Available online at www.sciencedirect.com

ScienceDirect

Defence Technology 12 (2016) 16–24

www.elsevier.com/locate/dt

Friction assisted solid state lap seam welding and additive manufacturing method

Prasad Rao KALVALA *, Javed AKRAM, Mano MISRA

Dept. of Metallurgical Engineering, University of Utah, Salt Lake City, UT 84112, USA

Received 3 October 2015; revised 2 November 2015; accepted 3 November 2015

Available online 24 November 2015

Abstract

This paper describes results of seam welding of relatively high temperature melting materials, AISI 304, C-Mn steels, Ni-based alloys, CP Cu, CP Ni, Ti6Al4V and relatively low temperature melting material, AA6061. It describes the seam welding of multi-layered similar and dissimilar metallic sheets. The method described and involved advancing a rotating non-consumable rod (CP Mo or AISI 304) toward the upper sheet of a metallic stack clamped under pressure. As soon as the distal end of the rod touched the top portion of the upper metallic sheet, an axial force was applied. After an initial dwell time, the metallic stack moved horizontally relative to the stationery non-consumable rod by a desired length, thereby forming a metallurgical bond between the metallic sheets. Multi-track and multi-metal seam welds of high temperature metallic sheets, AISI 304, C-Mn steel, Nickel-based alloys, Cp Cu, Ti6Al4V and low temperature metallic sheets, AA6061 were obtained. Optical and scanning electron microscopy examination and 180 degree U-bend test indicated that defect free seam welds could be obtained with this method. Tensile- shear testing showed that the seam welds of AISI 304, C-Mn steel, Nickel-based alloy were stronger than the starting base metal counterparts while AA6061 was weaker due to softening. The metallurgical bonding at the interface between the metallic sheets was attributed to localized stick and slip at the interface, dynamic recrystallization and diffusion. The method developed can be used as a means of welding, cladding and additive manufacturing.

Keywords: Lap seam welding; Friction assisted welding; Solid-state welding; Cladding; Additive manufacturing

1. Introduction

Conventional lap seam welding processes can be classified as fusion-based which include resistance seam, laser beam, electron beam, plasma arc welding, soldering, and brazing and solid-state-based which include ultrasonic welding and roll bonding. The lap seam welds produced by fusion based methods are often associated with a variety of problems, including cracking, high porosity, deleterious metallurgical changes, and high residual stresses. Resistance seam welding is difficult to apply to aluminum alloys because of their high conductivity, low strength at temperature, and tendency to degrade the electrodes [1] and aluminum and copper require more energy because of their low electrical resistance. Steels with high carbon equivalents need additional post-weld annealing treatments and some combinations of dissimilar metal resistance welds can form intermetallics resulting in poor mechanical properties or liquid metal induced embrittlement [2]. Cracking, expulsion of molten metal, and unclean work-piece surfaces can all cause defective resistance seam welds. Laser welds are sensitive to heat input. High laser pulse energy resulted in poor mechanical properties and increased discontinuities in weld joints [3]. When the heat input was too high, craters and pores appeared in the fusion zone of AZ 31 alloy [4]. Limitations of ultrasonic welding include an inability to weld large and thick base metals and a tendency of base metals to bond to the anvil or sonotrode [5]. Further ultrasonic welding method has not yet been fully optimized and a number of issues remain to be addressed [6]. Roll bonding of alloys such as Titanium to other alloys such as steels will result in the formation of titanium oxide and brittle intermetallic compounds. These metallurgical changes reduce their interface bond strength [7].

Cladding refers to the deposition of a filler metal on a substrate metal to impart corrosion, wear resistance or some desired property that is not possessed by the substrate metal. Examples of cladding include hard facing for the purpose of reducing wear, abrasion, impact, erosion, galling, or cavitation, weld cladding for the purpose of providing a corrosion-resistant

---

* Corresponding author. Tel.: +1 415 722 8105.
E-mail address: Prasad.Kalvala@utah.edu (P. R. KALVALA).

http://dx.doi.org/10.1016/j.dt.2015.11.001

surface and buttering for the purpose of adding one or more layers of weld metal to the face of the joint or surface to be welded. Conventional cladding processes can be classified as fusion-based including electric arc welding processes, brazing, electron beam welding, and laser beam welding and solid-state welding processes including explosive cladding, friction surfacing and roll bonding. The clad metals produced by conventional fusion-based methods are often associated with a variety of problems, including cracking, high porosity, deleterious metallurgical changes, and high residual stresses. High percentages of dilution, viz., the amount of base metal in the clad metal can occur in such fusion-based clad metals. Dilution percentages are typically very high, as high as 20%–50%, in most commonly used arc cladding processes such as submerged arc. Explosion cladding is typically restricted to metals with minimum elongation of 10%–15% and a notch toughness value above 30 J at bonding temperature [8]. Friction surfacing is limited by its inability to produce larger clad areas in less time.

