Development of Reduced-Activation High-Strength High-Conductivity Copper Alloys for Additive Manufacture of Fusion Reactor Components

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Additive manufacture (AM) of fusion reactor components enables materials and geometries unachievable through conventional machining [1]. Current high-strength-high-conductivity (HSHC) alloys used in Laser Powder Bed Fusion (L-PBF) include GRCop-84/42 [2], which utilize niobium chromide (Cr_2Nb) precipitates that resists coarsening in high temperature exposure [3] due to the low solubility within the copper matrix. Neutron-activation of niobium [4] makes Cu-Cr-Nb unsuitable for future fusion power reactors. We report development of three new reduced activation HSHC copper alloys using Gas Atomization (GA) with $TiCr_2$, $TaCr_2$, or TaV_2 Laves phase precipitates that maintain the favorable L-PBF properties of GRCop while eliminating niobium within the alloy. Precipitate size was refined during L-PBF, similar to GRCop, implying high tensile strength. A GA and powder Cold-Spray (CS) system was constructed for rapid nuclear alloy development and evaluation.

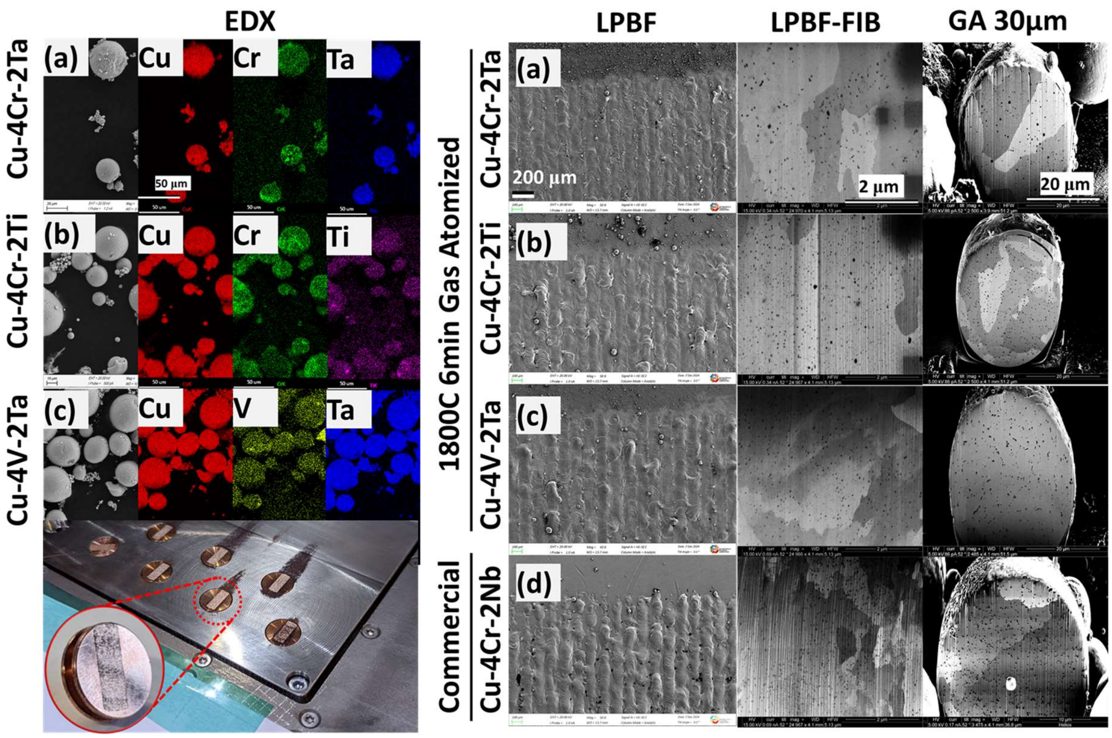

Fig. 1. Gas atomized powders showed consistent alloying with EDX analysis (a-c, left). L-PBF of atomized powders produced a layer of AMed material on SEM stubs inset into the build plate (bottom left). L-PBF parameters for reduced activation alloys (a-c, right) were equivalent to GRCop-42 (d). Refinement of precipitate size during L-PBF of novel alloys was similar to GRCop-42 (a-d, right).

