Materials and Design 88 (2015) 58–68

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/jmad

Friction welding of mild steel and titanium: Optimization of process parameters and evolution of interface microstructure

T.N. Prasanthi [a,1], C. Sudha [a], Ravikirana [b], S. Saroja [a,*,2], N. Naveen Kumar [c], G.D. JanakiRam [c]

[a] Microscopy and Thermo-Physical Property Division, Physical Metallurgy Group, Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, 603102, India
[b] Homi Bhabha National Institute — IGCAR, India
[c] Department of Metallurgical and Materials Engineering, Indian Institute of Technology-Madras, Chennai-600 036

ARTICLE INFO

Article history:
Received 9 May 2015
Received in revised form 25 August 2015
Accepted 27 August 2015
Available online 1 September 2015

Keywords:
Mild steel
Titanium
Friction welding
Heat treatment
Intermetallic phases
JMatPro

ABSTRACT

The present investigation deals with the efforts to form a defect free bonded interface between mild steel (MS) and titanium (Ti) using the rotation friction welding process. The conditions were optimized based on several trials by varying friction welding parameters like frictional force, upset force, burn-off length and rotational speed. It has been established that only fine FeTi particles formed in isolated regions at the interface of 'as welded' MS/Ti joints. The evolution of interface microstructure has been studied by diffusion annealing heat treatments in the temperature range of 500–800 °C for a duration of 100 h. Plastic deformation during friction welding reduced the recrystallisation temperature of MS. The variation in microchemistry was measured across the weld interface, which was used as input to predict the formation of various phases and the consequent change in the mechanical properties using the JMatPro® software. Intermetallics were present only as fine isolated particles in bcc-Fe matrix at the interface even after heat treatment at 800 °C for 100 h. The growth kinetics was found to be much slower in friction welded joints as compared to diffusion bonded and explosive clad joints.

1. Introduction

Evaluation of the weldability and microstructural stability of iron (Fe) and titanium (Ti) based dissimilar joint is important due to its application in the spent fuel reprocessing plant of fast breeder reactors [1,2]. Earlier investigations on 304L SS/Ti–5Ta–2Nb dissimilar joint fabricated using a solid state welding process (explosive cladding) revealed the formation of undesirable reaction zones at the interface during post-clad heat treatments [3]. Growth kinetics of these zones was observed to be high in explosive clads as compared to diffusion bonded joints [4]. This was attributed to the severe deformation of the two materials during explosive cladding, resulting in the formation of high number density of defects that acted as short circuit diffusion paths for the alloying elements. In order to obtain a fundamental understanding on the role of defects and alloying elements in accelerating/retarding the kinetics of formation of diffusion zones, a binary Fe–Ti system has been taken up for study. The joint has been fabricated employing both equilibrium and non-equilibrium (explosive cladding) processes and compared. Due to limitations in obtaining plates of pure iron with minimum dimensions of 500 × 500 mm required for explosive cladding, the joints have been fabricated with commercially available mild steel (MS) (Fe–0.14C) and grade-2 Ti.

Fabrication of MS–Ti diffusion couple is a challenge due to the (1) limited mutual solubility of Fe and Ti [5], (2) tendency for the formation of brittle intermetallic phases at the interface (diffusivity of Fe (in hcp Ti): 5×10^{-15} m^2/s and Ti (in bcc Fe): 5.5×10^{-14} m^2/s at 900 °C) [6], (3) large difference in their thermal expansion coefficients (Fe: 12 μm/m/K and Ti: 8.6 μm/m/K) [7], and (4) formation of thick oxide scales. The approach adopted in literature has been to initially form a bonded interface between Fe and Ti through the application of both high temperature (800–950 °C) and pressure (3 MPa for 0.5 to 1.5 h) in diffusion bonding set up followed by diffusion annealing heat treatments [8]. Diffusion bonding technique is effective to obtain Fe–Ti joints with adequate bond strength. However, formation of a continuous layer of intermetallic phases parallel to the joint interface could not be avoided even under optimized experimental conditions [9,10]. This poses problems when the main objective of the investigation is to study the diffusivities of elements in solid solutions rather than in ordered intermetallic phases. Friction welding is a promising solid state welding technique where by appropriate selection of process parameters it is possible to obtain joints with adequate bond strength and control the formation of secondary phases [11,12].

