Integrated Computational Materials Engineering Development of Alternative Cu-Be Alloys

Project Number: WP2138

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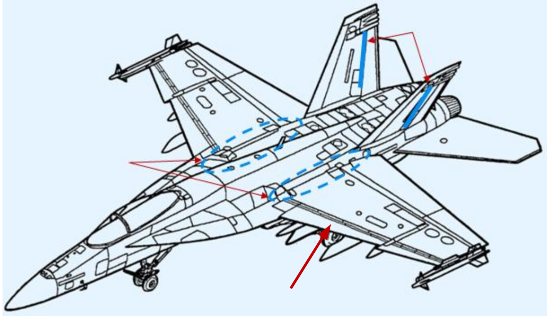
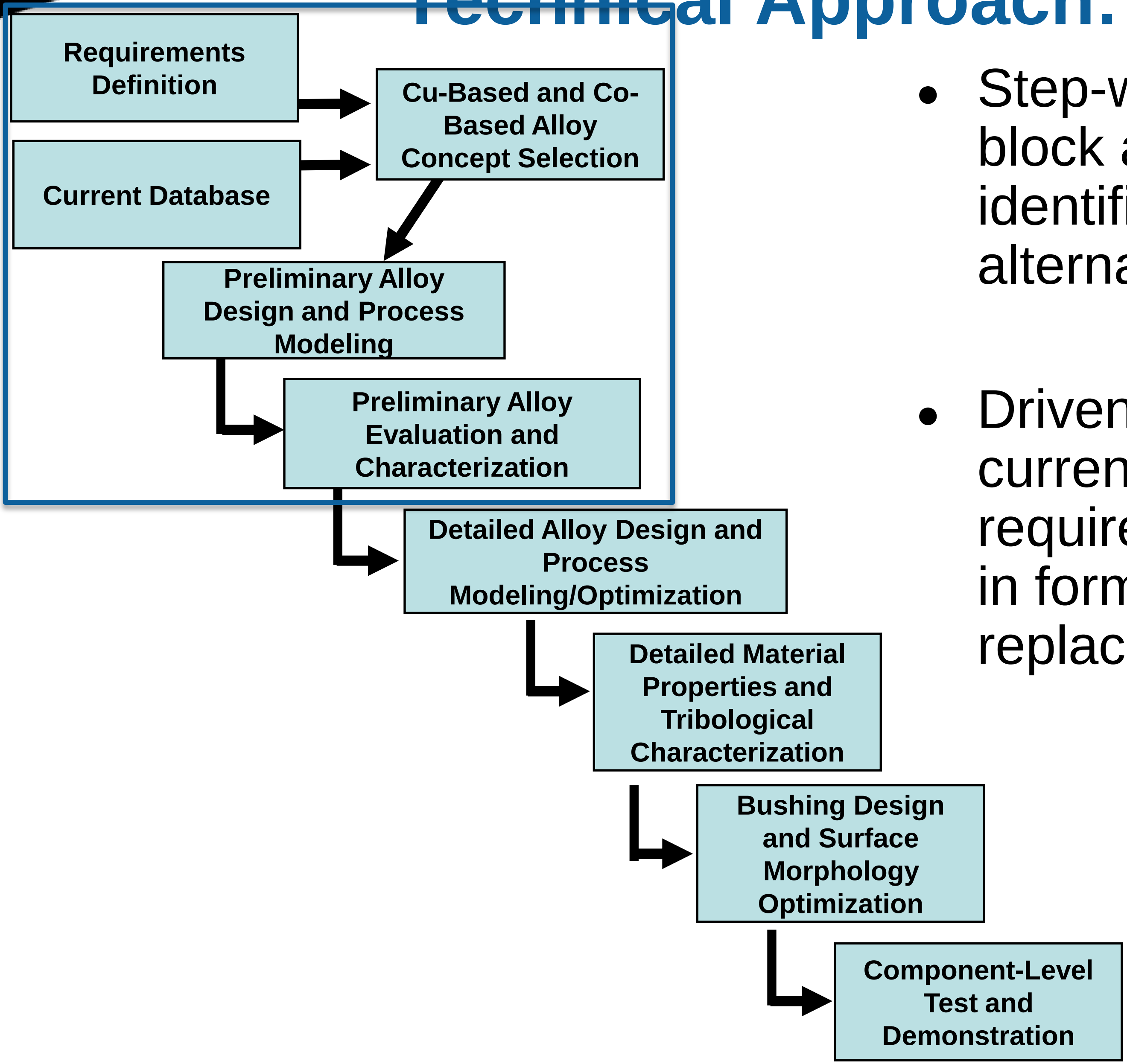
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Technical Objective

- Develop and characterize new alloy\processing route for Cu-Be alloy replacement in highly loaded wear applications.
- Development bushing designs for the enhancement of dynamic wear performance.
- Demonstration of new material\processing route and design in a full scale representative environment
- Execution of production as well as Environmental, Health and Safety impact assessment



Technical Approach: Overview



Requirements Definition

Current Database

Cu-Based and Co-Based Alloy Concept Selection

Preliminary Alloy Design and Process Modeling

Preliminary Alloy Evaluation and Characterization

Detailed Alloy Design and Process Modeling/Optimization

Detailed Material Properties and Tribological Characterization

Bushing Design and Surface Morphology Optimization

Component-Level Test and Demonstration

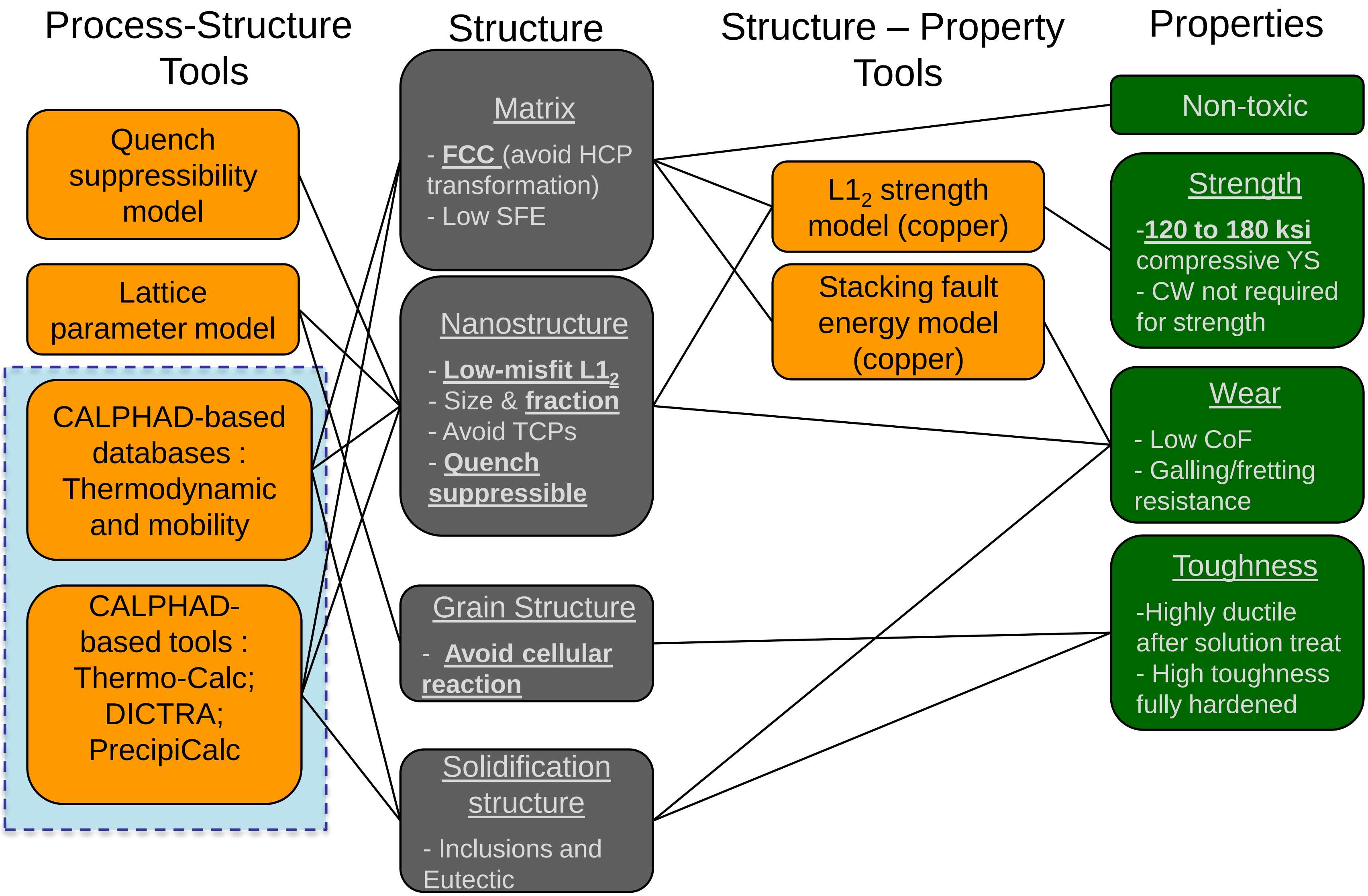
- Step-wise building block approach to identification of alternative alloy
- Driven by legacy and current design requirements for drop in form, fit, function replacement

Results: Alternative Cu-Be Alloy Concept Selection and Preliminary Cu-Be Alternative Alloy Design and Process Modeling

Cu-Based Alloys Drivers\Requirements

- Cu-Be alloys still represent the best combination of strength, wear properties and cost for highly loaded bushing applications
- QuesTek's NAVAIR-funded SBIR Phase II program demonstrated the feasibility of designing Be-free Copper-based alloys to achieve similar strength and wear behavior as Cu-Be alloys
    - ♦ However processability (especially hot-forgeability) limitations need to be addressed – focus of this effort
- QuesTek is addressing the key technical limitation through composition optimization to reduce the dependency on Sn (which causes hot-shortness) while still achieving required properties

Design Framework: Precipitation-strengthened Copper and Cobalt alloy



Process-Structure Tools

Quench suppressibility model

Lattice parameter model

CALPHAD-based databases : Thermodynamic and mobility

CALPHAD-based tools : Thermo-Calc; DICTRA; PrecipiCalc

Structure

Matrix

- **FCC** (avoid HCP transformation)
- Low SFE

Nanostructure

- **Low-misfit $L1_2$**
- Size & **fraction**
- Avoid TCPs
- **Quench suppressible**

Grain Structure

- **Avoid cellular reaction**

Solidification structure

- Inclusions and Eutectic

Structure – Property Tools

$L1_2$ strength model (copper)

Stacking fault energy model (copper)