Additive manufacturing methods and additive and selective subtractive manufacturing methods are conventionally used to fabricate layered, multi-material structural components. Layer-by-layer fabrication of three-dimensional components can be directly fabricated from a computer-aided design, CAD model of an object. Laser Engineered Net Shaping, Direct Metal Deposition, Selective Laser Melting, and Electron Beam Melting are among a number of processes being considered as additive manufacturing methods by which material addition is achieved through melting and solidification. Due to melting and solidification involved in these processes, the parts made by these techniques suffer from the following limitations [9–14]: (a) unmelted zones resulting in lack of bonding between powder particles; (b) porosity; (c) solidification cracking susceptibility; (d) a cast microstructure and micro-segregation leading to compositional in-homogeneities; (e) significant tensile residual stress build-up; (f) long production times for large components, often less than 1 gram/minute build rates; and (g) stiffness problems**.** Many dissimilar metal combinations cannot be deposited by these processes as the resultant deposited layers crack.

Solid-state additive manufacturing methods, where liquid to solid transformation is absent, have been used to address many of the shortcomings of liquid-to-solid-based additive manufacturing methods. Ultrasonic consolidation was the first solid state additive and selective subtractive manufacturing method to be applied, and was shown to overcome some of the limitations of fusion-based methods. In contrast to the fusion based additive manufacturing methods, ultrasonic consolidation is a typical additive and selective subtractive manufacturing method to build up a near-net shape part which is then machined to its final dimensions using an integrated, 3-axis CNC milling machine. Ultrasonic consolidation suffers from limitation such as the formation of inter-foil defects [15]. Further, in ultrasonic consolidation process, if the substrate is not stiff enough, no friction can occur between the foil being deposited and the substrate [16]. Additionally, a conventional ultrasonic consolidation process is conducted at 175 °C by employing a heated base plate. A major limitation of this process is that it can be applied to metallic layers which are few microns thick. Thus, conventional fusion-based and solid-state additive manufacturing methods and additive and selective subtractive manufacturing methods suffer from physical, metallurgical, and mechanical limitations.

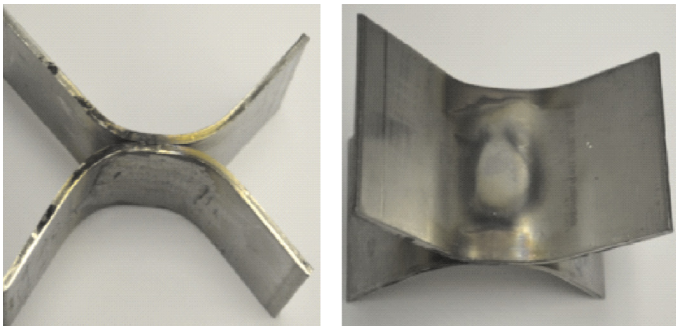
Fig. 1. Friction spot weld–AISI 304 – 3.5 mm.

Thus, there is a need to develop alternative methods for forming strong lap seam welds between a variety of hard and soft materials while avoiding the physical and metallurgical deficiencies of conventional welding methods. There is a further need for applying these lap seam welds for cladding and additive manufacturing applications. Our motivation for the work on lap seam welding emanated from our experimental work on friction spot welding method: Systems and Methods for Friction Spot Welding and Friction Seam Welding, S/N PCT/US2014/012355, Filed January 21, 2014. Our results of this work have shown that it is possible to develop metallurgically bonded spot welds of relatively thicker materials up to 3.25 mm, both low melting temperature alloys such as aluminum, magnesium, copper and high melting temperature alloys such as steel, stainless steel, Ni-based alloys. Typical spot welds of AISI 304 sheets are shown in Fig. 1. The success of this process motivated us to extend the same method with control of an additional parameter, viz., and traverse of the rod along the x-axis (Fig. 2(a)). The idea was found to be successful in obtaining a longitudinal seam weld between metallic sheets. The results of the longitudinal friction lap seam welding of different metallic sheets are reported in this paper.

2. Experimental

2.1. *Materials*

The following metallic sheets were used in this work: AISI 304; AISI 1012; Ni-based alloys: IN 600, IN 625, HX; AA 6061; commercially pure CP Cu, CP Ni, and Ti6Al4V. The thickness ranges of metallic sheets were 0.5–5.0 mm. The dimensions of the sheets used were as follows: 190 mm × 200 mm × thickness. Non-consumable rods, CP Mo with 25.4 mm dia. and AISI 304 with 25.4 mm dia. and R_a 1–2 μm were used to obtain the seam welds. CP Mo rod was used for seam welding of high temperature melting metallic sheets, AISI 304, AISI 1012, In 600, IN 625 and HX sheets, CP Cu, CP Ni, and Ti6Al4V. AISI 304 rod was used for low temperature melting metallic sheets, AA 6061. It can be noted that the non-consumable rods used were pin less in contrast to the