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Micro structure and mechanical properties of vacuum brazed martensitic stainless steel/tin bronze by Ag-based alloy

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ABSTRACT

A vacuum brazing process using an Ag-based alloy (Ag-28Cu, wt%) as a filler metal was carried out on a dissimilar combination of martensitic stainless steel/tin bronze to understand the material flow characteristic and the influence of micro structure evolution on the shear strength of the brazed joint. A suitable combination of brazing temperature (850 °C) and holding time (12 min) was found to be beneficial for eliminating internal gaps and voids and providing for a uniform circumferential thickness distribution to satisfy the technical requirements. Cu-based and Ni-based solid solution phases were generated between the filler metal and the Ni layer, which contributed to the shear strength. With the addition of an annealing process, a quantity of Fe from the martensitic stainless steel diffused into the Ni layer, and the intermetallic compound ($FeNi_3$) was generated. Under shear deformation, the brittle intermetallic compound promoted crack initiation, subsequent crack propagation, and final fracture failure, and the shear strength decreased from 260 MPa to 180 MPa.

1. Introduction

Composite structures of dissimilar materials of comprising stainless steel/copper alloys are used for specific requirements in industrial applications, including heat exchanges and magnetic shielding. According to the physical and mechanical features of the dissimilar combination, joining processes such as diffusion welding, friction welding, explosive welding, and fusion welding are all suitable for achieving good performance. The selection of welding process depends on the structure, technical requirement, and application condition.

Gas suspended arc welding for dissimilar joint of stainless steel/copper was conducted by Zhang et al. (2015a,b), and the effects of the welding parameters on the tensile strength of the joint were analyzed. A sound joint was formed and a highest tensile strength was obtained according to the optimal welding current and welding speed. Laser welding of a dissimilar joint of stainless steel/copper was carried out by Chen et al. (2015), and the influence of processing parameters including the welding speed, laser power, and incline angle of the laser beam was discussed on the mechanical properties, and fracture modes of the welded joint. Typical modes of fracture such as the interface, heat-affected zone (HAZ) and fusion zone depend on the process parameters. Electron beam welding of stainless steel/copper applied in a cryogenic systems within a 300 K to 4 K temperature range and pressures of several MPa was conducted by Lusch et al. (2015), and the yield region, hardness distribution, and leak-tightness were studied to qualify this kind of weld. The elastic region was measured for all tensile tests performed at variable temperatures, and there was no damage to the weld, which indicates that the weld joint is suitable for cryogenic applications. Electron beam welding of stainless steel/copper was carried out by Jyotirmaya et al. (2016), and the effect of beam oscillation on the performance of the welded joint was studied in terms of the mechanical properties. The beam oscillation during welding process can enhance the impact strength and elongation; however, it promotes the segregation of copper in the weld zone when the beam oscillation diameter is beyond an optimum value, resulting in poor mechanical properties. Residual stress on an electron beam welding joint of stainless steel/copper was measured by Zhang et al. (2015a,b), and the three-dimensional residual stresses were given. The peak three-dimensional residual stresses all appeared at the stainless steel/copper interface, and the magnitude of the residual stresses were 398 MPa, 479 MPa, and 273 MPa, respectively.

Laser brazing of a dissimilar joint of stainless steel/copper was carried out by Tetsuo et al. (2016), and the brazing process and suitable filler metals for the laser brazed joints were studied. An optimal brazing process to obtain high shear strength was confirmed by using a Cu-Si based filler metal at a certain laser power, spot diameter, laser irradiation angle, irradiation position shift, brazing speed, and filler metal feed speed. A brazing process of stainless steel/copper was

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performed using a Ag-50Cu filler metal in an Ar gas atmosphere with a conventional furnace, and a comparison of brazing ability with that of the eutectic alloy Ag-28Cu was investigated by Fukikoshi et al. (2013). The low-silver-content brazing filler metal exhibited good brazing ability and could be substituted for the Ag-28Cu filler metal. Vacuum brazing was carried in solution conditions to maintain the mechanical properties of dissimilar materials of stainless steel/copper, and the influence of the parameters on the maximum joint strength was discussed by Govindaraju and Balasubramanian (2013). A novel differential temperature vacuum brazing process coupled with heat treatment is beneficial for enhancing the joint strength of weaker alloys. Brazing process of stainless steel/copper with a filler metal Ag-28Cu was carried out, and the effect of nickel electroplating was discussed on the tensile strength and micro structure by Kumar et al. (2016). Fracture occurred on the stainless steel/brazed interface, which displayed two regions with different topographies. One part of the fracture surface was marked with coarse dimples, whereas the other part contained copper-rich grains.

