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

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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 δ -ferrite [1,2]. In addition, this steel exhibits excellent superplasticity up to \sim 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 σ -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

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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 $(10 \times 10 \times 4 \text{ mm}^3)$ 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 $\sim 5 \text{ min}$, 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 5×10^{-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 σ 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 \sim 50%) on diffusion bonding was also studied at a strain rate of 1×10^{-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 \sim 7 V, $\sim 50 \text{ A/dm}^2$, $\sim 90 \degree$ C for 3 $\sim 8 \min$ in a solution of 280 ml phosphoric



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.

acid (H₃PO₄), 220 ml sulfuric acid (H₂SO₄), 40 ml distilled water and 120 g chromium trioxide (CrO₃). EBSD maps were obtained in an area of 180 × 120 μ m² using a step size of 0.7 μ m, where the bonding interface was almost at the center of the width. Φ 3 mm discs were machined from the center of bonding interfaces, mechanically polished down to ~ 40 μ m and finally twin-jet electropolished in a solution of 10 ml HClO₄ + 90 ml CH₃CH₂OH. The microstructure was characterized using Tecnai G2 F30 transmission electron microscope (TEM) operating at 300 kV.

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% δ -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. γ is austenite and δ is ferrite.



Fig. 3. Microstructures of the diffusion bonding interfaces after holding at 1100 °C for 5 min using a pressure of (a) 5 MPa, (b) 10 MPa, (c) 12 MPa and (d) 20 MPa. γ is austenite and δ is ferrite.

(Fig. 3(b–d)), which indicated the grain boundary migration across the bonded interface. It led to an increase in the joint shear strength up to 407, 411 and 413 MPa, which corresponded to the pressure of 10, 12, 20 MPa, respectively. The joint shear strength increased slowly when

the pressure was higher than 10 MPa.

Fig. 4(a, b) shows the representative EBSD maps after holding at 12 and 20 MPa. Dark grey was ferrite and white grey was austenite. It is clear that austenite nucleated and grew at the boundaries of ferrite. As









Fig. 5. Fracture surfaces after holding at 1100 °C for 5 min using a pressure of (a) 5 MPa, (b) 10 MPa, (c) 12 MPa and (d) 20 MPa.



Fig. 6. Microstructures of the diffusion bonding interfaces after holding at 1100 °C using a pressure of 10 MPa for (a) 3 min, (b) 5 min, (c) 7 min, (d) 10 min, (e) 15 min and (f) 20 min. γ is austenite and δ is ferrite.



Fig. 7. (a, b, c, d) Representative EBSD maps after holding at 1100 °C using a pressure of 10 MPa for (a) 3 min, (b) 5 min, (c) 10 min and (d) 15 min; (e) misorientation angle distributions. $3-5^{\circ} =$ light blue, $5-10^{\circ} =$ green, $10-15^{\circ} =$ red, $15-20^{\circ} =$ navy blue and $> 20^{\circ} =$ dark. γ is austenite and δ is ferrite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

can be seen in Fig. 4(c), with an increase in holding pressure from 8 to 20 MPa, the fraction of low angle grain boundaries ($\leq 15^{\circ}$) was significantly reduced while the fraction of large angle grain boundaries (> 15°) greatly increased, indicating the grain boundary rotation.

Fig. 5(a) shows the fracture surface predominantly included dimples but also with some large cleavages under a small pressure of 5 MPa. With an increase in holding pressure, the number and size of cleavages (such as indicated by the arrows) tended to decrease and the dimples became smaller and homogeneous (Fig. 5(b–d)).

3.1.2. Effect of holding time on the bonding interface

Based on previous section, the medium pressure of 10 MPa was

selected because of a high joint shear strength (407 MPa). Fig. 6 shows the evolution of bonding interface with holding time. The fractions of austenite and δ -ferrite in matrix microstructure were always around ~ 50%. With an increase in holding time, the microstructure got coarser while the microstructure adjacent to the bonding interface was always finer due to recrystallization. After holding for 3 min, the bonding interface was sort of straight with dispersed voids (Fig. 6(a)). With an increase in holding time from 5 to 20 min, the bonding interface became curved and the number of voids was reduced (Fig. 6(b–f)). In addition, several voids were observed inside the ferrite or austenite (clearly shown in Fig. 6(b–d)), indicating the grain boundary migration across the bonded interface. Correspondingly, holding at 3 min only



Fig. 8. Different surface conditions and examples of (a) G2 and (b) G4.



