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Shear strength and fracture characteristics near the interface of diffusion bonding of Fe_3Al/Q235 dissimilar materials

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Abstract

In this study, Fe_3Al intermetallic and Q235 steel were jointed by the vacuum diffusion bonding. The shear strength of the Fe_3Al/Q235 interface was analyzed and the interfacial fracture morphology was observed by means of scanning electronic microscope (SEM). The experimental results indicated that the fracture location was on the Fe_3Al side, and the shear rupture morphology was the cleavage characteristics with little toughness fracture. Most micro-cracks propagated along the interface near the Fe_3Al side and sometimes leaned to the center of the interface. The Fe_3Al/Q235 diffusion bonding joint with excellent interface combination and the sufficient shear strength (112 MPa) can be obtained when the heating temperature was 1060 °C, the holding time was 45–60 min and the pressure was 12–15 MPa.

K e y w o r d s: diffusion bonding, interface, shear strength, fracture morphology

1. Introduction

The intermetallic compounds, such as Fe_3Al, TiAl and Ti_3Al et al. exhibit an excellent resistance to wear, oxidation and corrosion, as well as creep resistance at high temperature, low density and low raw material cost compared with other intermetallics [1–3]. Therefore, it is viewed as a low cost alternative to high temperature stainless steels [4–7]. However, Fe_3Al intermetallic would easily suffer from the weld cracks when being welded by the fusion welding processes, and the weld crack has become a great barrier to its engineering application [8, 9]. The Fe_3Al intermetallic was successfully welded by means of advanced vacuum diffusion bonding in order to restrain the production of the welding crack and brittleness phase near the interface of the Fe_3Al/Q235 dissimilar materials.

The vacuum diffusion bonding has progressed increasingly with the development of the computer and vacuum techniques, and it can be used in the joining of brittle materials and dissimilar materials [10–13]. In this paper, the Fe_3Al intermetallic and Q235 steel were joined by the vacuum diffusion bonding. The diffusion combined characteristics of the Fe_3Al/Q235 interface under the conditions of different parameters were analyzed. The shear strength of the diffusion bonding interface was measured by the pressure test machine and the special clamp. The shear fracture morphology of the Fe_3Al/Q235 interface was analyzed by means of scanning electron microscope (SEM), and the fracture mechanism of the Fe_3Al diffusion bonding interface was discussed.

This paper provides the experimental basis to the research of the shear strength and the fracture characteristics, which has an important significance to promote the application of the Fe_3Al intermetallic.

2. Experimental

The materials used in this experiment were Fe_3Al intermetallic and Q235 steel. Fe_3Al was prepared in the vacuum furnace, and Fe_3Al casting was hot rolled to a final plate, whose tensile strength was about 455 MPa and the elongation ratio was 5 %. The chemical compositions in the Q235 carbon steel were 0.25 % C, 0.2 % Si, 0.6 % Mn and 98.95 % Fe. The Fe_3Al intermetallic and Q235 steel were joined together by means of an advanced vacuum diffusion bonding technology. The size of Fe_3Al intermetallic and the Q235

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Fig. 1. The equipment of the diffusion bonding in the test.

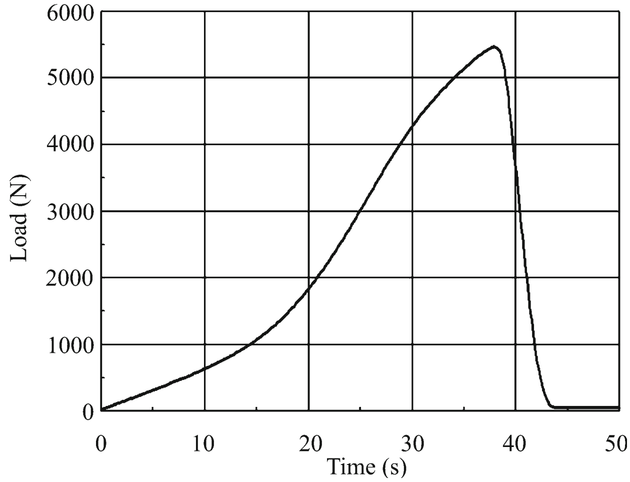

Fig. 2. Change of loading with time in the shearing test for the diffusion bonding joint.

steel was 100 mm × 20 mm × 20 mm, respectively.