The studies mentioned above all involve variable processes for joining dissimilar joints of stainless steel/copper, and each process has the specific features needed for welding joints. For the small-size precision electromechanical product, dimension accuracy and connection performance depend on a strict process control. Low-energy-density conventional arc welding of stainless steel/copper joints without filler metals is not proper for small-size precision products, because the width of the welding joint and the welding distortion are both out of the acceptable range. High-energy-density welding such as laser beam welding and electron beam welding is suitable for small-size precision product, because of the lower welding distortion, small residual stress, and narrow welding width. These methods are useful for forming line style welding joints, rather than the plane welding joints. The advantage of brazing is similar with that of high-energy-density welding, because it is the only feasible way to achieve a whole-plane metallurgy connection.

In this study, vacuum brazing of dissimilar materials of martensitic stainless steel/tin bronze using an Ag-based alloy (Ag-28Cu, wt%) as a filler metal was conducted, and the influence of the process parameters (temperature time, holding time, and cooling style) was investigated in terms of the circumferential thickness distribution of the product, internal defects, micro structure and shear strength of the brazed joints. Optimal vacuum brazing process parameters were confirmed and a sound precision electromechanical product with acceptable performance was obtained.

2. Structure and process

2.1. Product structure

With the requirement of directional magnetism, the product was composed of QSn6.5-0.1 tin bronze and 4Cr13 martensitic stainless steel with excellent magnetic shielding properties. The specific structure of the product is shown in Fig. 1. It was first manufactured into a rough specimen by brazing, and then milled into the designed structure. A final surface treatment in acid liquid was carried out. For the application processes after brazing, the required thickness did not exceed 7.20 mm, the required flatness was less than 0.03 mm, and the required shear strength of the brazed interface was at least 150 MPa. The QSn6.5-0.1 tin bronze and 4Cr13 martensitic stainless steel were assembled with a clearance of 0.05 mm.

Ag-28Cu silver-copper eutectic alloy foils were used as the filler metal to guarantee the high connection strength of the brazed joint. Prior to brazing, the filler metal and based metals were degreased, acid etched, detergent washed, and oven dried. As compared to Fe and Cu, the Ag and Ni are beneficial for wetting of the filler metal. However, the Ag is easy to oxygenate. A nickel layer with the a thickness of 3 μm was therefore plated onto the QSn6.5-0.1 tin bronze and 4Cr13 martensitic stainless steel using magnetic controlled sputtering to improve the spreadability and brazability of the sample.

2.2. Research procedure

To avoid the etching solution flowing into the disc-shaped interface of the base metals, vacuum brazing instead of fusion welding was used to achieve the joining of dissimilar materials without gaps in the interface. Four brazing process plots corresponding with the vacuum level are illustrated in Fig. 2. The brazing temperature and holding time are associated with the spreading of the filler metal, and thus they affect the circumferential thickness and the presence of defects including gaps and voids. An annealing process was added to the furnace cooling process to minimize residual stress and deformation in the interface, which affect the micro structure and connecting performance. Vacuum level of 10^{-3}–10^{-4} were used to avoid oxidation of the metals and volatilization loss of the elements.

The shear strength and micro hardness of the brazed joint was analyzed to evaluate the mechanical performance, and the composition of the reaction products, fracture morphology, and the physical phases of the interface products were analyzed by scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and rotating anodic X-ray dispersive (XRD) spectrometer to further confirm the micro structure characteristics.

3. Results and discussion

3.1. Distribution of circumferential thickness

Poor spreading of the filler metal can be reflected by the thickness distribution in the circumferential direction, and the thickness distribution is also a criterion to determine the process parameters. Fig. 3 shows the thickness variation for different groups of process parameters. At a brazing temperature of 840 °C and a holding time of 8 min, a high level of variance in the circumferential thickness of the specimen was observed, with the highest thickness of 7.40 mm and the lowest thickness of 7.30 mm, which indicates that the filler material inside was not fully melted and spread on the interface. When the brazed temperature was increased to 850 °C and the holding time remained at 8 min, the distribution of the circumferential thicknesses was relatively even, with the highest wall thickness of 7.29 mm and the lowest wall thickness of 7.24 mm. However, the thicknesses index in both cases were not within the expected flatness requirements.

Upon further increasing the holding time to 12 min, the circumferential thicknesses of the specimen was distributed more uniformly, with the highest wall thickness of 7.17 mm and the lowest wall thickness of 7.15 mm. Values that are within the required flatness requirements. A comparison among three different process parameters prove that the brazing temperature and holding time are extremely important for the flow of the filler metal. When the brazing temperature was 850 °C and the holding time was 12 min, an annealing process at 500 °C for 60 min was added to the furnace cooling process. No significant circumferential thickness differences were observed whether the specimens subjected to the annealing process or not. The addition of an annealing process has no effect on the distribution of circumferential thickness.

3.2. Examination on internal defects

For the brazed rough specimen, a flute with a depth of 4.5 mm was subsequently milled from the upper surface, thus exposing the brazed seam. To avoid the residual corrosive medium on the interface, gaps and voids in a brazed joint are not permitted. Thus, the presence of defects was examined by nondestructive evaluation, which finds evidence of defects without destroying the sample. High-energy X-rays were used to evaluate the defects in the brazed joint by imaging measurement and reconstruction.

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