Fig. 9. The evolution of the bonding interface with surface condition: (a) G1; (b) G2; (c) G3; (d) G4. Diffusion bonding at 1100 °C for 5 min under a constant pressure of 10 MPa. γ is austenite and δ is ferrite.

achieved a joint shear strength of 147 MPa due to the presence of many voids (Fig. 6(a)). When the holding time was 5 min, the joint shear strength was significantly increased to 407 MPa because of reduced number of voids (Fig. 6(b)). With a continuous increase in the holding time from 5 to 20 min, the shear strength was slightly increased from 407 to 413 MPa. Thus, holding for 5 min under a pressure of 10 MPa was used in the following experiments.

Fig. 7 shows representative EBSD maps with corresponding misorientation angle distributions. Obviously, austenite formed at the boundaries of ferrite during holding at 1100 °C and the microstructure became coarser when the holding time was extended. When the holding time was 3 min, the bonding interface was clearly observed in terms of small grains (Fig. 7(a)). With an increase in the holding time, the bonding interface became more and more ambiguous (Fig. 7(b–d)). When the holding time was 20 min, the bonding interface was undistinguishable due to curved bonding interface with coarse microstructure (Fig. 7(d)). As shown in Fig. 7(e), the fraction of large angle grain boundary (> 15°) increased with an increase in holding time while the fraction of low angle grain boundary ($\leq 15^{\circ}$) decreased.

3.1.3. Effect of surface condition on the bonding interface

Despite the best surface condition used above (G5 in Fig. 8), four additional roughness (G1, G2, G3 and G4) were prepared by different silicon papers for the investigation on diffusion bonding. Roughness average (Ra) is an average of the absolute values of the profile heights while the maximum height of the profile (Rt) is the vertical distance between the highest and lowest points of the profile over the evaluation length. The roughness increased from G5 to G1 (Fig. 8). For example, the surface of G2 and G4 was shown in Fig. 8(a) and (b).

Fig. 9(a) shows a large gap with many large voids along the bonding interface when the roughness was large (G1), leading to a very small joint shear strength of 86 MPa. Although a lower roughness (G2) reduced the gap (Fig. 9(b)), a very clear bonding interface was still observed and in turn resulted in a low joint shear strength of 93 MPa. With a decrease in the roughness to G3 and G4, the gap disappeared and only some small voids were observed (Fig. 9(c, d)), which obtained the high



Fig. 10. Diffusion bonding interfaces (a, c) without cold rolling and (b, d) with a cold rolling reduction of 60%. (a, b) solution treated at 1100 °C for 30 min and (c, d) solution heat treated at 1200 °C for 30 min. Diffusion bonding at 1100 °C for 5 min under a constant pressure of 10 MPa. γ is austenite and δ is ferrite.



Fig. 11. Microstructures of the diffusion bonding interfaces after holding at 1100 °C for a reduction of (a) 20%, (b) 30% (c) 40% and (d) 50% at a strain rate of 1×10^{-3} s⁻¹. γ is austenite and δ is ferrite.

joint shear strength of 198 and 375 MPa, respectively. The bonded interface in G5 condition obtained the highest joint shear strength of 407 MPa because of the best bonded interface (c.f. Figs. 3(b) and Figure 9(d)).

3.1.4. Effect of cold rolling on the bonding interface

Fig. 10(a, c) shows the bonding interfaces without cold rolling before diffusion bonding process. Obviously, the interface was straight dispersed with many small voids. After cold rolling by 60%, a little curved interface was observed and the voids along the interface became fewer (Fig. 10(b, d)). It means cold rolling was beneficial to the diffusion bonding.