Properties

Non-toxic

Strength

-**120 to 180 ksi** compressive YS
- CW not required for strength

Wear

- Low CoF
- Galling/fretting resistance

Toughness

-Highly ductile after solution treat
- High toughness fully hardened

NGCu-1: Design constraints and associated micro-structural features

Design constraint	Microstructural feature and properties	Risk factors
Easy to forge	- No Sn in alloy – No incipient melting - No other low-melting components/eutectics - Scheil solidification T of 1018°C	- High Ni in alloy – Can we eliminate segregation effectively?
Minimize cellular growth	- Lattice misfit of $L1_2$ and matrix reduced to ~ -0.75% - Grain-pinning dispersion to pin grain boundaries at lower end of forging (~0.5% of Ni-V FCC#2 at 850°C - ~4% V_f of $L1_2$ at 700C for sub-solvus treatment	- Is the lattice misfit small enough to eliminate cellular growth - Can a certain amount of cellular growth be tolerated?
Wear behavior	- Low SFE of matrix	- Will high Ni in matrix promote galling behavior?
Quench suppressibility	- lower solvus of $L1_2$ (580°C in absence of V)	- None – No issues in prior Navy alloys
Strength	- **Volume fraction of strengthening particles ~ 28% at 450°C (assuming 4% ppt at 700°C)** - **Expected YS > 135ksi**	- **Role of Mn on APB energy?** - **Can we get optimal size at 450°C?**

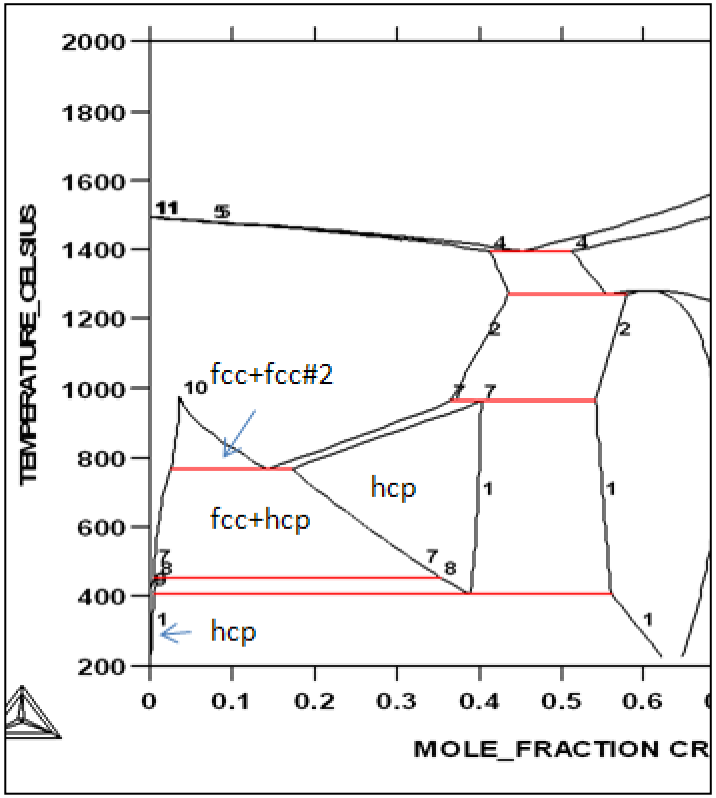
Comparison of NGCu-1 variants

Alloy	NGCu-1A (Sn-free) Lower -risk Lower- reward	NGCu-1B (with Sn) Higher-risk Higher-reward
Composition (wt%)	Cu-Ni-Al-Mn-V – ppm B	Cu-Ni-Al-Sn-V
Biggest risk	• Cellular growth leading to low ductility of aged alloy	• Forgeability
Main advantage	• Alloy is processable with no risk of hot-tearing during hot-working	• Addition of Sn has been shown to mitigate cellular growth and provide strength
Prototype size in current round	• Melt as 30lb VIM/VAR billet • Extrude to required dimensions for NG testing	• Melt as 5 lb arc-melted button • Extrude to 0.5” round rod
Wear behavior	• Expected to be equivalent	
Quench suppressibility	• Expected to be marginally better for NGCu-1A – Sn-free	
Strength	• **Expected to be better for NGCu-1B due to the role of the high diffusivity of Sn in helping the γ' growth kinetics – They reach optimal size faster**	

Co-Based Alloys Drivers\Requirements

- Best sliding wear resistance of any class of engineering metal
  - aCUBE is CoCrMo alloy showing excellent sliding wear performance
- Excellent CoF/wear resistance due to low ‘stacking fault energy’ of FCC-Co phase
  - **Tendency to transform FCC → HCP structure**
    - **Used in metastable FCC state @ Room temp.**
    - **Alloying to suppress martensitic transformation**
  - **Significant work-hardening associated with the phase transformation**
  - Existing CoCr alloy rely upon cold- or warm-work to achieve high strength (size dependent!)
- No equivalent to $L1_2$-strengthened Ni superalloys
- Excellent chemical/erosion resistance

Binary Co – Cr phase diagram



Precipitation Strengthened Co-Cr Alloy Design

- High Cr content – Wear/Corrosion
- Minimize the hardness and ease of machining in annealed state
    - Minimize interstitial elements (C, N)
    - Most machining before final solution heat treatment
- Design for a precipitation-strengthening dispersion
    - Solution-treatable following (rough) machining in annealed state
    - Efficient precipitation during tempering > ~700-900°C
    - Coherent phase is ideal: ($L1_2$ or γ') – Co_3Ti
    - Similar microstructures recently demonstrated for CoAlW (Cr-free) alloy … we need Cr (SFE)
    - Ensure good lattice parameter matching between the FCC matrix and ordered FCC ($L1_2$) particles
- Design for good solidification and hot-working
- Design for an efficient grain pinning dispersion
    - TiC can be effective at low phase fraction
    - Not explored in conceptual design

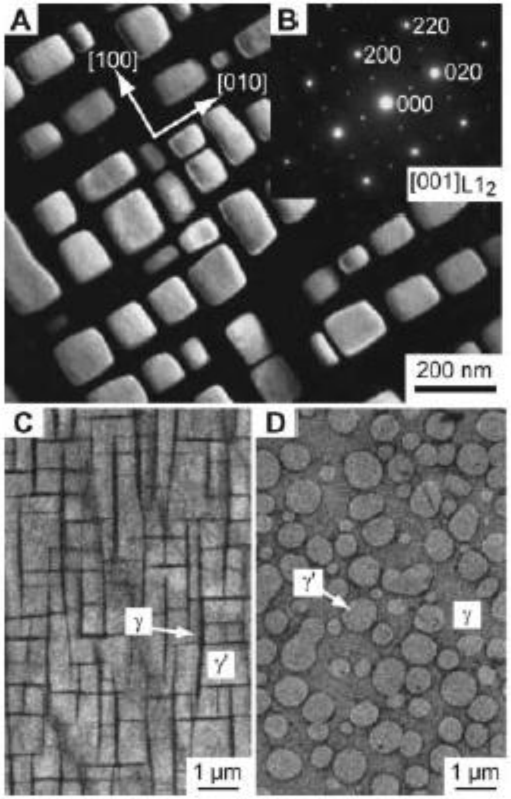
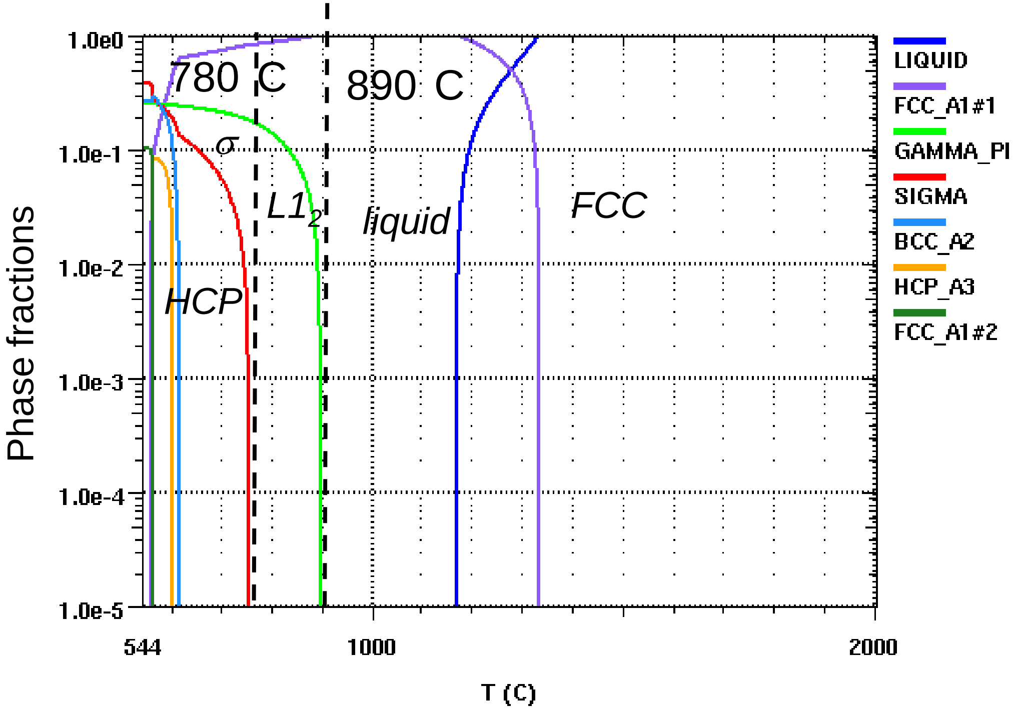


Fig. 1. Electron micrographs of Co-9Al-7.5W alloy annealed at 1173 K for 72 hours. **(A)** Dark-field image. **(B)** Selected area diffraction pattern. **(C** and **D)** Field emission scanning electron micrographs of Co-8.8Al-9.8W-2Ta (C) and Co-8.8Al-9.8W-2Mo (D) annealed at 1273 K for 1

7 APRIL 2006 VOL 312 **SCIENCE** www.sciencemag.org

NGCo-1A Design

Thermodynamic step diagram



Alloy	Solvus of γ'	V_f of γ'	δ (lattice misfit)	Aging Temp
QuesTek USMC B86 alloy Baseline	950°C	16%	0.4%	850°C
NGCo-1A	890°C	16%	0.4%	780°C

Lower solvus of the alloy – improved quench suppressibility

Risk Factors and Mitigation Strategy for Cobalt-based designs

FCC matrix + $L1_2$ strengthening precipitates

Risk Factor	Mitigation strategy
Quench suppressibility	• lower solvus of $L1_2$ (with respect to legacy QuesTek Co-alloy)
Cellular growth	• Match lattice parameters of $L1_2$ and matrix ($< 0.6\%$) • Grain-pinning dispersion to pin grain boundaries
Strength	• **Volume fraction of strengthening particles > 15% at 780°C**
Topologically close-packed (TCP) phases	• Keep stability limit of TCP phases below 780°C (aging temperature)
HCP transformation	• **Keep stability limit of HCP below 780°C (aging temperature)**

