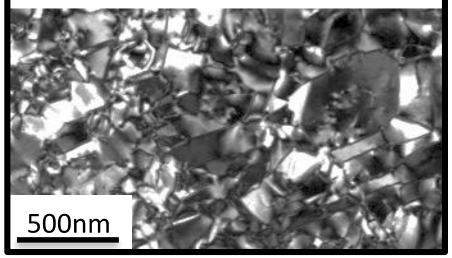


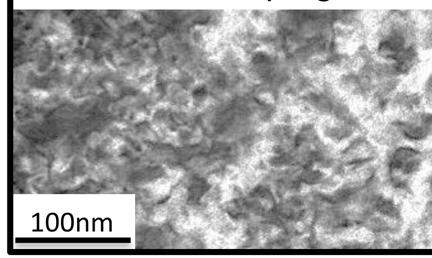




Secondary precipitation depends on composition and heat treatment

	$Ni_{56}Ti_{41}Hf_3$	$Ni_{56}Ti_{36}Hf_8$
Without 300C (12hrs)	Blocky Ni_4Ti_3 No H-phase	Fine H-phase No Ni_4Ti_3
With 300C (12hrs)	Blocky Ni_4Ti_3 and H-phase	Fine H-phase and Ni_4Ti_3





Preference for precipitation depends on Hf content
Presence of both phases depends on pre-age

TTT data table for current alloys examined

Composition	Heat Treatment	TEM	DSC	Phase Information	Hardness (HV)
$Ni_{50.3}Ti_{46.7}Hf_3$	SHT_{WQ}		Yes	No	620.7
$Ni_{50.3}Ti_{46.7}Hf_3$	SHT_{WQ} + $300(12)_{AC}$		Yes	No	630.3
$Ni_{50.3}Ti_{46.7}Hf_3$	SHT_{WQ} + $550(4)_{AC}$		Yes	No	586.2
$Ni_{50.3}Ti_{46.7}Hf_3$	SHT_{WQ} + $300(12)_{AC}$ + $550(4)_{AC}$	STEM	Yes	Fine H-phase, some Ni_4Ti_3	676.2
$Ni_{56}Ti_{41}Hf_3$	SHT_{WQ}	STEM,EDX	Yes	Light spherical features, no X.% disparity	706.5
$Ni_{56}Ti_{41}Hf_3$	SHT_{WQ} + $300(12)_{AC}$	HR-TEM	Yes	Blocky Ni_4Ti_3	752.0
$Ni_{56}Ti_{41}Hf_3$	SHT_{WQ} + $550(4)_{AC}$	TEM	Yes	Blocky Ni_4Ti_3, coarse martensite laths	661.6
$Ni_{56}Ti_{41}Hf_3$	SHT_{WQ} + $300(12)_{AC}$ + $550(1.5)_{AC}$	HR-TEM,STEM,EDX	No	Blocky Ni_4Ti_3, dispersed H-phase$_{(30nm)}$	657.4
$Ni_{56}Ti_{41}Hf_3$	SHT_{WQ} + $300(12)_{AC}$ + $550(4)_{AC}$		Yes	No	709.8
$Ni_{56}Ti_{41}Hf_3$	SHT_{WQ} + $300(12)_{AC}$ + $400(4)_{AC}$	HR-TEM	No	Blocky Ni_4Ti_3, dispersed H-phase$_{(10nm)}$	698.6
$Ni_{56}Ti_{36}Hf_8$	SHT_{WQ}		Yes	No	716.3
$Ni_{56}Ti_{36}Hf_8$	SHT_{WQ} + $300(12)_{AC}$		Yes	No	705.4
$Ni_{56}Ti_{36}Hf_8$	SHT_{WQ} + $550(4)_{AC}$	HR-TEM	Yes	Fine H-phase, heterogeneous $Ni_4Ti_{3(700nm)}$	700.0
$Ni_{56}Ti_{36}Hf_8$	SHT_{WQ} + $300(12)_{AC}$ + $550(4)_{AC}$	STEM,EDX	Yes	Fine H-phase and Ni_4Ti_3, heterogeneous $Ni_4Ti_{3(700nm)}$	768.8
$Ni_{56}Ti_{36}Hf_8$	SHT_{WQ} + $300(12)_{AC}$ + $400(4)_{AC}$	HR-TEM	No	Fine H-phase	692.0
$Ni_{56}Ti_{36}Hf_8$	SHT_{WQ} + $300(12)_{AC}$ + $400(1.5)_{AC}$		No		726.5