3.2. Effect of superplastic deformation on the diffusion bonding

This section investigated the variation of bonding interface with superplastic deformation at 1100 °C and a strain rate of 1×10^{-3} s⁻¹. The matrix microstructure consisted of ~ 50% austenite and ~ 50% δ -ferrite (Fig. 11). After deformation at a reduction of 20%, the elongated microstructure originated from cold rolling was still observed and the bonding interface was straight dispersed with some voids (Fig. 11(a)). When the reduction was 30%, the microstructure became polygonal



Fig. 12. (a, b, c, d) EBSD maps after holding at 1100 °C for a reduction of (a) 20%, (b) 30%, (c) 40% and (d) 50% at a strain rate of $1 \times 10^{-3} \text{ s}^{-1}$; (e) misorientation angle distribution. 3-5° = light blue, 5-10° = green, 10-15° = red, 15-20° = navy blue and > 20° = dark. γ is austenite and δ is ferrite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

due to recovery and recrystallization and the bonding interface became blurred (Fig. 11(b)). With an increase in the reduction up to 40 and 50%, the microstructure became coarser and the bonding interface became curved dispersed with fewer voids (Fig. 11(c, d)), indicating the grain boundary migration. When the deformation increased from 20% to 50%, due to constant strain rate, the exerted pressure increased and the bonding time also increased. It was benefit for void closure and led to strong bonded interface. Correspondingly, the shear strength was continuously increased from 395, 399, 406 to 418 MPa.

After deformation at a reduction of 20 and 30%, many austenite grains were observed along the bonded interfaces, which nucleated at the grain boundaries of ferrite (Fig. 12(a, b)). The corresponding fraction of low angle grain boundaries ($\leq 15^{\circ}$) was large (Fig. 12(e))

because increased dislocations formed sub-grains (Fig. 13(a)). Increasing the reduction up to 40 and 50% offered more energy and time for grain rotation and growth, leading to coarser microstructure (Fig. 12(c, d)). This made the diffusion bonding interface cannot be distinguished from matrix anymore. In addition, the dislocation accumulation and recovery (Fig. 13(b)) made an increase in the fraction of high angle grain boundaries (> 15°, Fig. 12(e)).

The representative fracture surface after a reduction of 20% showed many small dimples but with some cleavage facets (Fig. 14(a)). With an increase in the reduction up to 40%, the size and number of cleavage facets were significantly reduced (Fig. 14(b)), indicating a better diffusion bonding.



Fig. 13. TEM microstructures after holding at 1100 °C for a reduction of (a) 20% and (b) 50% at a strain rate of 1×10^{-3} s⁻¹.



Fig. 14. Fracture surfaces after holding at 1100 °C for a reduction of (a) 20% and (b) 40% at a strain rate of 1×10^{-3} s⁻¹.

4. Discussion

4.1. Analysis of the diffusion bonding parameters

The effect of surface condition, cold rolling, holding time and pressure was analytically investigated for isostatic diffusion bonding of a SAE 2507 duplex stainless steel. The surface roughness determines initial contacting of two faying surfaces. Zhang et al. has experimentally demonstrated that larger roughness leads to larger initial size and fraction of voids [22]. In present study, increasing surface roughness deteriorated the bonded interface by the increased fraction and size of voids (Fig. 9). It led to a decrease in the joint shear strength from 407 to 93 MPa. Cold rolling before diffusion bonding obtained a better bonding interface than that without cold rolling at the same bonding condition (Fig. 10). It is because of an improved superplasticity by cold rolling [33]. With an increase in the holding time and pressure, the bonding interface became curved, where the number of voids was reduced (Figs. 3 and 6). Chen et al. also reported a decreased fraction of voids with the increased holding time and pressure using ultrasonic inspection in the diffusion bonding of AA6061 [16]. However, too large holding time and pressure only led to a slight increase in the shear strength. This phenomenon was also stated by superplastic diffusion bonding of Cr22Ni6Mo3MnSi [27] and Cr22Ni5Mo3MnSi duplex stainless steels [28]. It is because a certain holding time of 5 min and a pressure of 10 MPa have already achieved a sound bonding. Further

increasing the holding time and pressure cannot make significant improvement in the diffusion bonding. The corresponding joint shear strength was 407 MPa, which was comparable to the base shear strength of 420 MPa under the same bonding condition.