Outcome of Preliminary Alloy Design and Process Modeling

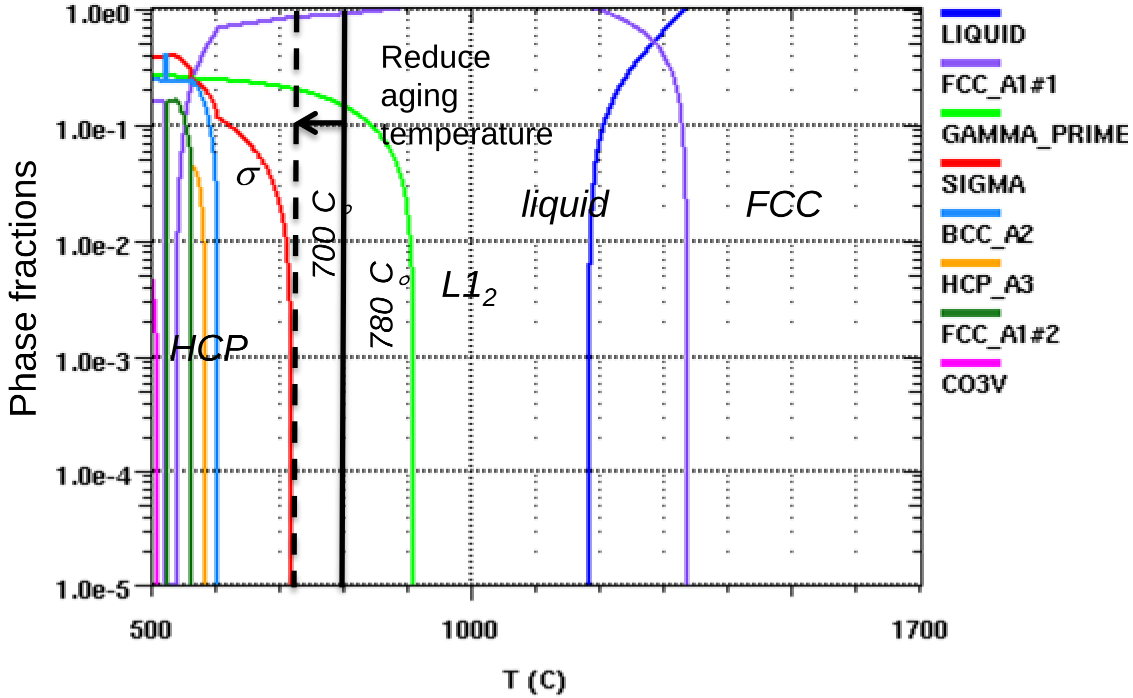
- Two QuesTek designs modeled and identified
  - Cobalt-based alloy
    - Modification of QuesTek's previous B86 alloy for the Marine Corp.
    - Modification necessary to improve the quench suppressibility of the alloy
  - Copper-based alloy(s)
    - Without Sn – lower fabrication risk; **higher risk in achieving required properties**
    - Variant of above with Sn – **Higher fabrication risk**; Less risk in achieving required properties – risk minimization strategy

COBALT ALLOY REDESIGN STRATEGY

NGCo-1A Microstructural Features

- Heat treatment at 780°C
- Target $L1_2$ phase fraction = 16%
  - ♦ Calculated achieved = 15.7%
- Target FCC-$L1_2$ lattice misfit = 0.4%
  - ♦ Calculated achieved = 0.41%
- Possible reasons for not achieving strength goal:
  - ♦ Volume fraction of strengthening $L1_2$ phase not sufficient – Needs to be increased?
  - ♦ Stress-induced FCC -> HCP transformation which promotes yielding

Strategy 1 – Increasing the $L1_2$ volume fraction by heat-treat optimization



Trade-offs

Pros:

- Higher volume fraction
- Higher driving force for precipitation

Cons:

- Longer aging time
- Higher risk for cellular precipitation
- Risk of sigma-phase (TCP) precipitation

δ=0.41%
V_f =15.7%

780 C

→

δ=0.55%
V_f =20.6%

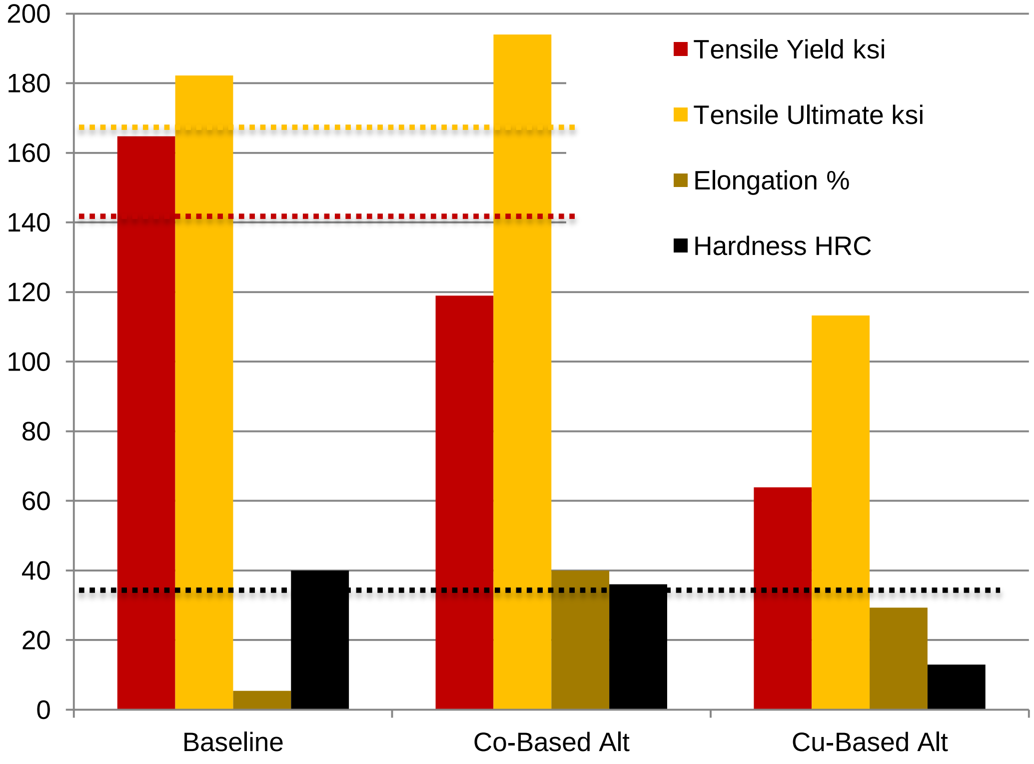
700 C

Strategy 2 – Compositional modification to prevent FCC→HCP transformation

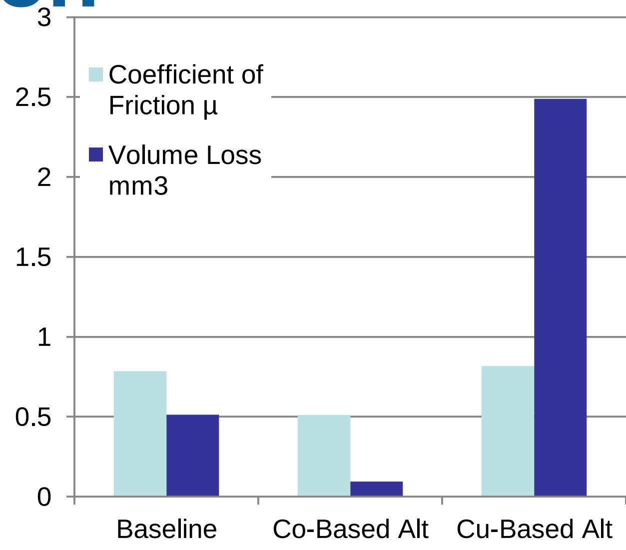
- Higher FCC stability needed?
  - X-Ray diffraction of Gage section of tensile bars to detect presence of HCP phase
- Both Ni and Fe stabilize FCC
  - Ni partitions to $L1_2$
  - Fe partitions to FCC matrix
  - Increase Fe content for more stable FCC?

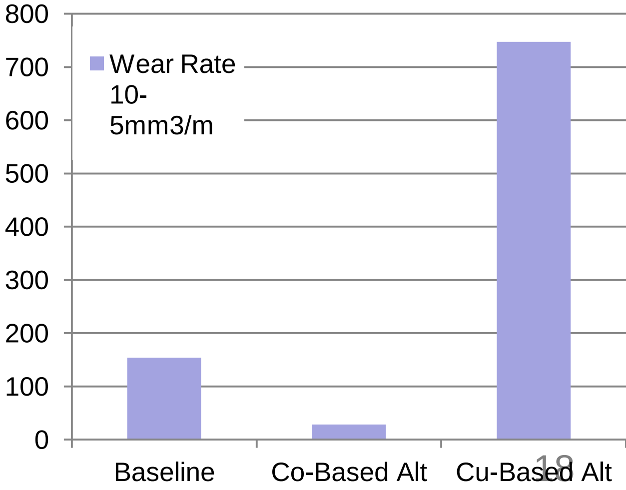
Results: Preliminary Alloy Evaluation and Characterization

Static Mechanical Properties
ASTM E 8



Dynamic Wear Properties
ASTM G 133





Upcoming Work

Requirements Definition

Current Database

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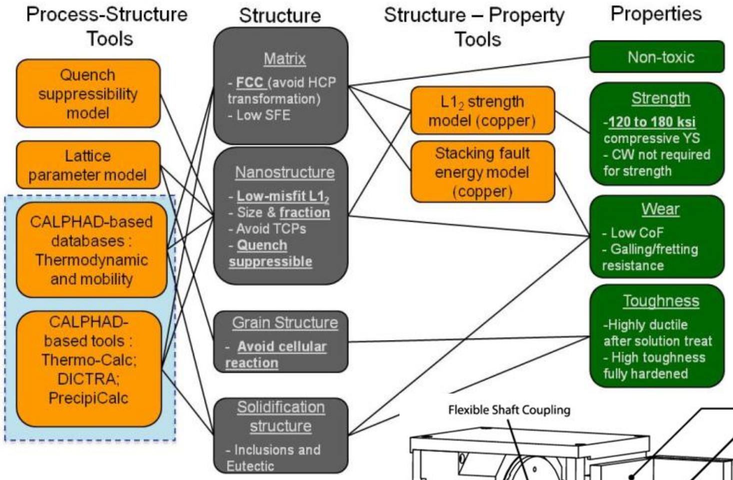
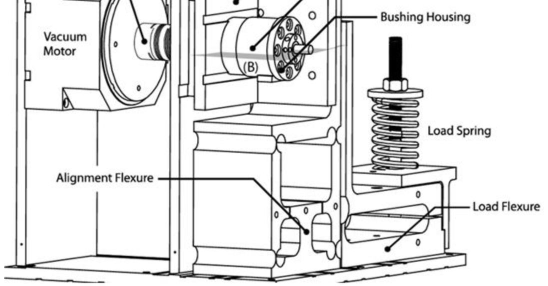
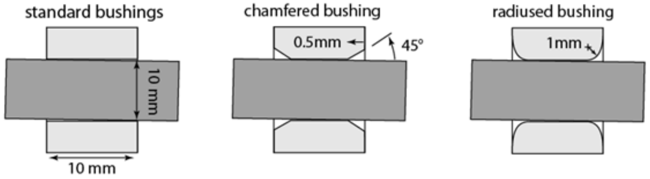
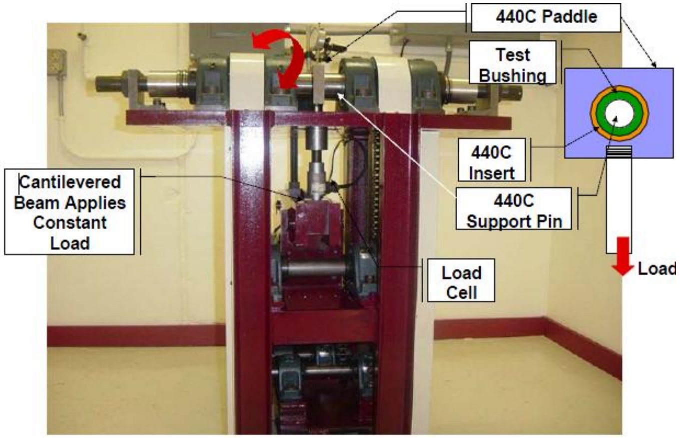
Component-Level Test and Demonstration









Questions?

BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

Acronyms

- UCAS - Unmanned Combat Air System
- UCLASS - Unmanned Carrier Launched Airborne Surveillance and Strike
- CALPHAD – CALculation of PHase Diagrams
- FCC – Face centered cubic
- SFE – stacking fault energy
- TCP – Topologically close-packed
- CW – cold-work
- YS – Yield strength
- HCP – Hexagonal close-packed
- CoF- Coefficient of Friction
- V_f – Volume fraction
- APB – Anti-phase boundary
- VIM – Vacuum induction melt
- VAR – Vacuum arc re-melt
- USMC – United States Marine Corp.
- RD – Round
- RCS – Round corner square

Preliminary Alloy Evaluation and Characterization: NGCu-1A and NGCo-1A Fabrication

- Alloys melted at 30lb sub-scale (SAES Getters) – 4” VAR
- Homogenized –
    - NGCu-1A - 975°C/48hrs
    - NGCo-1A - 1050°C/72hrs
        - Based on our solidification and homogenization simulations
- Grind outer layer to get 3.5” RD bar
- NGCu-1A - Extrude bar at 950°C down to 1.0” RD (12¼ :1 reduction ratio)
- NGCo-1A - Hot-roll bar at 1000°C down to 1.25” RCS (8 :1 reduction ratio)
    - Hot-working was performed at Special Metals, Huntington
- Optimized heat treatment to eliminate cellular growth and provide required strength
    - Sub-solvus temperature
    - Aging temperature

NGCu-1B – Sn Containing Variant - Fabrication

- **Final alloy:**
  - Cu-Ni-Al-V-Sn
  - Extrusion at lower temperatures to minimize risk of hot shortness

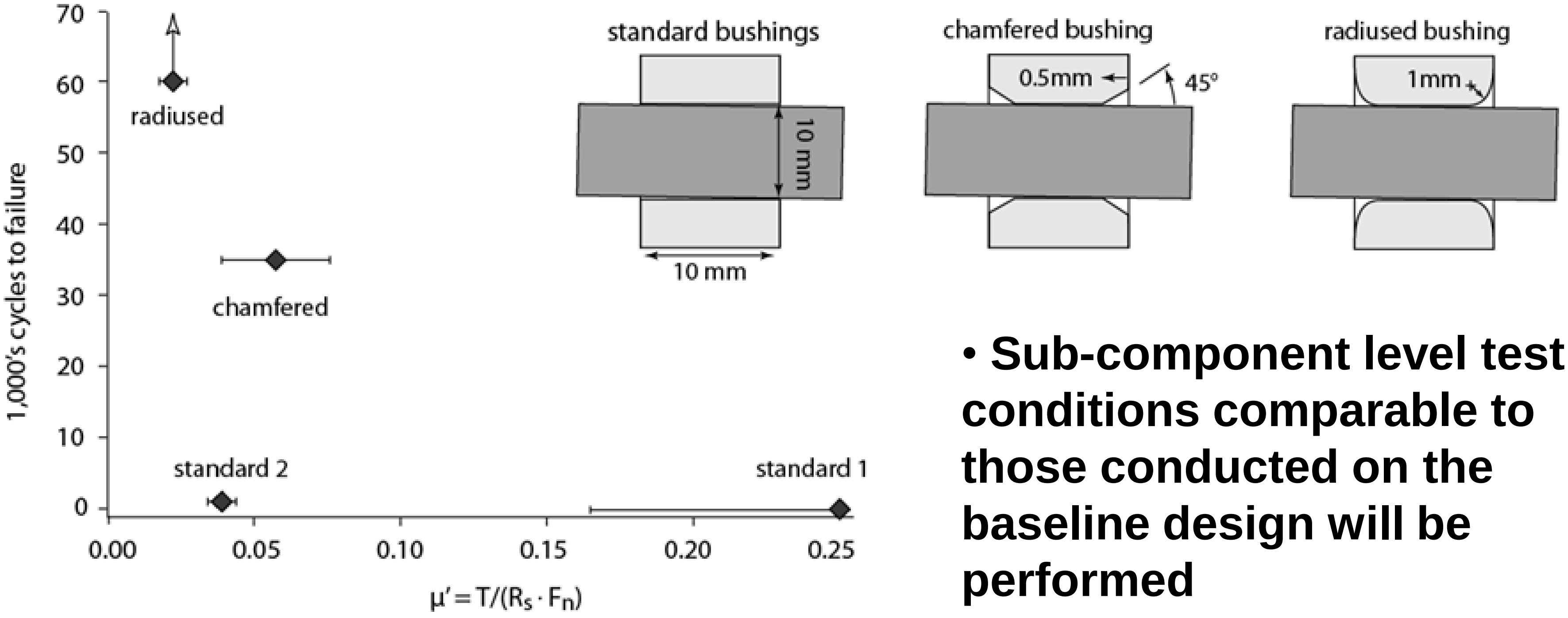
- Alloy was processed using spray-forming (Osprey) at Pennsylvania State University
  - Spray forming has been successfully completed (3 rounds of spraying to fine spray parameters)
  - Extrusion slugs fabricated from spray formed billets
- Grind outer layer to get 3.5” RD bar
- Extrude bar at 850°C down to 1.0” RD (12¼ :1 reduction ratio)
- Optimized heat treatment to eliminate cellular growth and provide required strength
  - Sub-solvus temperature
  - Aging temperature

Expect to complete by end of Sep, 2012

Technical Approach

Bushing Design and Surface Morphology Optimization

- **Novel, superior bushing designs and surface conditions will be developed and characterized to enhance the performance of the alloy and processes identified in previous tasks**



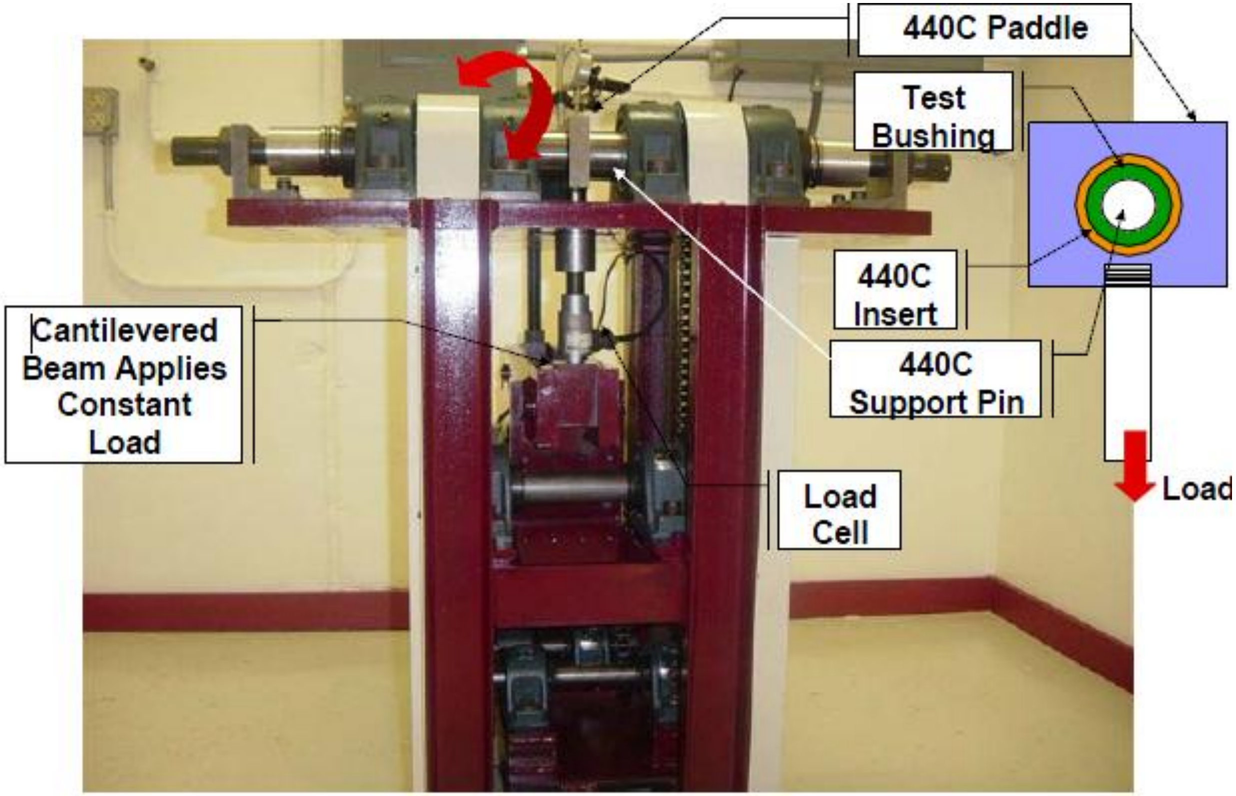
Thousands of cycles to failure plotted versus friction coefficient (μ') for standard and edge modified bushings.

- **Sub-component level test conditions comparable to those conducted on the baseline design will be performed**