The aim of the present investigation was to optimize the process parameters for rotation friction welding of MS and Ti and characterize the microstructure and properties of the weld. Further, the evolution of interface microstructure and its effect on the properties due to

* Corresponding author.
E-mail address: saroja@igcar.gov.in (S. Saroja).
[1] Ph.D. Scholar, Homi Bhabha National Institute (HBNI), Department of Atomic Energy (DAE).
[2] Head, Microscopy & Thermo-Physical Property Division and Professor, HBNI, DAE

http://dx.doi.org/10.1016/j.matdes.2015.08.141
0264-1275/

diffusion annealing in the temperature range of 500–800 °C for duration of 100 h has been studied. The variation in microchemistry across the interface has been evaluated using Electron Probe Micro Analysis (EPMA) which forms the input for predicting the various phases that can form at the interface and consequent change in the mechanical properties using JMatPro, a materials modeling software [13]. This investigation forms part of a study on interface and diffusion behavior for a comparison of these under equilibrium and non-equilibrium conditions, provided by the explosively clad MS/Ti joints.

2. Materials and methods

Chemical compositions of the plates used in the present study are given in Table 1. From MS and grade-2 Ti plates of dimension 1000 × 500 × 20 mm and 1000 × 500 × 12 mm respectively, rods of 10 mm diameter and 100 mm length were fabricated for friction welding. The contact surfaces were well polished up to a mirror finish to eliminate any surface roughness. During friction welding, the MS rod was kept in the static mode and the Ti rod was rotated and moved towards MS to avoid the higher extent of flash due to high deformation of Ti. Through a combination of compressive force and high temperature (~1425 °C generated during the process — for 304SS/MS) [14] the materials were joined together by plastic deformation. Several trial runs were carried out by varying the process parameters such as frictional force (FF), upset force (UF), burn off length (BOL) and the rotational speed (R). The selection of parameters for friction welding is based on literature available for Fe–Ti alloy systems [12,15]. It is understood that BOL and R are important parameters which dictate the interface microstructure. The selection of BOL of 2 and 3 mm in the present study is supported by Meshram et al. [12] and Dey et al. [15] and who have reported good bonding at 2 and 3 mm respectively when BOL was varied in the range of 2–5 mm. In the present study the rotational speed was varied in the range of 750–1500 rpm and found that 1000 rpm is optimum based on interface microstructure. This is also supported by studies in similar systems namely Ti-304 SS and Fe–Ti where R was maintained as 1500 and 1000 rpm respectively. The selection of frictional force and upset force is based on literature in similar systems [12,16].

After friction welding, the flash (materials that were expelled out at the interface) was removed by subsequent machining. Cross section of the bonded specimens having a dimension of 10 × 10 mm was extracted for further analysis. After grinding and polishing of the specimens by standard metallographic procedures, final polishing was carried out using smooth alumina suspension. To reveal the microstructure, MS side of the joints was etched with nital (5 ml HNO_3 in 95 ml Methanol) and Ti side with Kroll's reagent (4.5 ml conc. HNO_3 + 0.5 ml HF in 45 ml of distilled water). Based on the metallurgical analysis of all specimen fabricated during the trial runs, optimum friction welding parameters were identified.

The specimen fabricated under optimized condition was then sealed under vacuum in quartz tubes and subjected to diffusion annealing heat treatments in the temperature range of 500–800 °C for duration of 100 h. After heat treatment, the specimens were air cooled and prepared using the same procedure as detailed above for microstructural characterization.