The equipment of the vacuum diffusion bonding in the test is shown in Fig. 1. Oxidizing film on sample surface was removed by the mechanical and chemical methods before the vacuum diffusion bonding. The parameters of the diffusion bonding were: heating temperature $T = 1000–1080$ ℃, holding time $t = 15–60$ min, pressure $p = 10–17.5$ MPa and vacuum degree 1.33×10^{-4} Pa. The diffusion bonding joint was cut into sample of 20 mm × 8 mm × 8 mm (two samples were selected under the condition of each group technological parameters). The shear strength of the samples of diffusion bonding joint was measured in the LYS-50000 pressure test machine by using the special clamp. The loading speed of the shear strength test was 0.5 mm min^{-1}. Change of loading with time in the shearing test for the diffusion bonding joint is shown in Fig. 2.

Furthermore, the microstructure, the shear fracture morphology and the cleavage initiation near the Fe_3Al/Q235 diffusion bonding interface were analyzed by means of scanning electron microscope (SEM).

3. Results and analysis

3.1. Effect of the technological parameters on the Fe_3Al/Q235 interface morphology

The interface morphology and deformation degree of the diffusion bonding joint are the key factors to determine whether the Fe_3Al/Q235 joint can satisfy the application requirement. The testing results of the effect of the technological parameters on the interface morphology of the Fe_3Al/Q235 diffusion bonding in-

Table 1. Effect of the technological parameters on the Fe_3Al/Q235 interface morphology and the joint deformation

No.	Heating temperature T (℃)	Holding time t (min)	Pressure P (MPa)	Observation to the interface	Interface combined condition and deformation degree of joint
01	1000	60	17.5	a lot of micro holes	unbonded, undeformed
02	1020	60	17.5	existing micro hole	poor bonding, undeformed
03	1040	15	17.5	existing micro hole	unbonded, undeformed
04		30	17.5	no micro hole	poor bonding, undeformed
05		45	17.5	no micro hole	good bonding, undeformed
06		60	17.5	no micro hole	good bonding, undeformed
07		45	10.0	existing micro hole	poor bonding, undeformed
08	1060	45	12.0	no micro hole	good bonding, undeformed
09		45	15.0	no micro hole	good bonding, undeformed
10		45	17.5	no micro hole	good bonding, deformed slightly
11		60	17.5	no micro hole	good bonding, deformed slightly
12	1080	60	17.5	no micro hole	good bonding, deformed obviously

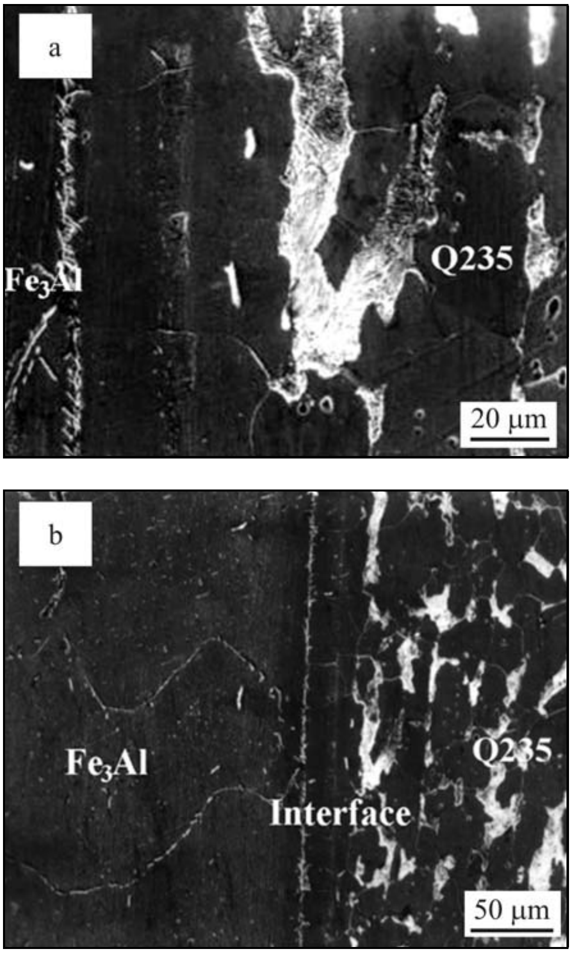

Fig. 3. The morphology of the Fe_3Al/Q235 diffusion bonding interface with the different technological parameters: (a) 1040 ℃ × 60 min, $P = 15.0$ MPa, (b) 1060 ℃ × 50 min, $P = 12.5$ MPa.