Technical Approach

Component-Level Test and Demonstration

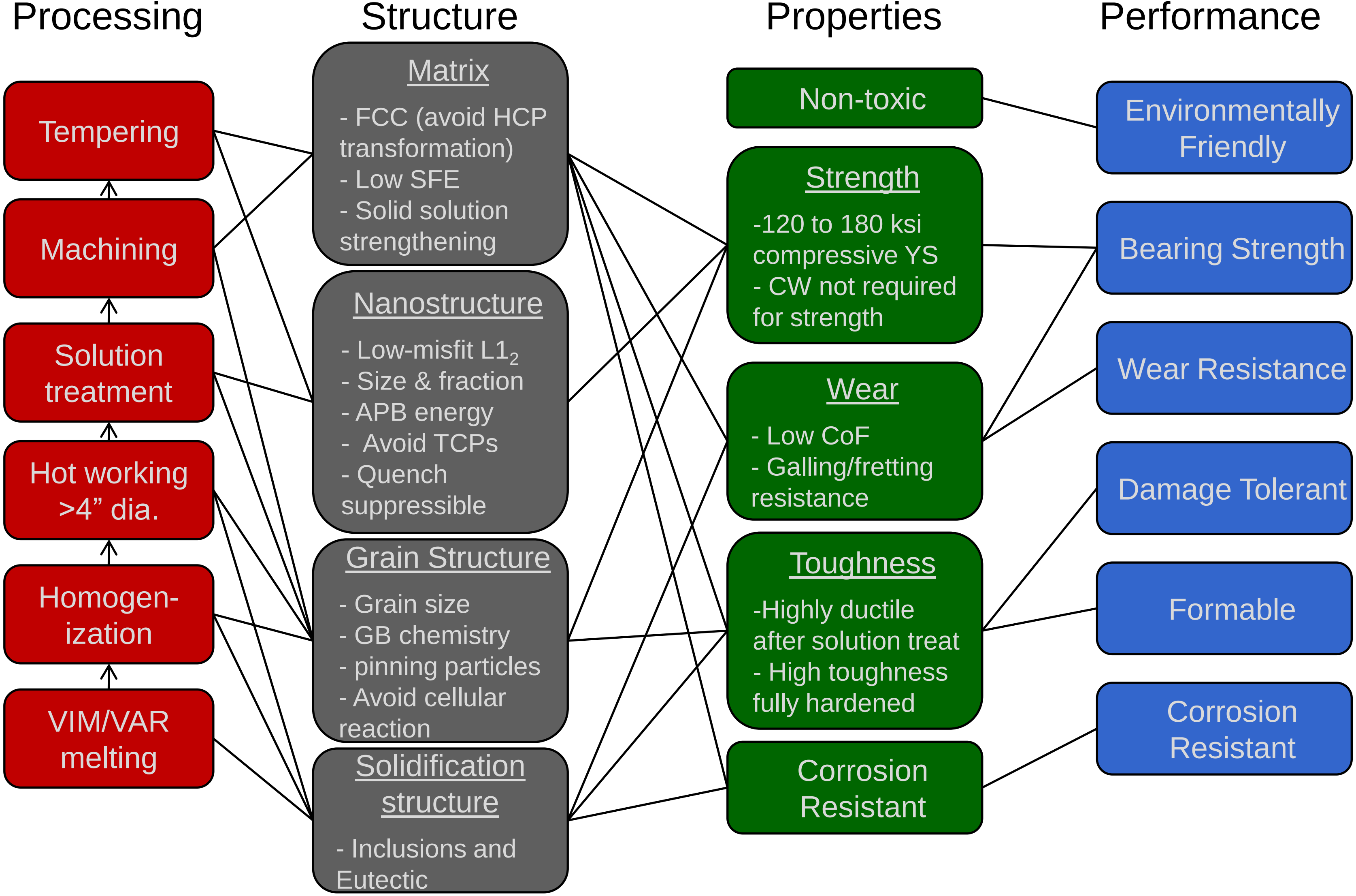
• Full-scale SAE AS81820 testing of bushings will be conducted to demonstrate performance under high loading conditions identified in requirement definition task at the onset of the program



•Full scale tests will be performed on baseline Cu-Be, alternative alloy\processing with baseline design and alternative alloy\processing with alternative bushing design.

Systems Design Chart:

Precipitation-strengthened Copper and Cobalt alloy



Processing

- Tempering
- Machining
- Solution treatment
- Hot working >4” dia.
- Homogen-ization
- VIM/VAR melting

Structure

Matrix

- FCC (avoid HCP transformation)
- Low SFE
- Solid solution strengthening

Nanostructure

- Low-misfit $L1_2$
- Size & fraction
- APB energy
- Avoid TCPs
- Quench suppressible

Grain Structure

- Grain size
- GB chemistry
- pinning particles
- Avoid cellular reaction

Solidification structure

- Inclusions and Eutectic

Properties

Non-toxic

Strength

-120 to 180 ksi compressive YS
- CW not required for strength

Wear

- Low CoF
- Galling/fretting resistance

Toughness

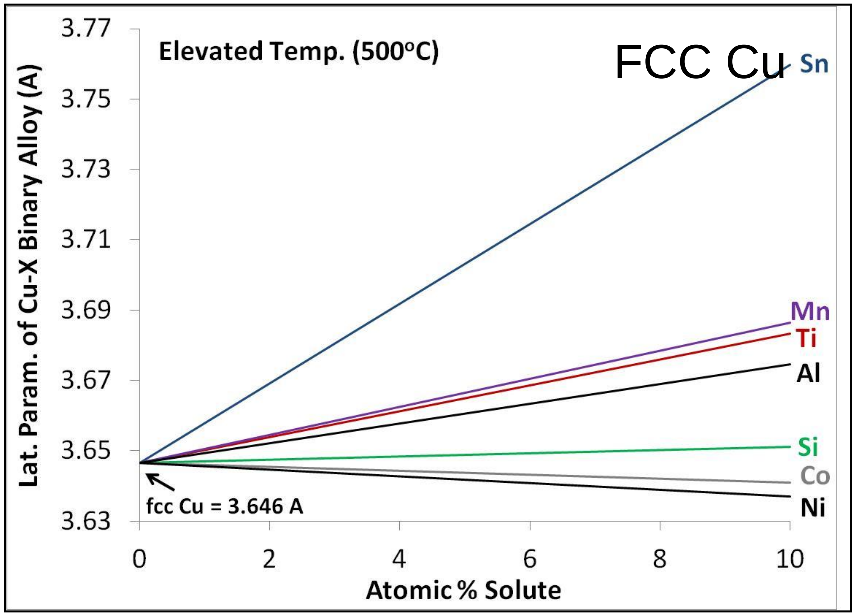
-Highly ductile after solution treat
- High toughness fully hardened

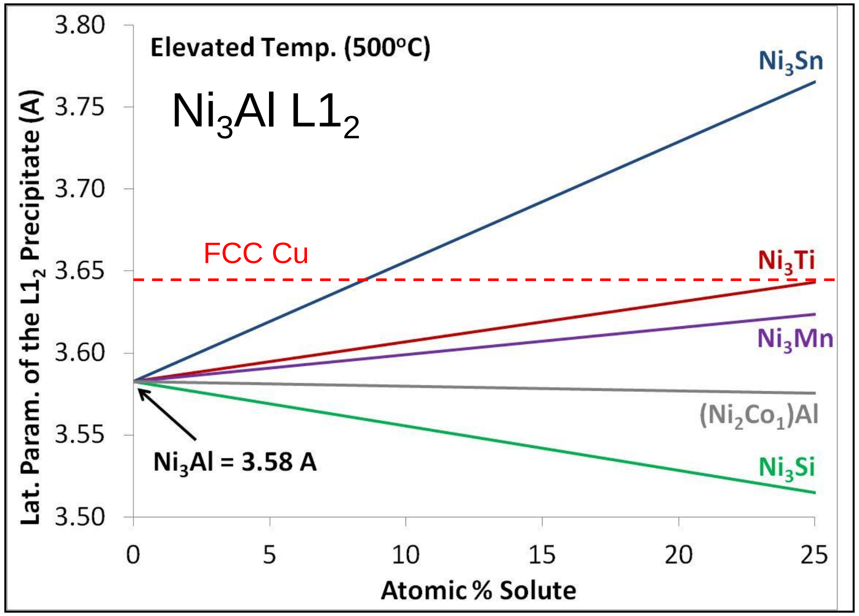
Corrosion Resistant

Performance

- Environmentally Friendly
- Bearing Strength
- Wear Resistance
- Damage Tolerant
- Formable
- Corrosion Resistant

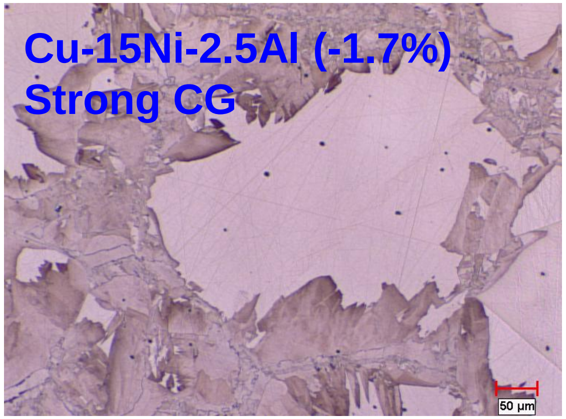
Lattice Parameter Model for FCC and $L1_2$



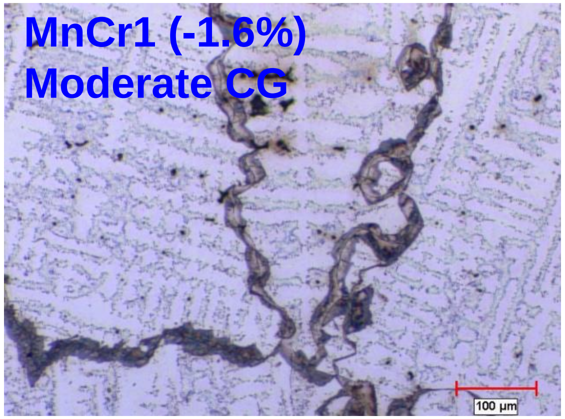


- We need to reduce matrix LP and expand $L1_2$ LP to minimize misfit
- Among substitutional elements, only Co and Ni have a smaller atomic radius than Cu
- Sn increases $L1_2$ LP most strongly – But causes incipient melting

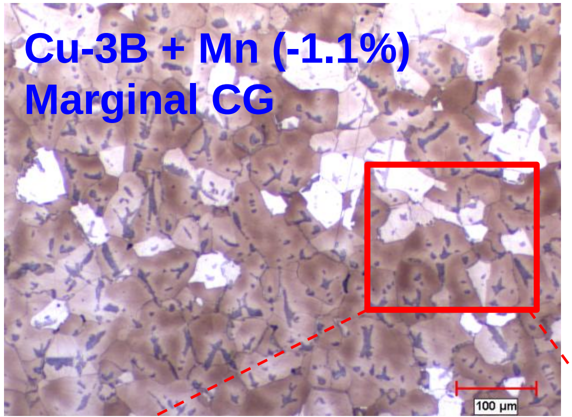
Microstructural observations correlate with LP model



