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Exploring Stability of Nanocrystalline Metals with Competing Solute Effects Under High Temperature Irradiation

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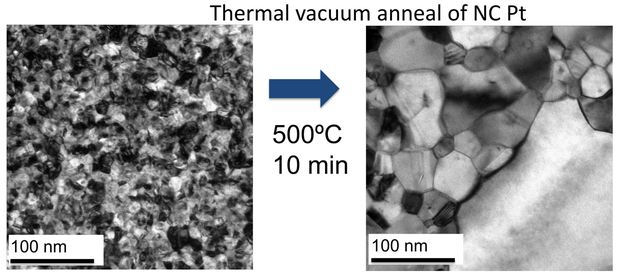
Introduction:

- Nanocrystalline (NC) metals have significant promise but a number of shortfalls exist for extreme environments
- NC metals have (some) desirable properties in comparison to coarse grain counterparts: higher yield strength, fatigue endurance, and radiation tolerance
- **Existing shortfalls**: grain coarsening under external stimuli

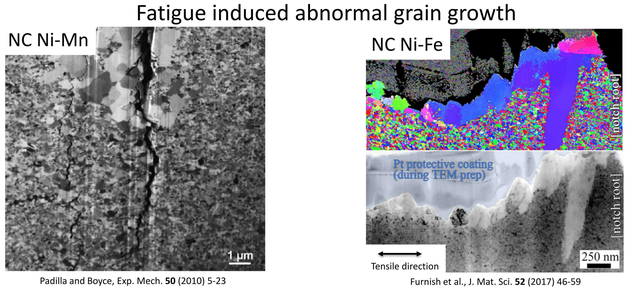
Thermal instability: Grain coarsening at low T/T_m annealing

Thermal vacuum anneal of NC Pt



Mechanical instability: Grain coarsening under dynamic loading

Fatigue induced abnormal grain growth

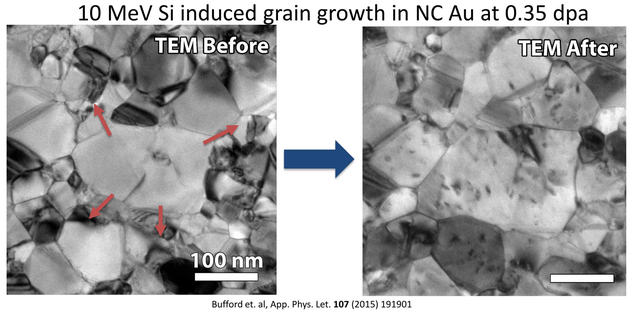


Padilla and Boyce, Exp. Mech. **50** (2010) 5-23

Furnish et al., J. Mat. Sci. **52** (2017) 46-59

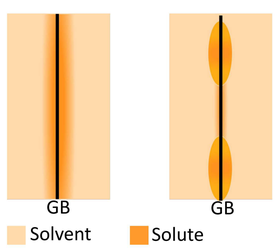
Radiation instability: Grain coarsening form neutron/ion damage

10 MeV Si induced grain growth in NC Au at 0.35 dpa



Bufford et. al, App. Phys. Let. **107** (2015) 191901

- Significant prior work successfully highlights route to minimize grain coarsening in thermal and mechanical NC systems through thermo and/or kinetic stabilization



GB solute design has been utilized to impact GB energy and mobility, examples:

- Reduce GB energy
- Solute drag
- Zener pinning

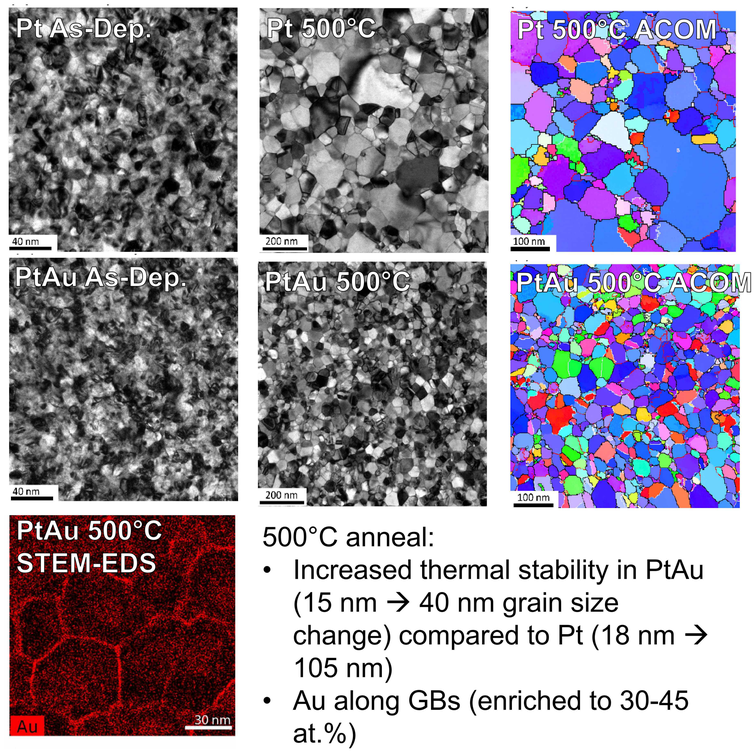
Results: Nanocrystalline Stability in Pt-Au

Problem Statement:
Does (or can) the *same solute design simultaneously* improve the response to these undesirable environments: thermal, mechanical, and irradiation NC metals?

