Journal of Manufacturing Processes 34 (2018) 603–613

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

# Characterization and analysis of diffusion bonding process in a Cr25Ni7Mo4MnSi duplex stainless steel

Xueping Ren[a], Xiaohui Chen[b], Zhiping Xiong[c,d,*]

[a] School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, P.R. China
[b] China Productivity Center for Machinery, China Academy of Machinery Science & Technology Group Co., Ltd., Beijing 10044, P.R. China
[c] School of Materials Science and Engineering, Beijing Institute of Technology, Beijing 100081, P.R. China
[d] Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, Louvain-la-Neuve 1348, Belgium

ARTICLE INFO

*Keywords:*
Duplex stainless steel
SAE 2507
Superplastic
Diffusion bonding

ABSTRACT

Similar diffusion bonding of a duplex stainless steel (Cr25Ni7Mo4MnSi) was performed using a Gleeble 3500 thermo-mechanical simulator. Isostatic diffusion bonding was carried out at 1100 °C. The effect of surface condition, cold rolling, holding time and pressure was systematically studied. Microstructures along bonding interface were characterized using scanning electron microscopy and electron backscattering diffraction. The mechanisms of diffusion bonding were analyzed in terms of plastic deformation, diffusion, and rotation and migration of grain boundaries. Small surface roughness and large cold rolling were beneficial for bonding process while increasing holding time and pressure first greatly and then slowly increased the joint shear strength. Holding for 5 min at a pressure of 10 MPa obtained the joint shear strength of 407 MPa, which is comparable to 420 MPa of the base material. The influence of superplastic deformation was also analyzed, indicating a larger deformation (20% to 50%) led to a larger joint shear strength (395 to 418 MPa). These demonstrate the feasibility of this steel for superplastic forming and diffusion bonding technique.

## 1. Introduction

Duplex stainless steel has high strength, large ductility and good pitting corrosion resistance due to its microstructure simultaneously containing austenite and $\delta$-ferrite [1,2]. In addition, this steel exhibits excellent superplasticity up to ~ 1500%, which varies with microstructure constituents, grain size, deformation and so on [3–5]. With the help of superplasticity, diffusion bonding which connects two faying surfaces by holding at a certain temperature for some time under external pressure, can achieve sound joints in a relative short holding time and small pressure [6–8]. Moreover, the complicated structure, such as honeycomb cellular structure, strengthening internal structure and reinforcing rib, can be easily formed with the aid of superplastic deformation and diffusion bonding [9,10]. In comparison with fusion welding, diffusion bonding can obtain a joint having homogeneous and even indistinguishable microstructure from matrix and in turn comparable mechanical properties with the base materials [11,12]. For counter-examples, butt-welded between 304 austenitic steel and 2205 duplex stainless steel using arc welding formed heat-affected zone consisting of Widmanstätten austenite embedded in the ferrite matrix [13]. Zhang et al. [14] studied the arc welding of Cr23Ni5Mo3MnSi duplex stainless steel, indicating a deterioration of impact toughness and pitting corrosion resistance due to insufficient austenite content and precipitation of $Cr_2N$ and $\sigma$-phase in the heat-affected zone.

Diffusion bonding has received much attention on titanium [6,15], aluminum [16,17] and magnesium [18,19] with the promotion by the application in the aerospace, aviation and automobile industry. For instance, the diffusion bonding of Ti-6Al-4V alloy at 900 °C for 60 min under a pressure of 5 MPa obtained a sound bonding joint [15]. The diffusion bonding of Ti-22Al-24Nb was also performed followed by superplastic forming, leading to a good formation of box-shaped component [6]. Experimental investigations on the diffusion bonding of AA6061 [16] and AA 7475 [17] were also reported. However, the studies on the diffusion bonding of stainless steels are relatively few. Sharma et al. investigated the diffusion bonding of 409 ferritic stainless steel associated with the improvement by impulse pressure [20,21]. Zhang et al. systematically studied the diffusion bonding of martensitic stainless steel (1Cr11Ni2W2MoV) under different surface roughness [22], holding temperatures [23], holding time [24] and pressures [25]. Furthermore, based on literature review, only several articles reported diffusion bonding of Cr23Ni6Mo1MnSi [26], Cr25Ni5Mo2MnSi [27], Cr22Ni5Mo3Mn2Si [28,29] and Cr25Ni7Mo3 [30,31] duplex stainless