Conclusions for Ni-Ti-Hf

- Pre-aging without additional treatment does not show H-phase, only Ni_4Ti_3.

- Existence of interface within large Ni_4Ti_3 precipitates.

Includes misfit dislocations.

- Increase in Hf from 3at.% to 8at.% under same aging conditions shows

suppressed nucleation and growth of Ni_4Ti_3 precipitation.

- Preference between Ni_4Ti_3 and H-phase switches when Hf content is increased.

- Large heterogeneous formation of $Ni_4Ti_{3-x}Hf_x$ exists in 8at.%Hf samples.

Future work for Ni-Ti-Hf

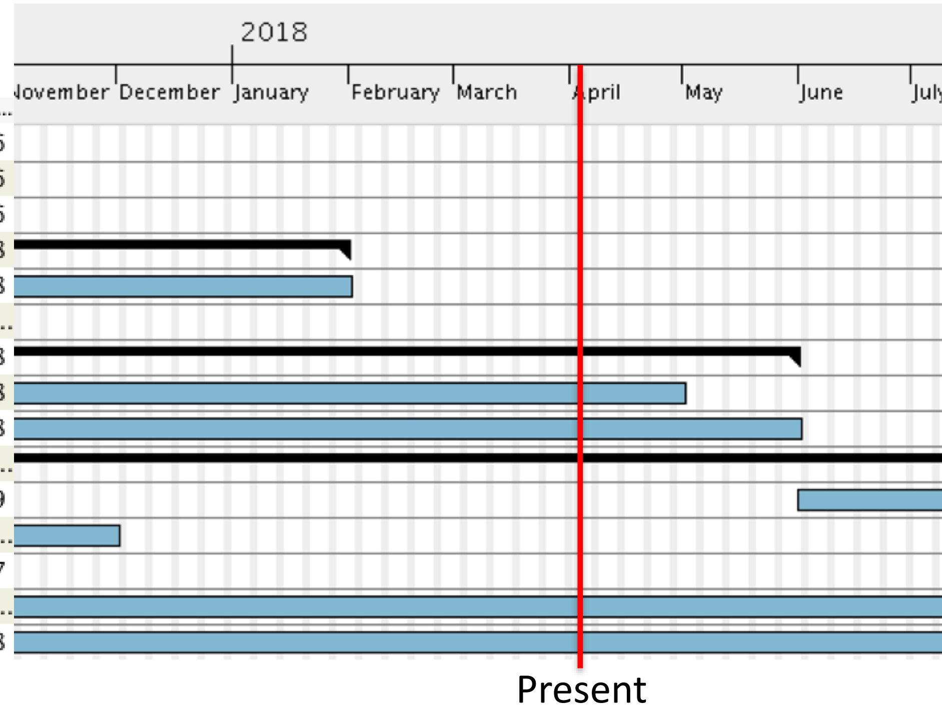
- Combine rolling contact fatigue with microstructure analysis and develop time/temperature/transformation to determine optimized alloy composition and heat treatment.

- Perform rolling contact fatigue on higher hardness alloys to confirm that higher hardness leads to better fatigue performance.

- Acta. Mat. paper on Ni-Ti-Hf microstructural optimization for tribology.

