Solidification Behavior of High-Entropy Alloy Filler During Brazing of Ni-Base Superalloy

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1. Background & Objectives
- Brazing avoids issues associated with fusion welding of Nickel-base superalloys (e.g. solidification cracking, liquation, ductility dip cracking).
- High-entropy alloys (HEAs) can be tailored to melt at an appropriate temperature while avoiding the inclusion of melting point depressants (e.g. boron). Meanwhile, they can maintain a single FCC phase.
- A Mn$_x$Fe$_{1-x}$Co$_{1-y}$Ni$_y$Cu$_{1-z}$ is HEA filler was developed and proven feasible for brazing [1].
- The goal is to understand the solidification behavior to better control the microstructure and joint properties.

2. Alloy Design
- **CALPHAD Results**
  - Solidification pathway should proceed from liquid to single-phase FCC regime.
  - Mn and Cu serve as melting temperature depressants.
  - Melting range is 1090-1145°C. Ni-base alloy 600 soldius is 1350°C.
  - During solidification in dendritic morphology, Cu and Mn were expected to segregate to the interdendritic regions that solidify last.

- **In-situ XRD on Laser-Melted Pure Filler**
  - Solid Before Melting (~16 ms)
  - Molten (0 ms)
  - Partially Re-Solidified (16 ms)
  - Fully Re-Solidified (120 ms)

- Peak indices labeled on chart refer to FCC phase. Each peak corresponds to a ring in the 2D pattern.
- Time stamps above each curve are relative to the instant at which the material through which the x-ray beam passes became molten.
- 2D patterns indicate differences in grain size and microstructure before and after re-solidification.
- The presence of a FCC sub-peaks developing after about 20 ms during re-solidification is a signature of the atomic segregation observed in post-mortem characterization.
- Further analysis on lattice evolution will be made to understand the segregation behavior.

3. Brazing Procedures
- **Temperature (°C)**
  - L1$_2$-Ni$_2$Al
  - L1$_2$-Cu$_2$Al
  - L1$_2$-Fe$_2$Al
  - L1$_2$-Co$_2$Al
  - L1$_2$-Mn$_2$Al
- **Diffusion Behavior**
  - During solidification, Cu and Mn are expected to segregate.

4. Results & Discussion
- **Monte Carlo Simulation Results**
  - Both filler and substrate index to a FCC phase with high volume fraction (~0.5)
  - Filler grains are refined and equiaxed
  - Interendritic elements (Cu, Mn, some Ni) are mostly pushed to the filler centerline.
  - Clear boundary between substrate and filler grains indicates either non-epitaxial nucleation or epitaxial growth followed by stress-induced dynamic recrystallization.
  - Extensive twinning, principally in substrate, is another signature of stress in system.
  - Lattice mismatch at filler-substrate interface could also be a source of stress.

5. Conclusions and Future Work
- **CALPHAD predicts filler solidification as a single FCC phase. In-situ XRD on laser-melted filler confirms the presence of one set of FCC peaks. Sub-peaks emerging in partially solidified filler indicate transient lattice evolution caused by segregation.**
- **Monte Carlo simulations predict segregation of Cu itself and Ni together with Mn.**
- **EES on brazes confirms that Cu, Mn, and Ni segregate to the last region to solidify.**
- **Future work:** Reveal element segregation, filler/substrate grain and lattice evolution in situ with synchrotron-generated XRD and assess mechanisms of twinning and dynamic recrystallization in the filler system.