Microstructural characterization was carried out using Leica MeF4A optical microscope and scanning electron microscope (XL 30 ESEM of M/s FEI) at an operating voltage of 30 kV. Leitz microhardness tester

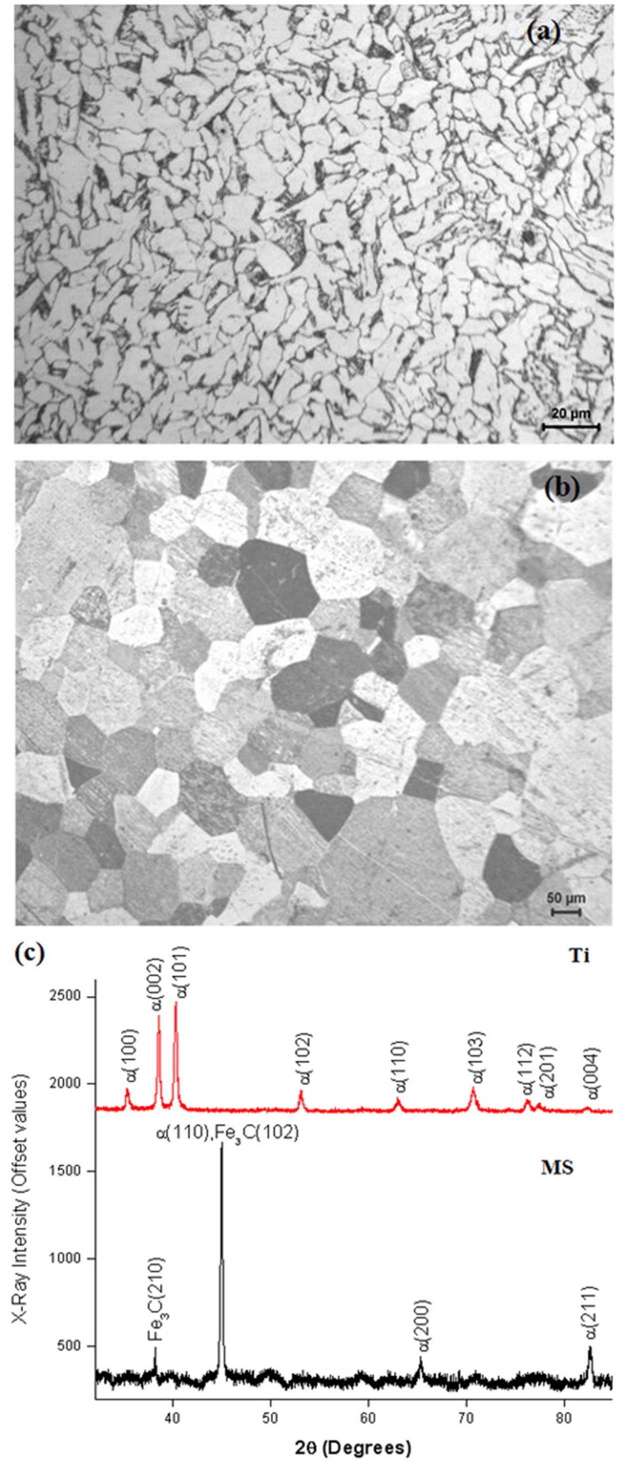

Fig. 1. Optical micrograph of a. mild steel showing ferrite + pearlite structure b. grade-2 Ti showing equiaxed α grains and c. XRD pattern obtained from MS and Ti before friction welding.

Table 1
Chemical composition (in wt%) of the materials used in the present study.

Material	C	S	P	Mn	Si	Al	Fe	N	H	O	Ti
Mild steel	0.141	0.032	0.03	0.786	0.138	0.028	Bal.	–	–	–	–
Grade-2 Ti	0.023	0.03	–	–	–	0.1	0.02	0.012	0.001	0.06	Bal.