Gantt Chart

Name	Begin da...	End da...
Residual stress and hardness testing on NiTi & NiTiHf1	8/3/15	8/1/16
XRD analysis of residual microstresses	8/3/15	1/1/16
Heat treatments & hardness testing for NiTiHf1	12/1/15	8/1/16
Rolling contact fatigue characterization of NiTiHf1	11/2/15	2/1/18
Failure analysis (XRD, OM, TEM, SEM)	6/1/16	2/1/18
RCF testing	11/2/15	11/2/...
Time/Temperature/Transformation of NiTiHf1	2/1/17	6/1/18
Ex-situ elucidation of T-T-T space (coarse resolution)	2/1/17	5/1/18
In-situ TEM & XRD studies of transformation kinetics & therm...	4/3/17	6/1/18
Alloy optimization - vary nickel and hafnium contents by 1-8 at%	1/1/16	9/30/...
In-situ studies of transformation kinetics & thermodynamics	6/1/18	8/1/19
Screen hardness, strengths, and residual stresses of alloy ma...	1/1/16	12/1/...
Ex-situ T-T-T mapping of most promising/interesting alloys	6/1/16	8/1/17
RCF testing of most promising/interesting alloys	11/1/17	9/30/...
Failure analysis	6/1/17	8/1/18



Center Proprietary – Terms of CANFSA Membership Agreement Apply

Thank you

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Project 17: Characterization of Microstructure Evolution in Nickel-Titanium-Hafnium Intermetallics

- Student: Sean Mills (Mines)
- Advisor(s): Aaron Stebner (Mines)

Project Duration

PhD: August 2015 to August 2019

Problem: Ni-Ti alloys experience high residual stress due to rapid quenching processes. The result is cracking and machining distortion. Not quenching leads to low hardness.

Objective: Elucidate the effect of Hf ternary alloying on metallurgy and bearing element performances.

Benefit: Hf-alloying could lead to reduction in residual stress by eliminating the need for rapid cooling while retaining high strength and hardness levels of quenched binary Ni-Ti.

Recent Progress

- Rolling contact fatigue (RCF) tests on $Ni_{54}Ti_{45}Hf_1$ and $Ni_{54}Ti_{43}Hf_3$ alloy specimens
- TEM characterization of microstructure evolution in 56at.% Ni alloys
- Continued Time/Temperature/Transformation (TTT) research

Metrics		
Description	**% Complete**	**Status**
1. Residual stress and hardness testing on $Ni_{55}Ti_{45}$ & $Ni_{54}Ti_{45}Hf_1$ (NASA)	80%	●
2. Literature review	80%	●
3. Rolling contact fatigue characterization of $Ni_{54}Ti_{45}Hf_1$ alloy	70%	●
4. Time/Temperature/Transformation of $Ni_{54}Ti_{45}Hf_1$ alloy	30%	●
5. Alloy optimization – vary nickel and hafnium contents by 1-8 at%	20%	●

Project 17: Characterization of Microstructure Evolution in Nickel-Titanium-Hafnium Intermetallics

Graduate Student – Sean Mills (CSM)
Faculty/Advisors – A.P. Stebner (CSM)
Industrial Mentors – C. DellaCorte & R.D. Noebe (NASA Glenn)

Program Goal

Development of Ni-Ti-Hf alloys with high strength, hardness and toughness via superelasticity