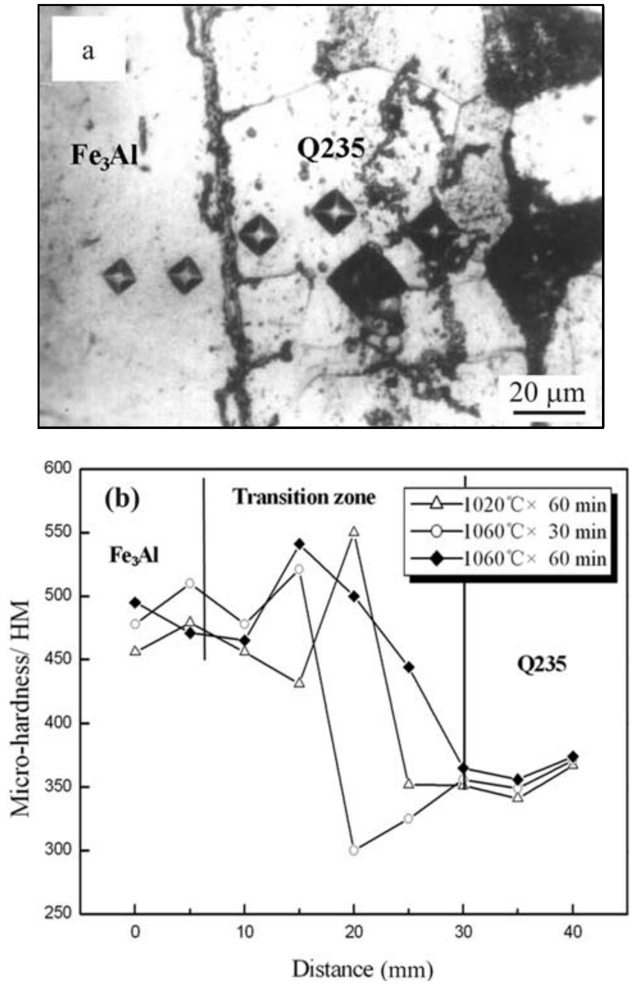

Fig. 4. Microhardness distribution in the Fe_3Al/Q235 diffusion welding joint: (a) the measured locations, and (b) the microhardness distributions.

terface and the joint deformation degree of the joint are shown in Table 1.

As is shown in Table 1, when the holding time and the pressure were constant, with the increase of the heating temperature, the diffusion bonding combined near the Fe_3Al/Q235 interface and the number of the micro hole gradually decreased. Nevertheless, when the heating temperature was too high (1080 ℃), the deformation degree of the joint increased significantly. In addition, it was noted that when the heating temperature and the holding time were constant, the pressure increased from 10 to 17.5 MPa, Fe_3Al/Q235 diffusion bonding joint combined more closely. Moreover, when the pressure was 17.5 MPa, the Fe_3Al/Q235 joint deformed slightly. With the increase of the holding time, the number of the micro hole near the Fe_3Al/Q235 interface gradually decreased. The experimental results indicated that the diffusion bonding joint did not deform when the pressure was smaller than 17 MPa.

Figure 3a,b shows the feature of the Fe_3Al/Q235 diffusion bolding interface: it was found that there was an excellent metallurgical combination free of the micro hole when the heating temperature $T = 1040$ ℃, the holding time $t = 15$–60 min, and the pressure $P = 17$ MPa.

