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Failure mechanisms in cobalt welded with a silver–copper filler

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ABSTRACT

Cobalt silver–copper (Co–AgCu) weldments approximate the stresses and failure mechanisms of beryllium aluminum–silicon (Be–AlSi) welds, which have strategic importance but are hazardous to study. Failure tests of these surrogate Co–AgCu welds, examined in tension and four-point bending, show that residual stresses and post-welding heat treatment have little or no effect on strength, whereas weld quality and geometry are extremely important. Scanning electron microscopy images reveal abundant defects in poor welds, which usually fail through propagation of preexisting cracks. Fracture surfaces show a variety of morphologies, ranging from dimples in the AgCu filler, to cleavage steps in the CoCu peritectic, and suspected intergranular fracture in the cobalt base. Spatially resolved acoustic spectroscopy reveals significant changes in microstructure near the base–filler interface, whereas wavelength dispersive analysis shows high Cu concentrations in this area.. Contrary to finite element predictions, these welds were found to be stronger during face bending than root bending, likely resulting from the increased number of cracks and imperfections in the Co base. These computations correctly predict that weld strength depends on geometry and that welds fail either in the cobalt base, or along the base–filler interface. Crack compliance measurements show that the largest residual stresses are located along this interface. However, these stresses are unlikely to influence failure due to their direction, whereas stresses in the weld root are too small to have observable effects on failure. The strength of Co–AgCu welds depends strongly on geometry, penetration, and weld quality, but little on residual stresses, and this conclusion is tentatively extended to Be–AlSi welds.

1. Introduction and Goals

The cobalt silver–copper (Co–AgCu) welding system was developed as a surrogate for beryllium aluminum–silicon (Be–AlSi) welds in order to improve understanding of the toxic Be–AlSi system without use of special facilities and risk of illness [1,2]. In this surrogate concept, Co–AgCu must mimic, as accurately as possible, the behavior of Be–AlSi, including the interactions between the Be base and the AlSi filler. Cobalt is an ideal surrogate for beryllium-based weldments, due to the mechanical, thermal and crystallographic similarities of the two elements. Both cobalt and beryllium have a hexagonally close packed crystal structure (HCP), which endows both elements with relatively high stiffness and similar melting points [3–5]. Behavior of the Ag–Cu filler during welding is also of interest because silver–copper filler metal in cobalt welds was found to best emulate the chemistry of the Be–AlSi system, as both systems are characterized by a lack of miscibility between filler and base metals [1]. Furthermore, the mismatches in the coefficient of thermal expansion (CTE) and Young's modulus (E) between AgCu and Co are similar, although not as extreme, as the mismatches of CTE and E in the Be–AlSi system. Criss and Meyers [1] provide a detailed description of surrogate development, welding techniques, and why the Co–AgCu surrogate can simulate the behavior of Be–AlSi rings, PIGMA welded at Los Alamos National Laboratory.

The study of Co and specifically its behavior during welding is important for other reasons. Cobalt is used as an alloying element in a variety of steels, carbides, and corrosion resistant alloys [4], and is a primary constituent of batteries, magnets, and superalloys [6–8]. Cobalt–chromium–molybdenum alloys (e.g. Vitallium, Megallium) are used in dentistry and biomedical implants [9]. Vitallium is usually joined via soldering or brazing [9], but may be joined by torch [10] or TIG [11]. Cobalt–chromium base alloys (Stellite) are generally used as hardfacings, which are applied using a variety of welding, cladding and brazing techniques [12,

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13]. Heat resistant alloys, often consisting of Co–Cr–Ni–W, are also welded or brazed [4].

The eutectic, AgCu filler metal is commonly used as a filler for vacuum brazing [14]. Silver–copper alloys are also used in jewelry and tableware [e.g., sterling silver (92.5% Ag); 15], and as electrical contact alloys [16].

Despite the diverse usage of the components of our Co–AgCu system, information is lacking on the brazing of cobalt–copper, due to possible liquid metal embrittlement [17], and welding regarding HCP cobalt base alloys. A majority of cobalt's structural alloys (e.g. Stellite, Vitallium) utilize the high temperature face centered cubic (fcc) phase [17], and differ structurally from pure cobalt, which is HCP. Cobalt usage in batteries usually involves cobalt oxide, cobalt hydroxide or lithiated cobalt oxide (Li_xCoO_2) [4,18], all of which differ from pure cobalt structurally and chemically. Some samarium-cobalt magnets ($SmCo_5$) do possess a hexagonal crystal structure [19], but are not welded. As such, there is limited information regarding fabrication and welding of pure cobalt. Because development of Co based superalloys is ongoing [20,21], understanding the behavior of the pure metal is important.

In this paper, the Co–AgCu system is used to investigate the effects that residual stress, weld geometry, weld quality, and post welding heat treatment have on weld failure, and it extrapolates these results to welded Be–AlSi. Geometric effects are expected to be of importance, since their influence on weld failure is known (e.g., [22–24]). The welding techniques discussed in the previous work [1], were used to create 11 new welds, which were analyzed alongside the single complete weld from the previous study.