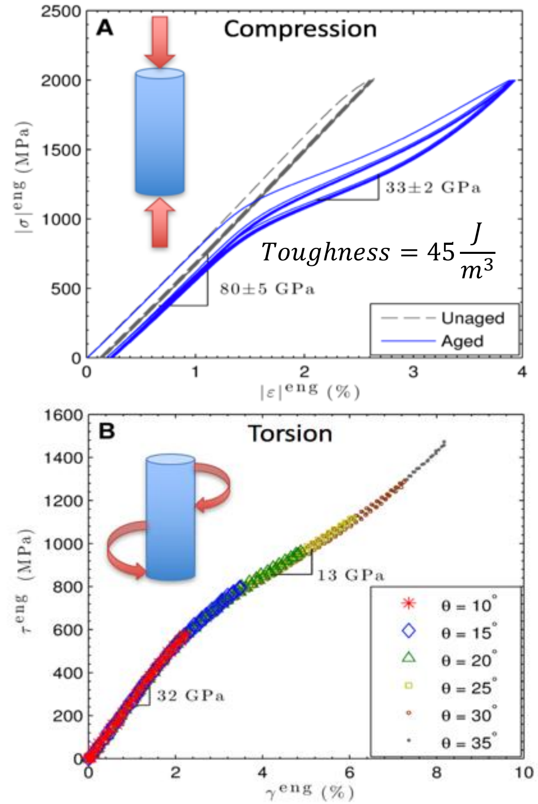
Approach

Characterize residual stress and fatigue properties of Ni-Ti with added levels of Hf

Correlate properties to microstructural variations between alloys

Benefits

A new class of bearing materials with high strength and high damage tolerance



Very Small Hysteresis Superelasticity of $Ni_{54}Ti_{45}Hf_1$

Project Duration
Aug. 2015 to Aug. 2019

Center Proprietary – Terms of CANFSA Membership Agreement Apply

Previous rolling contact fatigue tests

Test Date	2/16	3/16	4/16	5/16	6/16	7/16	8/16	9/16	10/16
Sample Composition	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$
Secondary Processing	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age
Stress (GPa)	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.8	1.8
Lifespan (10^8 cycles)	.33	>1.7	>1.7	>1.7	>1.7	>1.7	>1.7	1.47	>1.7

Test Date	8/16	9/16	11/16	11/16	12/16	1/17	2/17	3/17	3/17
Sample Composition	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$
Secondary Processing	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age
Stress (GPa)	1.9	1.9	2.0	2.0	2.0	1.9	1.9	1.9	1.9
Lifespan (10^8 cycles)	.12	.31	.08	.22	.48	1.2	1.32	1.28	>1.7

Test Date	2/17	2/17	4/17	4/17	5/17	5/17
Sample Composition	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{55}Ti_{45}$	$Ni_{55}Ti_{45}$
Secondary Processing	$900C_{WQ}$ +400C Age	$900C_{WQ}$ +400C Age	$900C_{AC}$ +400C Age	$900C_{AC}$ +400C Age	$1000C_{WQ}$ +400C Age	$1000C_{WQ}$ +400C Age
Stress (GPa)	1.9	1.9	1.9	1.9	1.9	1.9
Lifespan (10^8 cycles)	>1.7	>1.7	>1.7	1.18	>1.7	>1.7

Current rolling contact fatigue tests

Test Date	7/17	8/17	8/17	9/17	9/17	11/17	12/17	1/18	1/18
Sample Composition	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{45}Hf_1$	$Ni_{54}Ti_{43}Hf_3$	$Ni_{54}Ti_{43}Hf_3$	$Ni_{54}Ti_{43}Hf_3$	$Ni_{54}Ti_{43}Hf_3$
Secondary Processing	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{AC}$+ 400C Age	$1000C_{WQ}$+ 400C Age	$1000C_{WQ}$+ $300C(12hrs)_{AC}$	$1000C_{WQ}$+ $300C(12hrs)_{AC}$	$1000C_{WQ}$+ $300C(12hrs)_{AC}$
Stress (GPa)	2.0	2.0	2.0	2.0	2.0	1.9	1.9	2.0	2.0
Lifespan (10^8 cycles)	.33	.94	.74	.72	.36	>1.7	>1.7	>1.7	>1.7

Test Date	2/18	2/18
Sample Composition	$Ni_{54}Ti_{43}Hf_3$	$Ni_{54}Ti_{43}Hf_3$
Secondary Processing	$1000C_{WQ}$+ $300C(12hrs)_{AC}$	$1000C_{WQ}$+ $300C(12hrs)_{AC}$
Stress (GPa)	1.9	2.0
Lifespan (10^8 cycles)	>1.7	.81