---

[*] Corresponding author at: School of Materials Science and Engineering, Beijing Institute of Technology, Beijing 100081, PR China.
*E-mail address:* zhiping.xiong@uclouvain.be (Z. Xiong).

https://doi.org/10.1016/j.jmapro.2018.07.005
Received 12 March 2018; Received in revised form 28 June 2018; Accepted 3 July 2018

steels.

In present study, the isostatic diffusion bonding of Cr25Ni7Mo4MnSi duplex stainless steel was systematically investigated in terms of surface condition, cold rolling, holding time and pressure. In addition, the effect of superplastic deformation on diffusion bonding was also studied. The diffusion bonding interface was characterized using scanning electron microscopy (SEM) and electron backscattering diffraction (EBSD). The purpose of this paper is to understand important factors and mechanisms involved in the diffusion bonding of this duplex stainless steel, offering the information for the evaluation of its feasibility of superplastic forming/diffusion bonding.

## 2. Experimental details

The strips of 12 mm were prepared in the laboratory using an electric arc furnace and argon-oxygen decarburization followed by casting and hot rolling. The chemical composition is as follows: 24.96Cr, 7.00Ni, 3.85Mo, 0.28 N, 0.02C, 0.54Si, 1.04 Mn, 0.09Cu, 0.028 P, 0.003S and balanced Fe in weight percentage. It is referred to as SAE 2507. The strips were solution heated at 1350 °C for 30 min using resistance furnace (fluctuation ± 1 °C) followed by water quenching. The polygonal microstructure (Fig. 1(a)) consisted of 95% ferrite and 5% austenite. Fractions of phases were calculated based on pixel quantities of different grey scales using Image J with the assistance of Photoshop. Then they were cold rolled at a reduction of 60%, leading to the elongated microstructure (Fig. 1(b)).

The samples used for diffusion bonding ($10 \times 10 \times 4$ mm$^3$) were cut along the cold rolling direction. Their surfaces were mechanical polished using different silicon papers (400#, 600#, 800#, 1200# or 2000#) in order to obtain different roughness. Then it was washed by ultrasound in acetone for ~ 5 min, rinsed with ethanol and quickly dried by the air. The roughness was measured along the sample surface up to 1.25 mm length using Taylor Hobson Talysurf with a diamond stylus of 2 μm tip radius. Similar diffusion bonding of Cr25Ni7Mo4MnSi duplex stainless steel was performed at a Gleeble 3500 thermo-mechanical simulator under a vacuum of $5 \times 10^{-3}$ Torr. The bonding temperature was chosen as 1100 °C. It is because that at this temperature the SAE 2507 has an intermediate superplasticity and too high temperature is not suitable for engineering practice. In addition, the $\sigma$ phase, which is detrimental to mechanical properties [32], is absent. The effect of holding temperature on microstructure and superplasticity has been investigated in a previous study [3]. For isostatic diffusion bonding, the pressure during bonding was between 5 and 20 MPa and the holding time was 3, 5, 7, 10, 15 and 20 min. The effect of superplastic deformation (20 ~ 50%) on diffusion bonding was also studied at a strain rate of $1 \times 10^{-3}$ s$^{-1}$. The sample for the SEM characterization of bonding interface was cut perpendicular to the bonding interface, mechanical polished and etched using a mixture of concentrated nitric and hydrochloric acids. The EBSD sample was electropolished at ~ 7 V, ~ 50 A/dm$^2$, ~ 90 °C for 3 ~ 8 min in a solution of 280 ml phosphoric acid ($H_3PO_4$), 220 ml sulfuric acid ($H_2SO_4$), 40 ml distilled water and 120 g chromium trioxide ($CrO_3$). EBSD maps were obtained in an area of $180 \times 120$ μm$^2$ using a step size of 0.7 μm, where the bonding interface was almost at the center of the width. Φ3 mm discs were machined from the center of bonding interfaces, mechanically polished down to ~ 40 μm and finally twin-jet electropolished in a solution of 10 ml $HClO_4$ + 90 ml $CH_3CH_2OH$. The microstructure was characterized using Tecnai G2 F30 transmission electron microscope (TEM) operating at 300 kV.