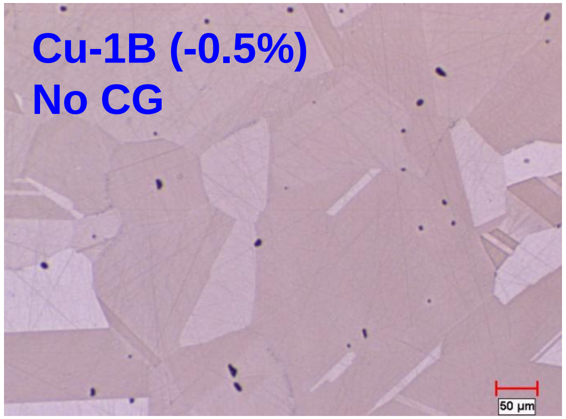
Cu-15Ni-2.5Al (-1.7%)
Strong CG



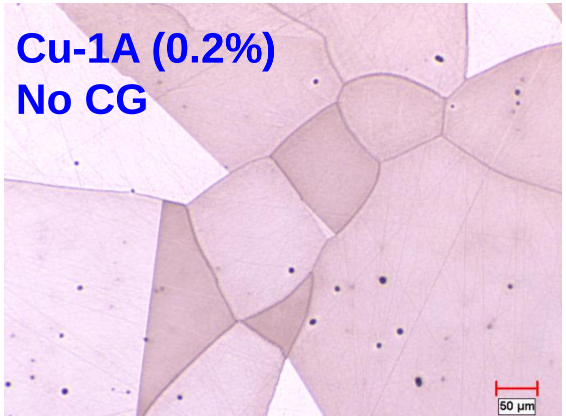
MnCr1 (-1.6%)
Moderate CG



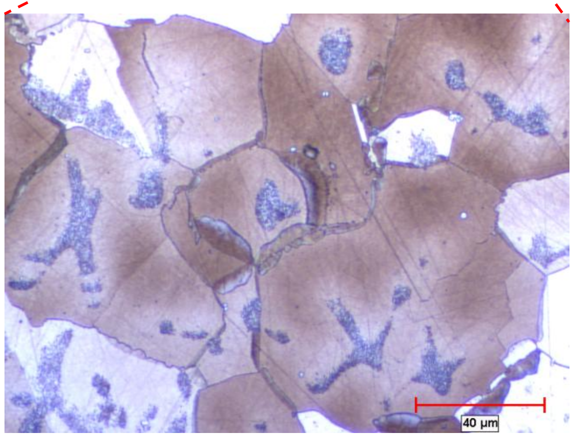
Cu-3B + Mn (-1.1%)
Marginal CG



Cu-1B (-0.5%)
No CG

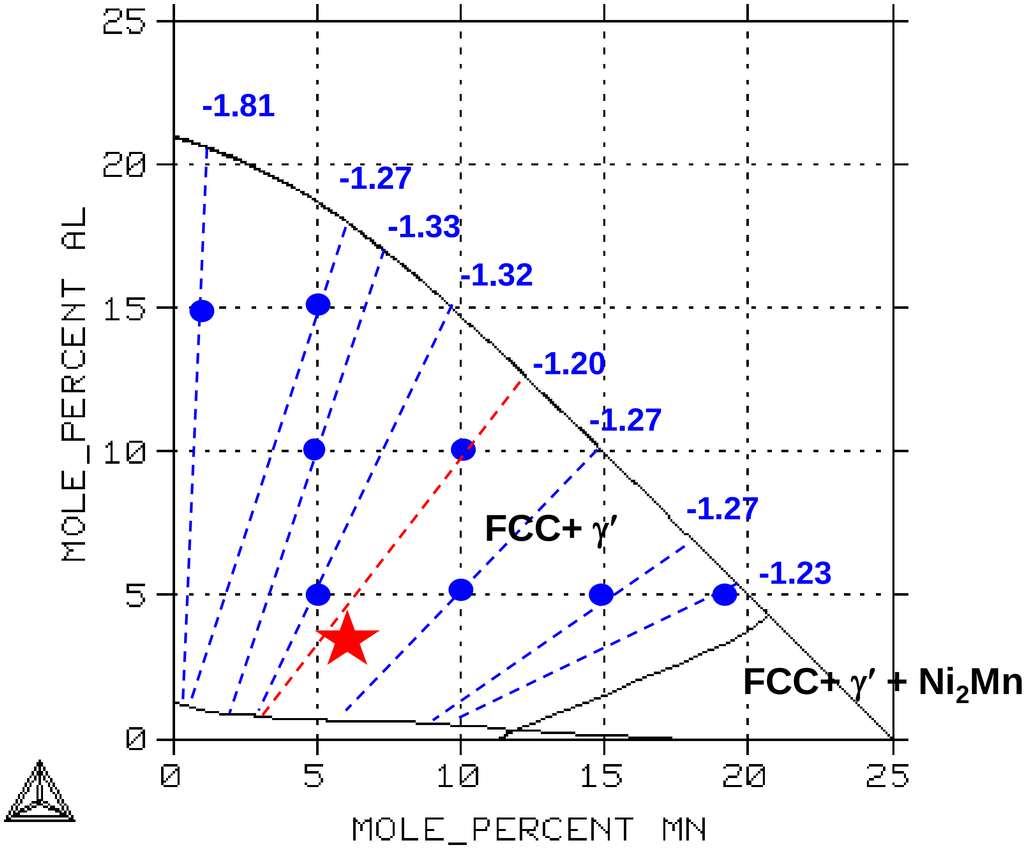


Cu-1A (0.2%)
No CG



All alloys received a sub-solvus + Temper at 500°C treatment
Alloy designations are internal QuesTek designations from previous Navy program

Effect of Mn and Al at 500°C



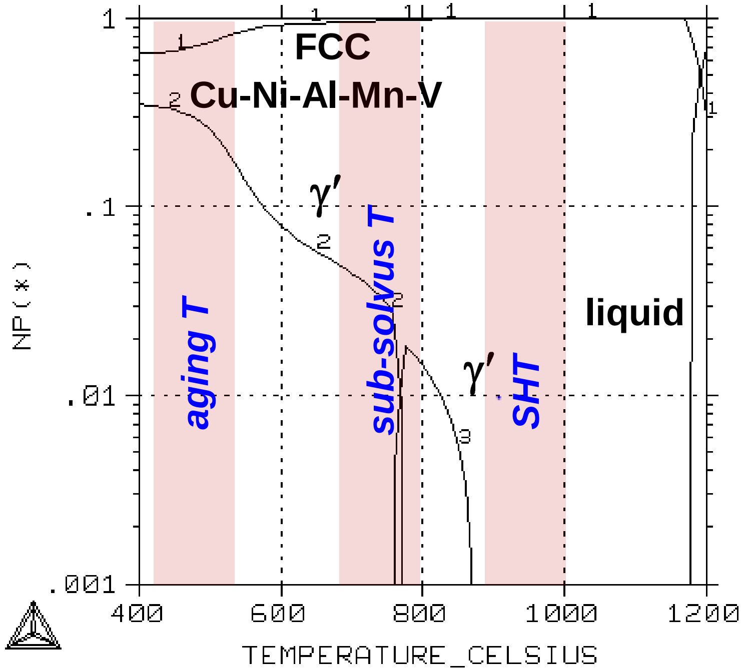
Constrained Cu-Ni_3Mn-Ni_3Al pseudoternary

Cu-xMn -yAl -3*(x+y)Ni (at%)

- Consider a Cu-Ni-Mn-Al system
    - ♦ FCC Cu matrix with γ' $Ni_3(Al,Mn)$ precipitates
- By balancing the Ni with Mn and Al, we can bring the lattice misfit down to -1.2%
- Goal is ~ -0.6%

Final Alloy Composition and Attributes – NGCu-1A

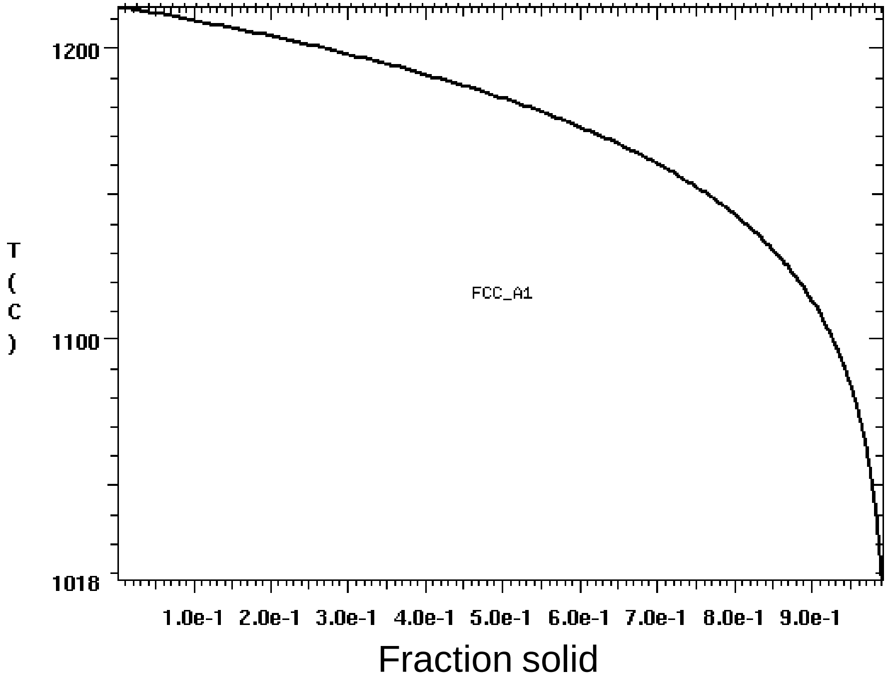
- Lowering aging T lowers lattice misfit
- Increasing Ni (overbalance) increase gamma_prime V_f
- Increasing Ni reduces lattice misfit (more Ni in FCC)



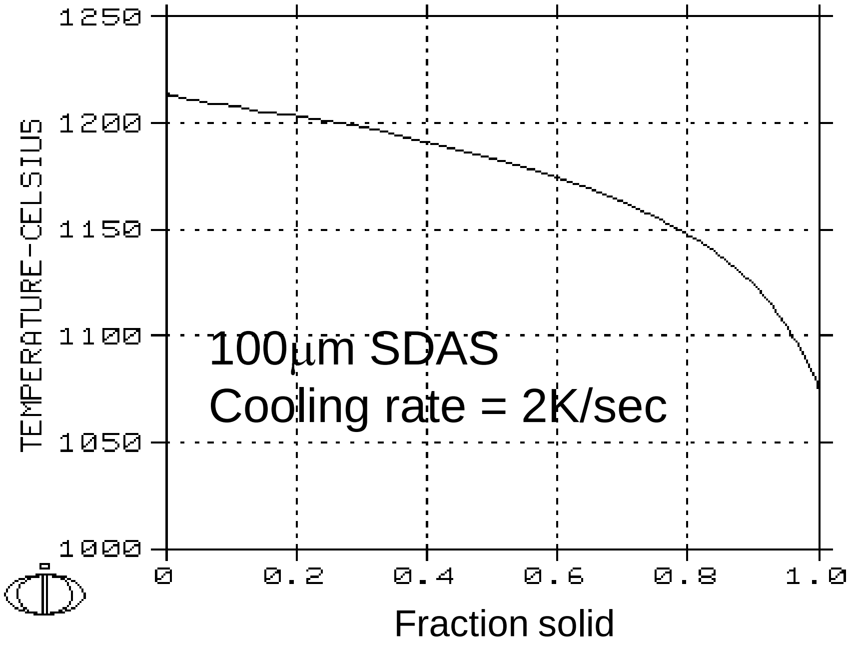
- V added to extend the γ′ solvus so that:
  - ♦ We can pin the GBs during forging
  - ♦ A double step sub-solvus treatment can be carried out to lock the GB further
- **Solution heat treatment at 900 – 1000°C**
- **Aging temperature of 450 – 500°C**
- **Final misfit of -0.75% (if sub-solvus treated at 700°C)**

Solidification of NGCu-1A

Scheil – No diffusion in solid and infinite diffusion in liquid



DICTRA – Diffusion in solid and liquid – accounts for back-diffusion during solidification