The microhardness measured locations of the Fe_3Al/Q235 diffusion bonding joint and the testing results are shown in Fig. 4a,b. These results indicate that the microhardness of the Fe_3Al intermetallic matrix and Q235 matrix were approximately 490 HM and 350 HM after the diffusion bonding thermal cycle, respectively. Furthermore, the microhardness of the Fe_3Al/Q235 diffusion bonding interface changed with the different technological parameters.

3.2. *The shear strength near the Fe_3Al/Q235 diffusion interface*

The experimental results of the shear strength of

T a b l e 2. The shear strength of the Fe_3Al/Q235 diffusion bonding interface

No.	Technological parameter ($T \times t$, P)	Shear area (mm^2)	Maximum load F_m (N)	Shear strength σ_γ (MPa)	Average shear strength (MPa)
01	1000 °C × 60 min, 17.5 MPa	9.98 × 8.02	3346	40.8	39.9
02	1000 °C × 60 min, 17.5 MPa	9.97 × 7.99	3115	39.1	
03	1020 °C × 60 min, 17.5 MPa	9.97 × 7.98	5370	67.5	67.5
04	1020 °C × 60 min, 17.5 MPa	9.98 × 8.00	5395	67.6	
05	1040 °C × 60 min, 15.0 MPa	9.95 × 7.96	7072	89.2	90.8
06	1040 °C × 60 min, 15.0 MPa	9.98 × 8.02	7408	92.5	
07	1060 °C × 30 min, 15.0 MPa	9.98 × 8.00	3377	42.3	43.4
08	1060 °C × 30 min, 15.0 MPa	10.00 × 7.98	3551	44.5	
09	1060 °C × 45 min, 15.0 MPa	9.97 × 7.96	5301	66.8	67.0
10	1060 °C × 45 min, 15.0 MPa	9.96 × 7.98	5341	67.2	
11	1060 °C × 60 min, 12.0 MPa	9.93 × 7.96	8960	114.3	112.3
12	1060 °C × 60 min, 12.0 MPa	10.00 × 7.93	8657	110.2	
13	1080 °C × 60 min, 12.0 MPa	9.95 × 7.98	6392	80.5	82.1
14	1080 °C × 60 min, 12.0 MPa	10.02 × 7.96	6668	83.6	

the Fe_3Al/Q235 diffusion bonding interface with the different parameters using the digital display pressure machine are shown in Table 2.

The experimental results indicated when the holding time was 60 min, the pressure was 12–17 MPa, the heating temperature increased from 1000 to 1060 ℃, the shear strength increased from 39.9 to 112.3 MPa (Fig. 5a). In fact, with the increase of the heating temperature, the atoms near the interface obtained enough energy and diffused sufficiently. Thus, an excellent metallurgical combination of the Fe_3Al/Q235 bonding interface was formed. Nevertheless, when the heating temperature increased to 1080 ℃, the shear strength near the bonding interface decreased to 82.1 MPa.

When the heating temperature increased to 1060 ℃, with the increase of the holding time, the shear strength of the interface increased greatly. Nevertheless, too long holding time leads the microstructure to become coarser and the shear strength decreases (Fig. 5b). The experimental results indicated that when the heating temperature was 1060 ℃, the holding time was 45–60 min and the bonding joint did not deform macroscopically (P = 12–15 MPa), and the high shear strength without the micro hole was achieved for the Fe_3Al/Q235 diffusion bonding joint.

3.3. The fracture analysis of the Fe_3Al/Q235 diffusion interface

The fracture morphology of the Fe_3Al intermetallic has the brittleness cleavage characteristics (Fig. 6a). After the diffusion bonding, the fracture morphology of the Fe_3Al/Q235 diffusion bonding interface changed greatly, the SEM micrograph of the shear fracture morphology near the Fe_3Al/Q235 diffusion interface is shown in Fig. 6b.