Superplastic deformation at a reduction of 30% obtained a good bonding interface (Fig. 11(b)) and a high joint shear strength of 399 MPa. Increasing the deformation up to 50% led to an improved joint shear strength of 418 MPa. It indicates the feasible combination of superplastic formation and diffusion bonding techniques, which can use for complicated structure formation [9,10].

4.2. Diffusion bonding mechanisms

With the help of superplasticity, the diffusion bonding is accelerated and boosted [8,17,29,34]. Enjo et al. [35] reported that, when the Ti-6Al-4V alloy had a better superplasticity, higher tensile strength of the joint was obtained by diffusion bonding at 850 °C for 600 s under a pressure of 2 MPa. The bonding strength also can be improved by the enhancement of superplasticity using cyclic phase transformation, such as titanium alloy (TA17) [36] and duplex stainless steels [29,34]. On one hand, for the diffusion bonding in the non-superplastic stainless steels, the martensitic stainless steel (1Cr11Ni2W2MoV) achieved a sound bonding after holding at 1100 °C for 20 min under a pressure of 15 MPa [23]; the 409 ferritic stainless steel obtained a sound bonding after holding at 850 °C for 30 min with an impulse pressure of 40 MPa [20,21]. On the other hand, the present study reached a sound bonding only after holding at 1100 $^{\circ}$ C for 5 min under a pressure of 10 MPa for SAE 2507 duplex stainless steel. It indicates the great contribution from superplasticity to the diffusion bonding.

The diffusion bonding can be separated into two stages. The first stage is the contacting process of two faying surfaces. Because of inevitable roughness in the surfaces, the asperities first contact with each other and external load concentrates in these areas, leading to large stress concentration [12]. This can induce superplastic deformation of contacting asperities and in turn accelerate the increase of the contacting areas [8]. As a result, the local stress is reduced and the plastic deformation is slowed down. This first stage finally leads to a quick void closure and a plannar array of voids (such as Fig. 9(b, c)). After the achievement of close contact on bonding interface, the second stage is predominantly controlled by subsequent diffusion and grain boundary migration [7]. The observed recrystallization along the bonded interface such as in Figs. 4 and 7 is triggered by local superplastic deformation, leading to the grain refinement. These refined grains contribute to grain boundary diffusion by providing many interfaces, leading to an increased diffusivity in the bonding process [37]. These recrystallized grains in the vicinity of bonded interface were also detected by superplastic diffusion bonding between Ti-6Al-4 V alloy [15] and SAE 2205 duplex stainless steel [27]. In addition, the plastic deformation adjacent to the voids can progressively fill the voids simultaneously with the help of mass diffusion from the adjacent regions. This mass diffusion is promoted by the stress gradient along the bonding interface [31,38]. With an increase in the pressure and hold time, an increased fraction of large angle grain boundaries (Figs. 4(c) and Figure 7(c)) indicates the grain boundary rotation. Moreover, the grain boundary migration across the bonding interfaces (such as Figs. 6(d) and Figure 7(c)) further improves the bonded interface [39,40].

The above discussion leads to a conclusion that the superplastic behavior during diffusion bonding can accelerate the bonding process by quickly carrying two fraying surfaces close together through plastic deformation, and by filling interfacial voids in a short time through massive diffusion and grain boundary rotation and migration. This can lead to a sound bonding in a short time under a low pressure. Correspondingly, a large joint shear strength, comparable to base material, can be achieved.