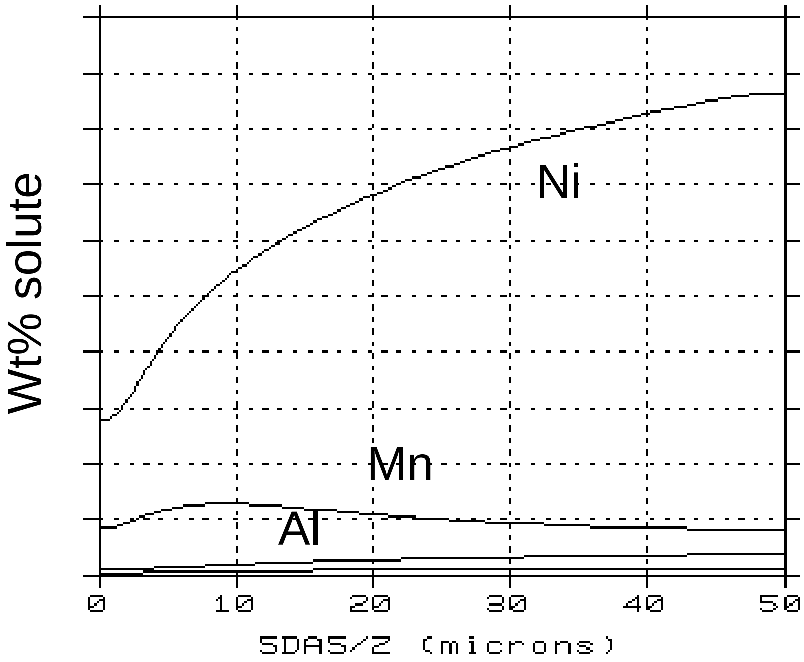


100µm SDAS
Cooling rate = 2K/sec

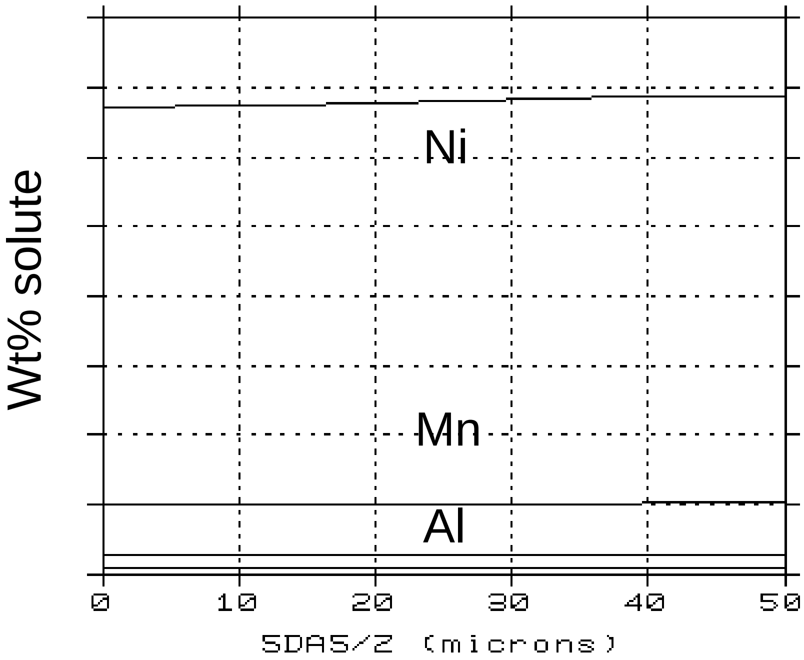
- Scheil solidification temperature - 1018°C
- Dictra solidification temperature - 1075°C

Homogenization of NGCu-1A

As cast



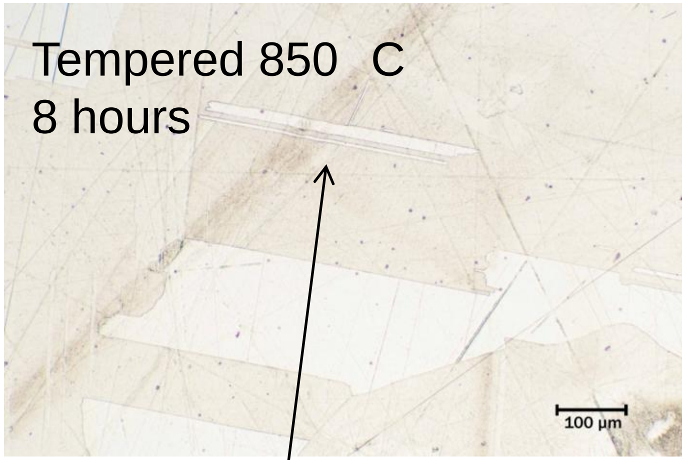
After 975°C/48hrs



- Homogenization at 975°C/48hrs should be sufficient to eliminate most of the as-cast microsegregation

Modeling and design in Previous USM program – QuesTek alloy B86

- Co-Cr-Ti-Ni-Fe-V alloy
- Design for FCC – $L1_2$ lattice parameter matching for stable, coherent dispersion
  - ♦ Avoid cellular growth reactions at g.b
  - ♦ Stabilize FCC (vs. HCP) at tempering temperature



Annealing twins (evidence of FCC with low SFE)

No cellular growth or unusual grain boundary particles

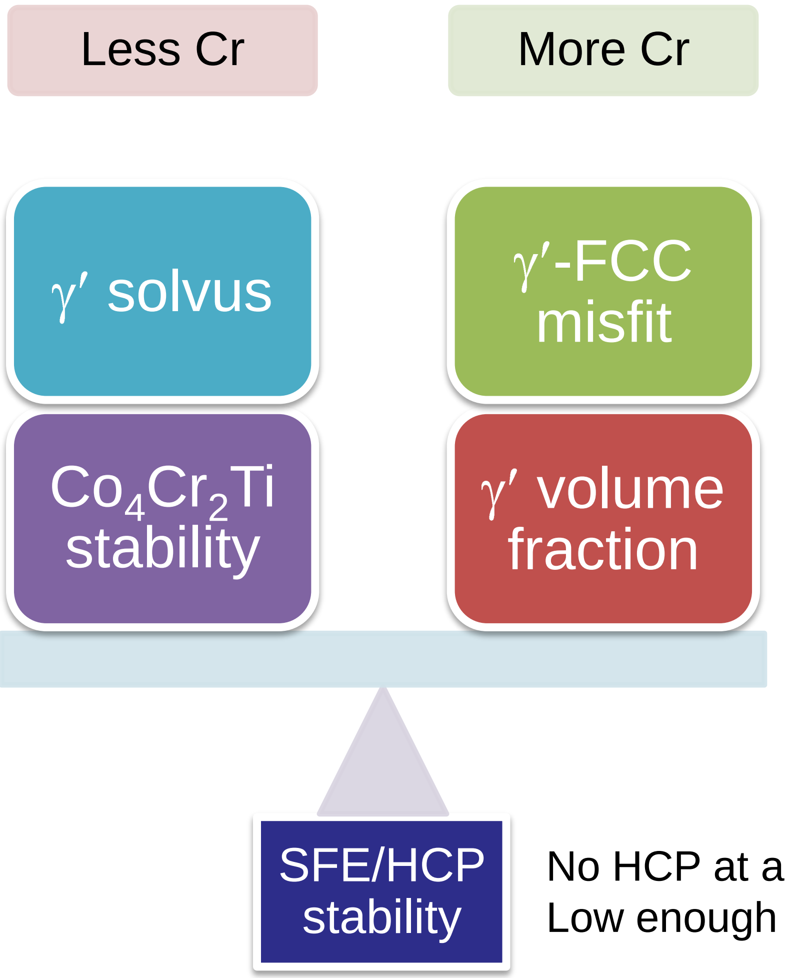
<u>Measured hardness</u>

Homogenized: 310 hv +/- 14.5
8 hr Temper: 357 hv +/- 11.3
24 hr Temper: 377 hv +/- 4.5

Estimated UTS of ~140 ksi after SHT
Estimated UTS of ~180 ksi after 24 hr. tempering

Very high hardness after quenching from homogenization – alloy lacked sufficient quench suppressibility – focus of redesign is to make the alloy more quench suppressible