The fracture of the Fe_3Al/Q235 diffusion bonding

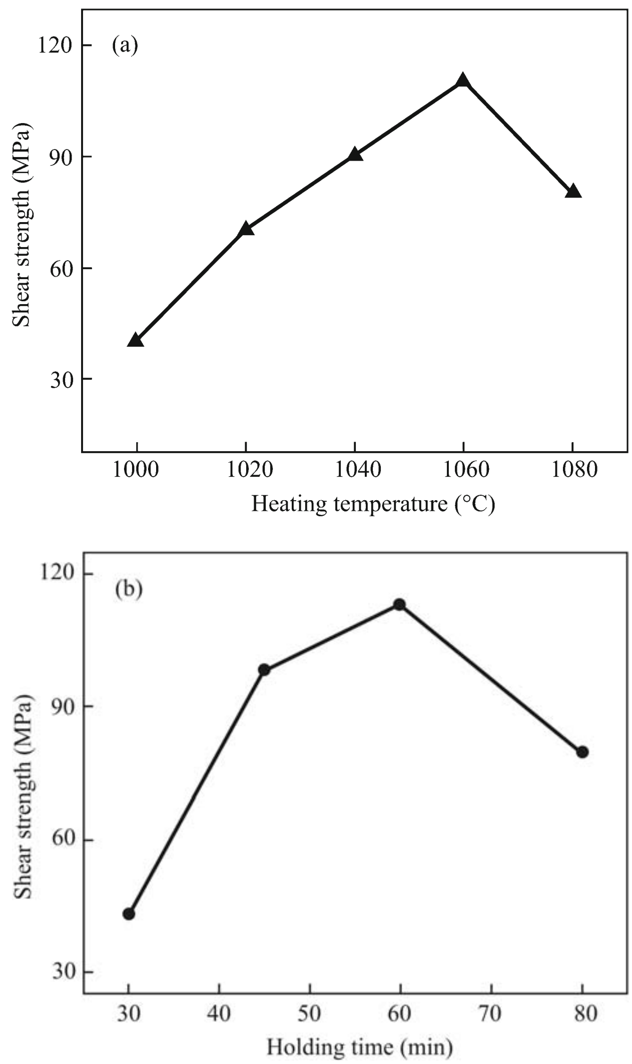

Fig. 5. The influence of (a) the heating temperature, and (b) the holding time to the shear strength of the Fe_3Al/Q235 diffusion bonding interface.

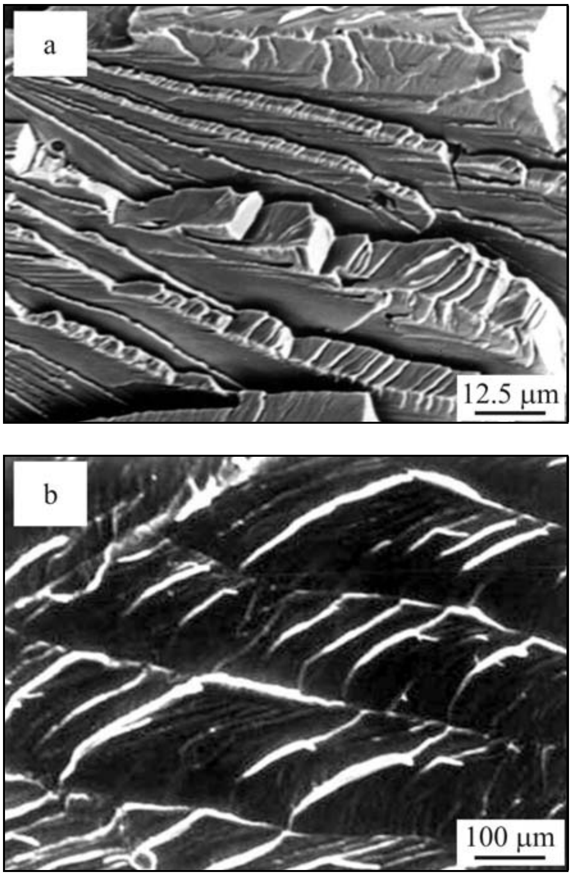

Fig. 6. Fracture morphology of the Fe_3Al intermetallic at room temperature: (a) the cleavage fracture, and (b) the cleavage step.