5. Conclusion

The similar diffusion bonding of SAE 2507 duplex stainless steel under different conditions was investigated by the microstructure characterization of the bonding interface and by the evaluation of the joint shear strength, leading to the following conclusion:

- (1) Holding at 1100 °C for 5 min under a pressure of 10 MPa led to a joint shear strength of 407 MPa, which is comparable to 420 MPa of the base material under the same diffusion condition. Superplastic deformation by 30% and 50% at 1100 °C and 1×10^{-3} s⁻¹ respectively achieved the joint shear strengths of 399 and 418 MPa, indicating the feasible application in the formation of complicate structures.
- (2) Increasing holding time and pressure first significantly and then only slightly increased the joint shear strength when the holding time and pressure exceeded certain values, accompanied by a decrease in the number of voids and a curved bonding interface.
- (3) The diffusion bonding can be improved by pre-cold rolling because of an enhanced superplasticity. The improvement of surface condition is also beneficial to the diffusion bonding.
- (4) Superplastic diffusion bonding is realized by plastic deformation, massive diffusion, and rotation and migration of grain boundaries along the bonding interface.

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References

- Lo KH, Shek CH, Lai J. Recent developments in stainless steels. Mater Sci Eng R 2009;65:39–104.
- [2] Garfías-Mesias L, Sykes J, Tuck C. The effect of phase compositions on the pitting corrosion of 25 Cr duplex stainless steel in chloride solutions. Corros Sci 1996;38:1319–30.
- [3] Chen XH, Ren XP, Xu H, Tong JG, Zhang HY. Effect of solution treatment on the super plasticity and bonding property of 00Cr25Ni7Mo3N duplex stainless steel. J Univ Sci Technol Beijing 2012;34:404–9.
- [4] Li S, Ren X, Ji X, Gui Y. Effects of microstructure changes on the superplasticity of 2205 duplex stainless steel. Mater Des 2014(55):146–51.
- [5] Sagradi M, Pulino-Sagradi D, Medrano R. The effect of the microstructure on the superplasticity of a duplex stainless steel. Acta Mater 1998;46:3857–62.
- [6] Wang C, Zhao T, Wang G, Gao J, Fang H. Superplastic forming and diffusion bonding of Ti-22Al-24Nb alloy. J Mater Proc Technol 2015;222:122-7.
- [7] Wang Z, Ridley N, Lorimer G, Knauss D, Briggs G. Evaluation of diffusion bonds formed between superplastic sheet materials. J Mater Sci 1996;31:5199–206.
- [8] Maehara Y, Komizo Y, Langdon T. Principles of superplastic diffusion bonding. Mater Sci Technol 1998;4:669–74.
- [9] Han W, Zhang K, Wang G. Superplastic forming and diffusion bonding for honeycomb structure of Ti-6Al-4V alloy. J Mater Proc Technol 2007;183:450–4.
- [10] Xun Y, Tan M. Applications of superplastic forming and diffusion bonding to hollow engine blades. J Mater Proc Technol 2000;99:80–5.
- [11] Pilling J. The kinetics of isostatic diffusion bonding in superplastic materials. Mater Sci Eng 1988;100:137–44.
- [12] Lagos M, Retamal C. An alternate theoretical approach to solid-state bonding. Scripta Mater 2011;64:402–5.
- [13] Yıldızlı K. Investigation on the microstructure and toughness properties of austenitic and duplex stainless steels weldments under cryogenic conditions. Mater Des 2015;77:83–94.
- [14] Zhang Z, Jing H, Xu L, Han Y, Zhao L. Investigation on microstructure evolution and properties of duplex stainless steel joint multi-pass welded by using different methods. Mater Des 2016;109:670–85.
- [15] Lee HS, Yoon JH, Park CH, Ko YG, Shin DH, Lee CS. A study on diffusion bonding of superplastic Ti–6Al–4V ELI grade. J Mater Proc Technol 2007;187:526–9.
