

DESIGN CONSIDERATIONS FOR MATRIX COMPOSITIONS OF SELF-HEALING METAL-MATRIX COMPOSITES

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ABSTRACT

Self-healing composites involve the complex interaction of mechanisms at multiple length-scales and across numerous processing-structure-property relationships. Identifying potential alloy systems, which can be designed to exhibit self-healing, can be a tremendous and tedious undertaking. When dealing with systems possessing multivariate effects, a systematic approach can be used to find the optimal combination of processing steps and microstructures in order to achieve the desired self-healing behavior. In an effort to facilitate the development of self-healing composites, a systems design approach motivated by thermodynamics was used in determining alloying element(s) selection and processing/healing conditions. The steps were then used to provide a route to predict matrix and interfacial bond strength, oxidation resistance, and strength recovery after healing. This study will reveal potential matrix compositions and processing/healing steps in addition to preliminary data demonstrating the efficacy of this design methodology to improving the self-healing capabilities in high-specific strength metal matrix composites.

Self-healing metal-matrix composites have garnered interest as potentially transformative materials leading towards novel smart materials of the future. The latest research involves high specific strength alloys paired with shape-memory wire reinforcements to aid in fracture closure. In order to facilitate the development of high specific strength matrix materials exhibiting self-healing characteristics, a systems design approach has been utilized. Performance criteria for the matrix include high strength and low density. Other considerations which apply directly to self-healing characteristics include retained strength at elevated temperatures ($>0.5T_M$), a microstructure exhibiting a non-continuous eutectic second-phase, and a low eutectic temperature. From these considerations, several alloy systems have been considered and are discussed in this presentation.

For each system, binary alloy combinations were investigated using computational thermodynamics and phase equilibria from the literature to determine the suppression of the eutectic temperature for each alloying element. The solid-solution strength of each alloy combination was explored in order to obtain the highest strength in the final alloy combination. Special consideration was given to alloying elements exhibiting the highest solid solubility. From these binary combinations, high strength ternary alloys were identified which would potentially exhibit self-healing characteristics when paired with shape memory alloy wires in a composite.

Recent research into the properties affecting self-healing capabilities has shown the chemistry of the liquid healing phase is critical to promote healing [1-3]. Additionally, oxidation at the fracture surface has been found to degrade self-healing potential in metallic systems. The reduction in strength is thought to be caused by the lack of bonding at the fracture interface upon crack closure due to the presence of this surface oxide [1]. However, literature has described how additions of elements with strongly oxidative characteristics, such as rare earth elements, increase the interfacial bond strength at

metal-oxide interfaces [4-8]. This increased strength has been attributed to the preferentially formed high-melting point metal oxides at the interface [4-6]. These additions have also been shown to increase wettability and refine the grain structure in the alloy [4-8]. The demonstrated properties could potentially promote healing and aid in strength retention after healing. Thus, this study also investigates the addition of elemental species, which in their oxidized state possess a highly negative free energy of formation, to metal matrices. With the goal of quantifying self-healing efficiency, plane-strain fracture toughness testing was utilized to study the effect of reactive elemental species during healing.

In order to investigate this phenomenon, different binary alloy combinations were considered from several low-melting alloys for use as a prototype. The binary alloy system was required to meet the following criteria: possess one binary with an alloying element more reactive than the base metal and the other binary with a less reactive element and allow for 20% non-continuous liquid in the matrix at elevated temperatures. Two antimony alloys were found to match this criterion; antimony-copper (Sb-Cu) and antimony-zinc (Sb-Zn), with zinc as the reactive element and copper the non-reactive.

Samples of both alloys were cast, homogenized, and machined ($W = 10\text{mm}$, $L = 10\text{mm}$, $D = 14.5\text{mm}$). The samples were cut in half, polished to a 4000-grit finish, and then bonded back together in open-air furnaces set to a temperature yielding 20% liquid in the matrix. Each sample had a chevron-notch machined into it and subsequently tested for plane-strain fracture toughness. After testing, the samples were examined using optical microscopy (OM), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS).

Results from the fracture toughness experiments indicate that the preferential formation of eutectic microstructure along the bond line of the Sb-Zn alloy samples, simulating self-healing, favorably affects the plane-strain fracture toughness. This property is attributed to the increase in wettability caused by the addition of the reactive element. During bonding, it is believed that the eutectic phase in the microstructure melted and diffused toward the inner cut line, resulting in higher fracture toughness values due to the chemical bonds formed. Analysis of the data also demonstrates an increase in fracture toughness with an increase in the bonded area of the sample.

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