The present work utilizes tension and 4-point bending to produce weld failures in the Co–AgCu weldments, and combines these tests with the crack compliance (slitting) method to determine the effect of residual stresses. The weldments are further characterized using scanning electron microscopy (SEM) and wavelength dispersive analysis (WDS), by developing a novel use of optical microscopy, and by applying a recently developed method, spatially resolved acoustic spectroscopy (SRAS). SRAS is a laser ultrasonic technique which produces maps of the surface acoustic wave velocity (SAW) [25,26]. The SAW velocity for a particular propagation direction depends strongly on the crystallographic orientation of the material and so can be used to map the microstructure of a material. Combining a number of velocity maps with different acoustic wave propagation directions can generate information about the *c*-axis orientation for hexagonal materials, or the complete grain orientation for some specific crystallographic symmetries [26].

Effects of low temperature heat treatment on weld strength are examined, in order to determine whether residual stress amelioration is possible. Finite element models were constructed to understand our residual stress measurements and fracture results. This combination of measurements, images and quantitative models shows that residual stresses do not substantially impact failure in Co–AgCu weldments, but that weld geometry, material quality, and defects and imperfections govern weld strength and failure. The insight provided by this report into the behavior of welded cobalt pertains to development and joining of new cobalt alloys, as well as the behavior of the original Be–AlSi system.

2. Experiments and techniques

2.1. Materials

The weld base was 99.95% pure cobalt, hot rolled to 7.6 mm (Sophisticated Alloys). The cobalt plate was then heat treated at 325 °C for 100 h to homogenize the grain structure of our metal.

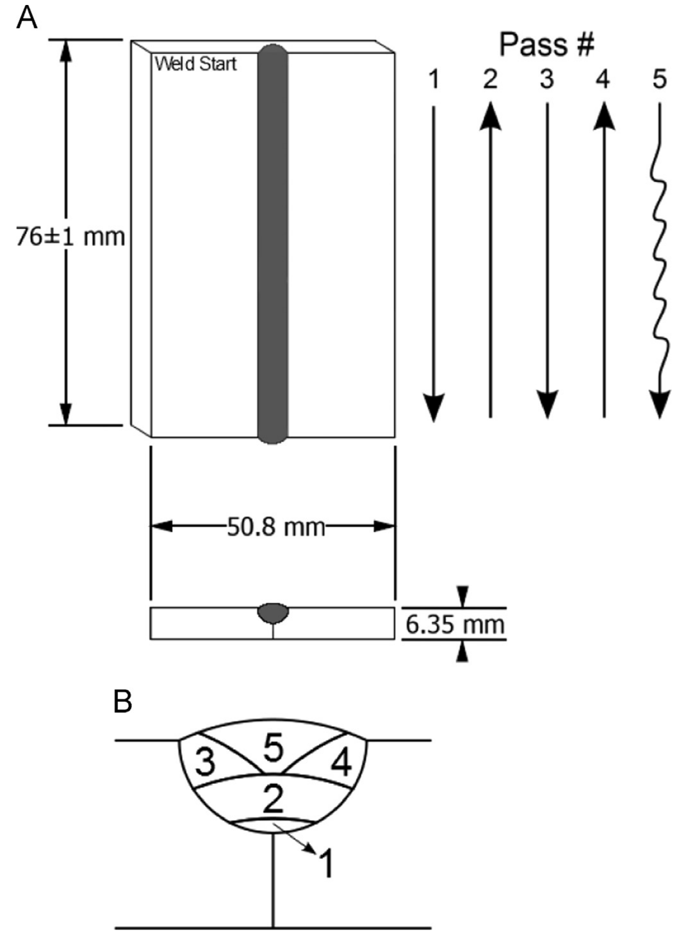

Fig. 1. A: Pass locations, directions, and weldment geometry used in the Co–AgCu TIG welds. Two cobalt samples sharing a single U-groove are joined by 5 passes in alternating directions. The final, oscillating pass is indicated by a wavy line. B: Approximate weld-bead locations. Dimensions are all ±0.08 mm unless noted otherwise.

Some studies [27] have reported the persistence of the FCC phase after refining the grain structure by rolling, but our previous x-ray measurements indicate that minimal FCC is present after this heat treatment [1].

The filler wire was 72–28% AgCu (obtained from Lucas Milhaupt), which is at the eutectic point. It is available from a number of sources, and is often referred to by its AWS specification, BAg-8 [28].

2.2. Welding equipment, materials and parameters

Eleven additional welds were produced. Our welding setup, materials and geometry are identical to the previous study [1], where they are described in more detail. All welds were produced by a single ASME aerospace certified welder. He employed a TIG welder with high frequency stabilization (Miller Aerowave), which was set to direct current electron negative (DCEN).

All welds utilized two standard parts, each consisting of a 76 mm long, 25.4 mm wide, 6.25 mm thick block of 99.95% cobalt with a 3.2 mm radius J-groove (Fig. 1). The thicknesses of the J-groove and part were verified accurate to 0.08 mm.

Prior to welding, the parts were positioned above a heated, porous refractory substrate with a purpose built clamp. The clamp was furnace heated to above 300 °C, the parts were loaded at approximately 250 °C, and welding occurred at a substrate temperature of approximately 230 °C.