- [16] Chen G, Shi Q, Li Y, Han Z, Yuan K. Experimental investigations on the kinetics of void shrinkage in solid state bonding of AA6061 at high temperatures and high pressures. Mater Des 2016;89:1223–6.
- [17] Pilling J, Ridley N. Solid state bonding of superplastic AA 7475. Mater Sci Technol 1987;3:353–9.
- [18] Somekawa H, Hosokawa H, Watanabe H, Higashi K. Diffusion bonding in superplastic magnesium alloys. Mater Sci Eng A 2003;339:328–33.
- [19] Torun O, Karabulut A, Baksan B, Çelikyürek I. Diffusion bonding of AZ91 using a silver interlayer. Mater Des 2008;29:2043–6.
- [20] Sharma G, Dwivedi DK. Effect of pressure pulsation on bond interface characteristics of 409 ferritic stainless steel diffusion bonds. Vacuum 2017;146:152–8.
- [21] Sharma G, Dwivedi DK. Impulse pressure-assisted diffusion bonding of ferritic stainless steel. Int J Adv Manuf Technol 2018:1–13.
- [22] Zhang C, Li M, Li H. On the shear strength of similar diffusion bonded 1Cr11Ni2W2MoV stainless steel hollow structural components: effect of void morphology. J Manuf Proc 2017;29:10–7.
- [23] Zhang C, Li H, Li M. Detailed evolution mechanism of interfacial void morphology in diffusion bonding. J Mater Sci Technol 2016;32:259–64.
- [24] Zhang C, Li H, Li M. Interaction mechanism between void and interface grain boundary in diffusion bonding. Sci Technol Weld Join 2015;20:123–9.
- [25] Zhang C, Li H, Li M. Detailed analysis of surface asperity deformation mechanism in diffusion bonding of steel hollow structural components. Appl Surf Sci 2016;371:407–14.
- [26] Yeh M, Tseng Y, Chuang T. Effects of superplastic deformation on the diffusion welding of superdux 65 stainless steel. Weld J 1999;78:301–4.
- [27] Komizo Y, Maehara Y. Solid state diffusion bonding using superplasticity of δ/γ duplex stainless steels. Trans Jpn Weld Soc 1988;19:83–91.
- [28] Islam M, Ridley N. Isostatic diffusion bonding of a microduplex stainless steel. Scripta Mater 1998;38:1187–93.
- [29] Li S, Ren X, Hou H. The effect of thermal cycling in superplastic diffusion bonding of 2205 duplex stainless steel. Mater Des 2015;86:582–6.
- [30] Ridley N, Salehi M, Pilling J. Isostatic diffusion bonding of microduplex stainless steel. Mater Sci Technol 1992;8:791–5.
- [31] Todd RI, Hodges C, Wong Y, Wang Z, Ridley N. Objective modelling of diffusion bonding in superplastic duplex stainless steels. Mater Sci Forum 1997;243–245:675–80.
- [32] Nieh TG, Lesuer DR, Syn CK. Characterization of a commercial superplastic stainless steel, SuperDux64. Mater Sci Eng A 1995;202:43–51.
- [33] Li SX, Ren XP, Lu ZM. Effect of cold rolling reduction on the superplasticity of 00Cr22Ni5Mo3N duplex stainless steel. J Plast Eng 2014;21:97–101.
- [34] Qu H, Hou H, Li P, Li S, Ren X. The effect of thermal cycling in superplastic diffusion bonding of heterogeneous duplex stainless steel. Mater Des 2016;96:499–505.
- [35] Enjo T, Ikeuchi K, Akikawa N, Ito M. Effect of the microstructure of base metals on

X. Ren et al.

- the diffusion welding of Ti-6Al-4V alloy. J Jpn Inst Metals 1980;44:659-65.
- [36] Qin B, Sheng G, Huang J, Zhou B, Qiu S, Li C. Phase transformation diffusion bonding of titanium alloy with stainless steel. Mater Charact 2006;56:32–8.[37] Wang W, Yang M, Yan D, Jiang P, Yuan F, Wu X. Deformation mechanisms for
- superplatic behaviors in a dual-phase high specific strength steel with ultrafine grains. Mater Sci Eng A 2017;702:133–41.
- [38] Zhang C, Li M, Li H. Diffusion behavior at void tip and its contributions to void
- and the second se of duplex stainless steel. Mater Sci Eng A 2001;319-321:779-83.
- [40] Zhang C, Li H, Li M. Formation mechanisms of high quality diffusion bonded martensitic stainless steel joints. Sci Technol Weld Join 2015;20:115–22.