GA powder samples were AMed with L-PBF in an Exact-Metal printer using a modified build plate to hold scanning electron microscopy (SEM) stubs (bottom left). GA GRCop, Cu - $TiCr_2$, $TaCr_2$, and TaV_2 alloy powders were consolidated into a single layer, **Fig. 1** (a-c, right), using 378 W of laser power from an L-PBF Yb-source of 1070 nm wavelength, scanned at 632 mm/s with 130 µm hatch spacing by beam of 100 µm in diameter; GRCop and novel alloys were printed with identical laser settings implying similar laser coupling to these new alloys. The square-cube cooling law in GA powder particles resulted in a sweep of cooling rate vs powder diameter, demonstrated in GRCop [5], that is replicated in Cu - $TiCr_2$, $TaCr_2$, and TaV_2 alloys where decreased precipitate size was observed at increased cooling rates as powder diameter decreased. Focused Ion Beam (FIB) sectioning of GA powder and L-PBF samples showed precipitates were refined by the rapid melting and re-solidification by a factor of ~10x in L-PBF compared to 30 µm powder particles, implying a suitabile replacement for GRCop, where precipitate refinement improved Orowan strengthening of yield and ultimate tensile strength. Precipitates in these AMed alloys were similar in size and area fraction [6] to existing copper alloys resistant to neutron damage, providing sinks for vacancies, interstitials, and helium generation that results in voids and material degradation. Similarly sized $NbCr_2$ precipitates suppressed void formation under self-similar-ion irradiation up to 40DPA.

A compact GA and CS system, **Fig. 2** (a) produced small samples of novel alloys on the order on 0.05-0.1g of material per batch allowing rapid tuning of alloy composition and GA parameters. A high temperature tube furnace alloys low-solubility elements at up to 2500°C, and an additive manufactured GA nozzle array produced 10-100 µm powder diameters (b) in a supersonic argon flow with an in-flight cooling rate of ~$1x10^5$ K/s. Melting of elemental powders for novel copper alloys at 1800°C for 6 min produced homogenous alloying for all three material combinations, shown in Energy Dispersive X-ray (EDX) analysis in **Fig. 1** (a-c, left). The system enables CS of powders onto adjacent strips on a target coupon for future neutron-damage simulations using self-similar-ion + helium co-irradiation. This techniques permits simultanious evaluation of several alloys, where powder particle diameter controlles precipitate size, adjacent stripes select alloy composition, and DPA gradient along the strip length controls ion damage magnitude. This technique will allow simultaneously evaluation of projected neutron damage effects in several candidate alloys as a function of precipitate size and DPA to qualify and optimize alloy composition for fusion reactor use, where high conductivity components are needed in RF systems and high-heat-flux first wall and divertor areas. Work supported by US DOE under DE-SC0014264.

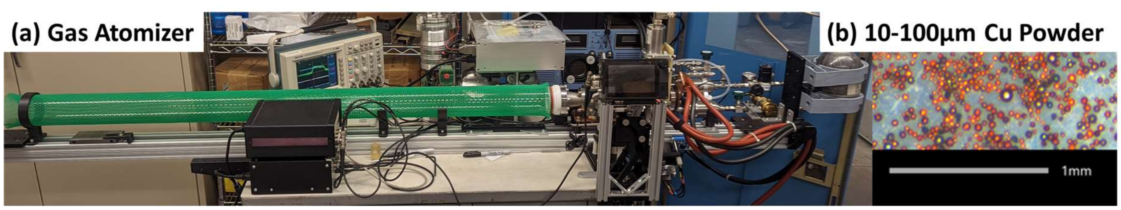

Fig. 2. A gas atomizer (a) produced atomized copper alloy powder particles by melting elemental mixtures within a tube furnace at 1800C that was injected into a supersonic argon atomization gas flow that breaks up the melt into fine droplets. Atomized powder diameters range from 10-100um in diameter (b).

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