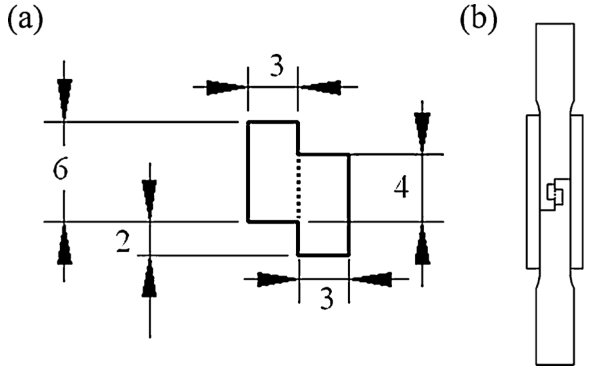

**Fig. 2.** Schematic illustration of (a) lap shear specimen and (b) lap shear test mold. The unit is in centimeter. The bonding interface is indicated by a dotted line.

In order to measure the joint strength, the sample was machined as shown in Fig. 2(a) and the lap shear test was carried out using the designed mold (Fig. 2(b)). The joint shear strength was calculated by dividing the force with the interfacial area. At least, two samples were tested for each condition. The repetition was very good, showing a standard deviation smaller than 15 MPa.

## 3. Results

### 3.1. Isostatic diffusion bonding

### 3.1.1. Effect of holding pressure on the bonding interface

Fig. 3 shows the microstructures of the bonding interfaces after holding at 1100 °C for 5 min under different pressures. There was no significant change in matrix microstructure consisting of ~ 50% austenite and ~ 50% $\delta$-ferrite. Smaller grains (such as indicated by arrows) along the bonded interfaces were observed, probably indicating the recrystallization occurred. After holding at 5 MPa, the interface was straight. It contained many discontinuous voids (Fig. 3(a)), most of which distributed along the phase boundaries. It obtained a joint shear strength of 193 MPa. With an increase in the pressure, the number of voids decreased, and the bonded interface became curved (Fig. 3(b–d)). Several voids also dispersed in the interior of ferrite or austenite

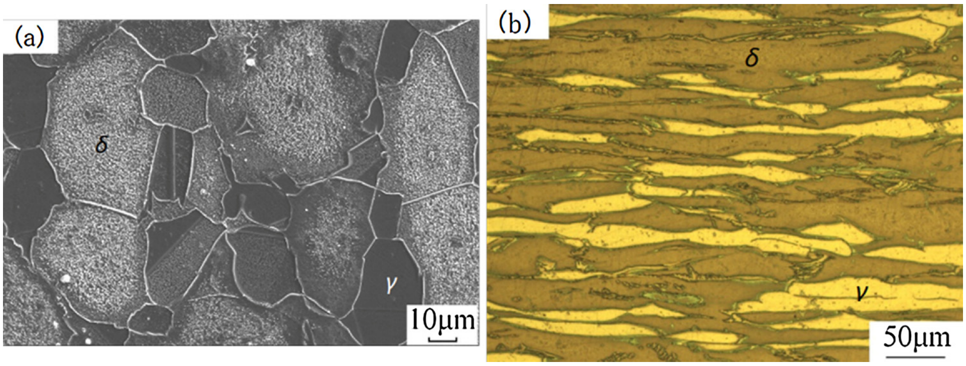

**Fig. 1.** Microstructure after (a) solution treatment and (b) cold rolling. $\gamma$ is austenite and $\delta$ is ferrite.