Critical design parameters



≈12%

Less Cr

More Cr

≈18%

≈ 850 C

γ' solvus

γ'-FCC misfit

≈ 0.5%

Slow kinetics
Low solvus

Co_4Cr_2Ti stability

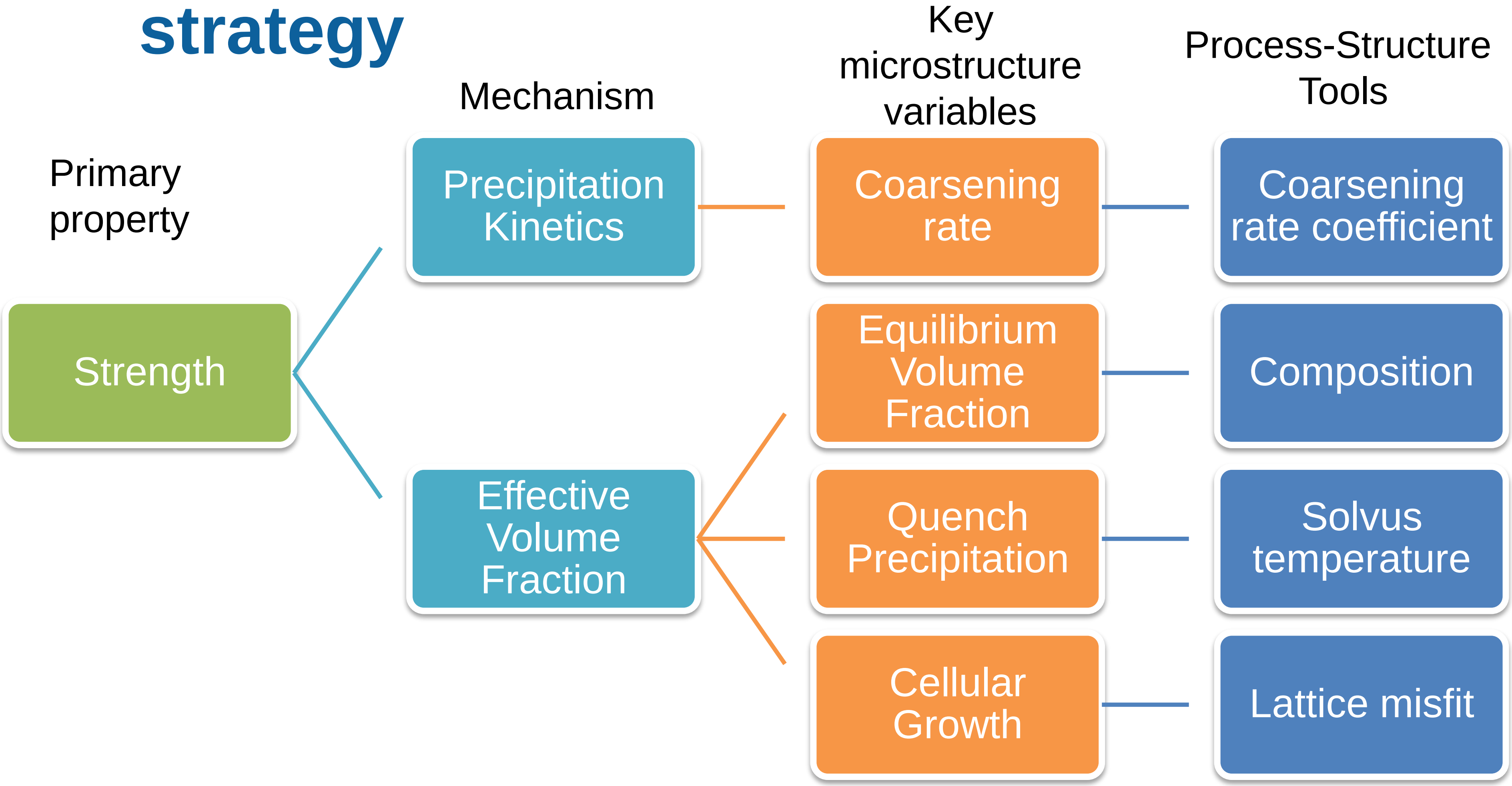
γ' volume fraction

≈ 10-15%

SFE/HCP stability

No HCP at aging temperature
Low enough for wear resistance

Cobalt-based Alloy Design strategy



Primary property

Mechanism

Key microstructure variables

Process-Structure Tools

Strength

Precipitation Kinetics

Effective Volume Fraction

Coarsening rate

Equilibrium Volume Fraction

Quench Precipitation

Cellular Growth

Coarsening rate coefficient

Composition

Solvus temperature

Lattice misfit

Tuning the phase stability

1. γ' solvus should be reduced → quench suppresibility

2. γ' solvus can not be too low → slow kinetics and low phase fraction

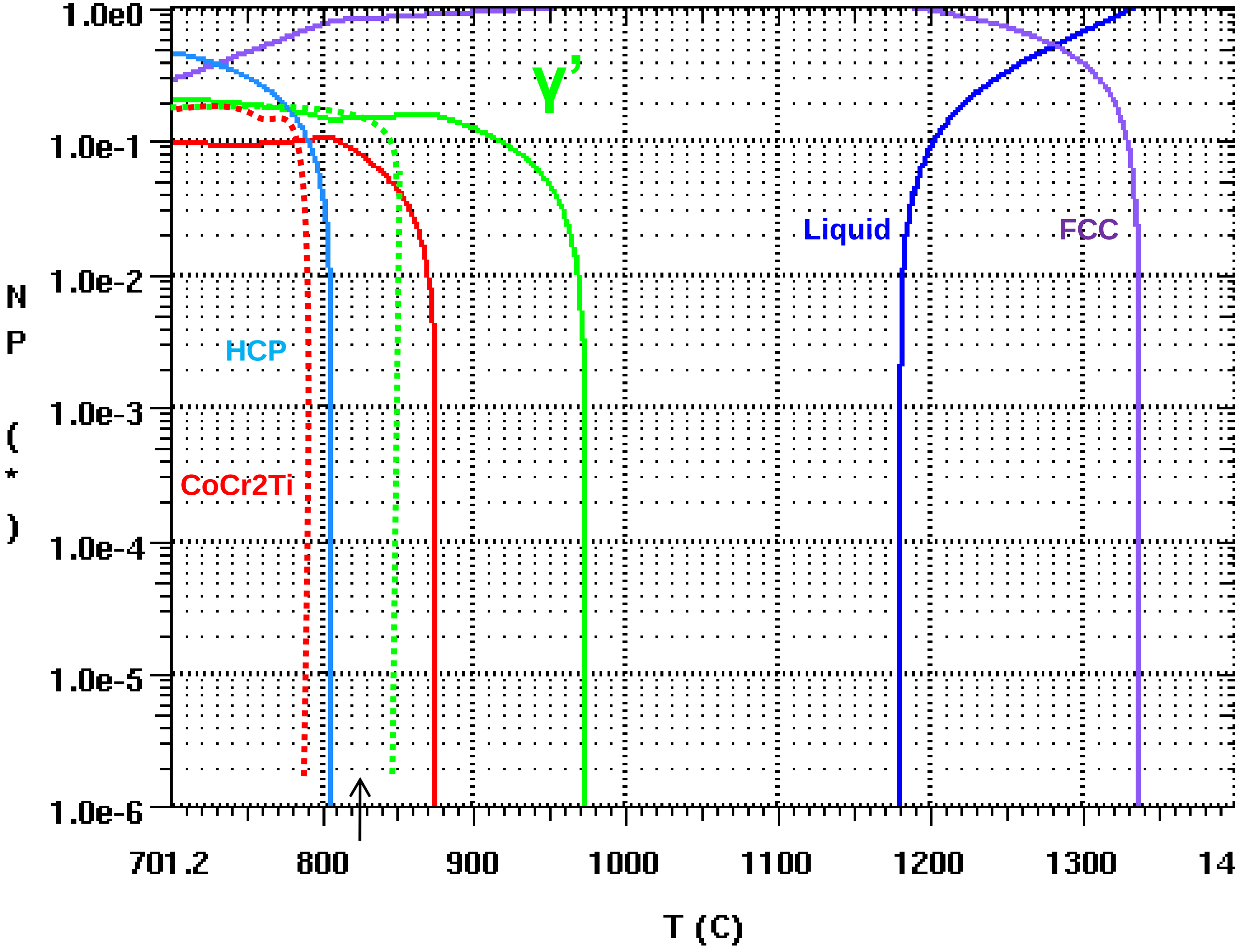
3. Co_4Cr_2Ti solvus should be reduced..

4. Depends on the final aging temperature for γ' precipitation, the solvus of HCP can go up or down to be just below the aging temperature

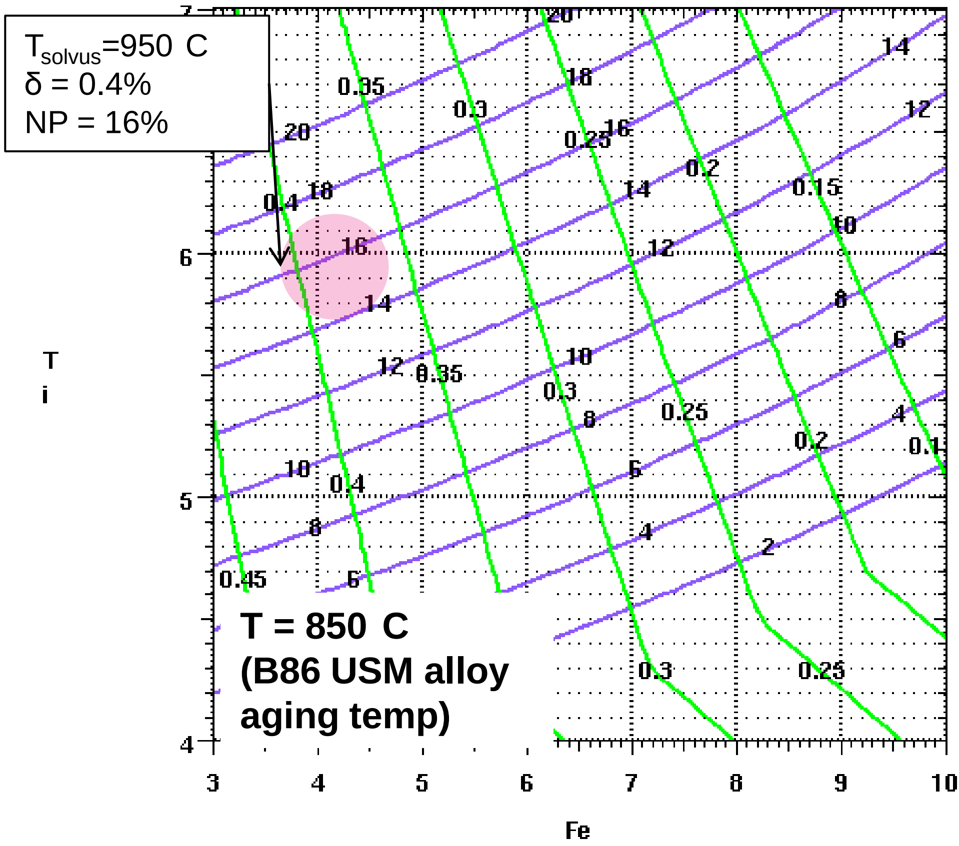
Co-Cr-Ti-Ni-Fe-V alloy

Solid lines – Previous QuesTek B86 alloy

Dashed lines – Desired for current program

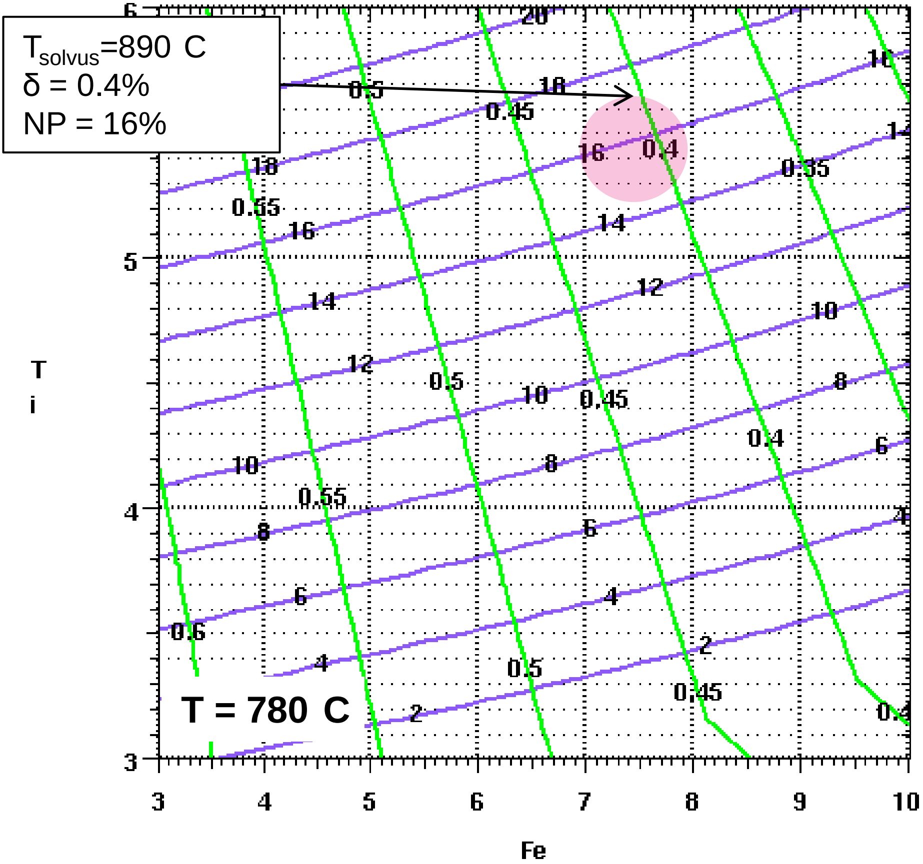


Redesign of Fe content



T_{solvus}=950 C
δ = 0.4%
NP = 16%

T = 850 C
(B86 USM alloy aging temp)



T_{solvus}=890 C
δ = 0.4%
NP = 16%

T = 780 C

By increasing iron content and lowering the aging temperature, the same lattice misfit and phase fraction is obtainable while achieving lower solvus temperature

Transition Plan

- F-35, F-18, UCAS, and UCLASS platforms briefed in requirements definition task, and regularly updated via interval program reviews
- Initial mechanical properties\performance results from preliminary alloy design and process modeling task to be used to ensure buy-in at design\stress\structural integrity levels
- First steps in validation and demonstration to be executed in the Detailed Material Properties and Tribological Characterization task (final FY13 task item)
- Potential ESTCP program could build on demonstration article for further demonstration on expanded scale