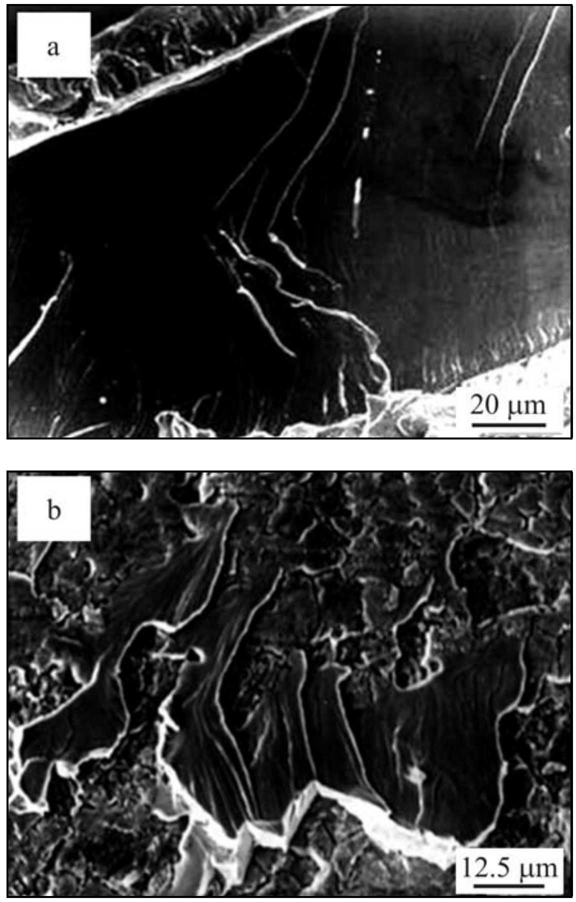

Fig. 7. Shear fracture morphology of the Fe_3Al/Q235 diffusion bonding interface: (a) the river patterns, and (b) the tearing feature.

interface exhibited the cleavage characteristics, and there were a lot of the river patterns in the cleavage face. In fact, the fracture occurred at the Fe_3Al/Q235 interface near the side of Fe_3Al matrix. In addition, the Fe-Al intermetallic was easy to form due to the high Al density near the Fe_3Al side, so the propagation of the micro crack can be observed on the cleavage face of the Fe_3Al/Q235 bonding interface. Furthermore, when the micro crack met the grain boundary or the other barriers, its direction changed and the river pattern was formed, or it would transcend the grain boundary and the transgranular fracture was formed [14, 15].

There were crystal boundary, phase boundary, impurity, etc. near the Fe_3Al/Q235 diffusion bonding interface, which made the micro crack tip slide deformation uneven, and then propagated along the interface of the Fe_3Al side. The observation of SEM indicated that the shear fracture of the Fe_3Al/Q235 interface presented the characteristics of the toughness, and there were a few tearing edges at the edge of the diffusion bonding interface. When the heating temperature was higher, the elements near the interface diffused sufficiently and their distribution was uniform due to the high ductility deformation in the part of the edge. In addition, there were Cr, Nb elements, etc. in the Fe_3Al side. In the diffusion bonding process, Cr, Nb existed in the form of the precipitated phase near the interface, so the propagation of the micro crack was effectively prevented.

The fracture of the Fe_3Al/Q235 diffusion bonding interface showed the brittleness cleavage morphology, and there were a lot of the fine river patterns on the cleavage fracture face (Fig. 7a). Moreover, it was also noted that there were a few deformed tearing edges at the edge of the Fe_3Al diffusion bonding interface (Fig. 7b), this is favorable to enhance performance of Fe_3Al/Q235 diffusion bonding interface.

4. Conclusions

1. With the increase of the heating temperature, the holding time and the pressure, the atom diffusion ability and the combined capacity near the Fe_3Al/Q235 diffusion bonding interface *will increase.*

However, when the heating temperature and the pressure increase, the diffusion bonding joint deforms obviously, so the heating temperature and the pressure should be limited.

2. When the heating temperature was 1060 ℃, the holding time was 45–60 min and the pressure was 12–15 MPa, the Fe_3Al/Q235 diffusion bonding joint with a higher shear strength ($\sigma_r = 112$ MPa) and the sufficient diffusion was obtained.

3. The shear fracture morphology of the Fe_3Al/Q235 diffusion bonding interface *had cleavage characteristics,* which had a few features of the toughness fracture, the fracture location was near the interface of the Fe_3Al side and most cracks propagated along the interface of the Fe_3Al side.

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