- Why Pt-10Au? Noble metal binary system, large miscibility gap, favorable enthalpy of segregation and mixing for proposed solute induced NC stability; Pure Pt is control

PtAu thermal stability

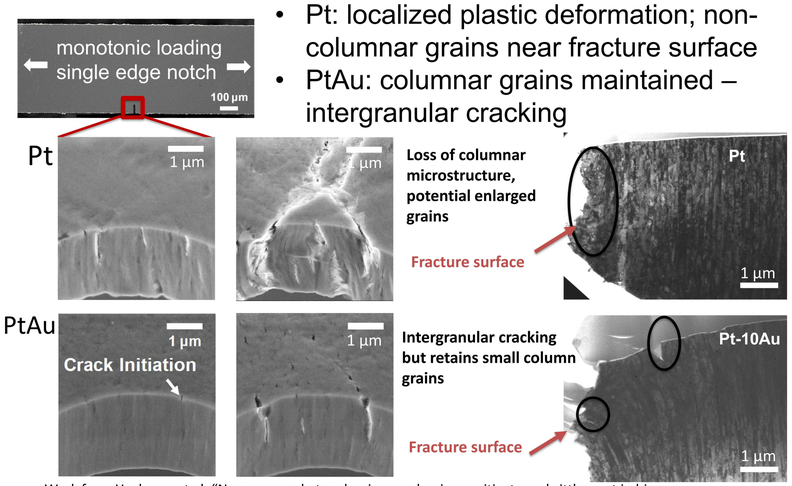
- Annealed at 500/700°C for 30 minutes; grain size and chemical distribution



500°C anneal:

- Increased thermal stability in PtAu (15 nm → 40 nm grain size change) compared to Pt (18 nm → 105 nm)
- Au along GBs (enriched to 30-45 at.%)

PtAu mechanical stability



- Pt: localized plastic deformation; non-columnar grains near fracture surface
- PtAu: columnar grains maintained – intergranular cracking

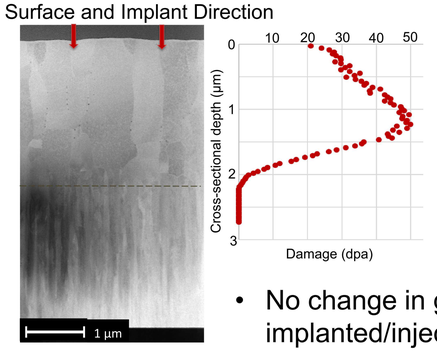
Work from Heckman et al, "New nanoscale toughening mechanisms mitigate embrittlement in binary nanocrystalline alloys, Nanoscale 10, 21231-21243 (2018).

Irradiation Induced Grain Coarsening:

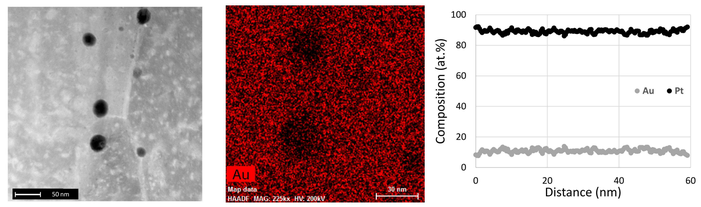
PtAu irradiation stability

- Pre-irradiation heat treatment – similar to thermal study
- 500°C/2hrs; 20 MeV Au^{4+}; RT, no external heating
- PtAu thin film (~ 5 μm thick); 1 x 10^{16} ions/cm^2

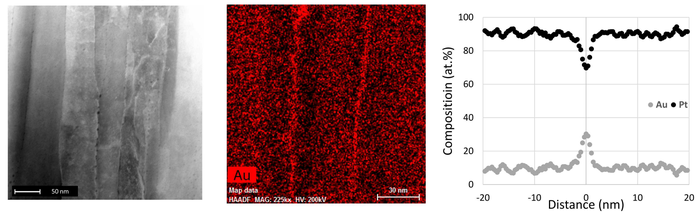
Surface and Implant Direction



- Significant room temperature grain coarsening observed in the irradiation zone
- No change in grain size beyond implanted/injection ion zone
- Irradiation zone (below): Au in solution (ion beam mixing effect) and ~400 nm columnar grain size



- Below irradiation zone: Au segregation at GB and retains 35 nm columnar grain size



Conclusions: Competing Stability Mechanisms

- Moderate but not complete thermal stability in PtAu; attributed to thermo/kinetic effect of Au enrichment at GBs
- PtAu is effective at stabilizing grain size under tensile loading but undesirable GB decohesion and intergranular cracking issue
- PtAu under irradiation leads to significant grain coarsening (>8X increase in grain size) due to ion beam mixing; results in PtAu without any preferred Au segregation
- NC stability through solute design for three different external stimuli: Au in Pt has varied success – extensive room to improve how to utilize a single solute GB design for multiple environments!

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