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# Fine structure at the diffusion welded interface of $Fe_3Al$/Q235 dissimilar materials

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**Abstract.** **The interface of $Fe_3Al$/Q235 dissimilar materials joint, which was made by vacuum diffusion welding, combines excellently. There are $Fe_3Al$, FeAl phases and $a$-Fe (Al) solid solution at the interface of $Fe_3Al$/Q235. Aluminum content decreases from 28% to 1·5% and corresponding phase changes from $Fe_3Al$ with $DO_3$ type body centred cubic (*bcc*) structure to $a$-Fe (Al) solid solution with B2 type *bcc* structure. All phases are present in sub-grain structure level and there is no obvious brittle phases or micro-defects such as pores and cracks at the interface of $Fe_3Al$/Q235 diffusion joint.**

**Keywords.** **$Fe_3Al$/Q235 dissimilar material joint; vacuum diffusion welding; fine structure.**

## 1. Introduction

In recent years, considerable interest has been generated in intermetallic compounds because intermetallic compounds have unique properties, such as high yield strength at high temperature and excellent oxidation and corrosion resistance because of their long range ordered structure and coexistence of metallic bond (Mckameey *et al* 1991). When specially compared to other intermetallic compounds such as $Ni_3Al$ and $Ti_3Al$, $Fe_3Al$ is cheaper and its strength increases with the increase of temperature below 600°C (Rabin *et al* 1994). $Fe_3Al$ is thought of as one of the most prospective structural materials in industry. At the same time, the weldability also has attracted the attention of several researchers (David *et al* 1989; Gao *et al* 2000). Until now the welding of similar $Fe_3Al$ intermetallic compound was realized using electronic beam welding (EBW) and tungsten inert gas welding (TIG) (David and Zacharia 1993; Ding *et al* 2000), but now it is necessary to bond $Fe_3Al$ intermetallic compound with common carbon steel in order to realize its full advantages when considering economic benefit in practical applications. Physical and chemical performance of $Fe_3Al$ are more different from that of Q235 steel, so they are difficult to be welded with common fusion welding methods. Hence diffusion welding and brazing are used widely (He and Cao 1986).

In this paper, $Fe_3Al$/Q235 dissimilar materials were successfully welded together by means of advanced vacuum diffusion welding. The microstructural features at the interface of $Fe_3Al$/Q235 dissimilar materials were examined by means of scanning electron microscopy (SEM). The phase constitution was investigated through X-ray diffraction (XRD). The chemical composition at the interface of $Fe_3Al$/Q235 and lattice orientation between $Fe_3Al$, FeAl phases and $a$-Fe (Al) solid solution were analysed using transmission electron microscope (TEM). This is important for studying the weldability of $Fe_3Al$ and enlarging the application of $Fe_3Al$ intermetallic compound.

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## 2. Experimental

Experimental materials are $Fe_3Al$ intermetallic compound and Q235 carbon steel. Chemical composition and thermophysical properties of $Fe_3Al$ intermetallic compound used in the test are shown in table 1. Chemical composition of Q235 steel is (wt%): C 0·17, Mn 0·48, Si 0·28, S 0·018, P 0·020. $Fe_3Al$ and Q235 were welded together by radiation heating and vacuum diffusion bonding. Parameters in the diffusion welding were: heating power 45 kVA, vacuum $5 \times 10^{-6}$ Torr, heating temperature $T = 1050$ ~ 1100°C, holding time $t = 60$ min, pressure $P = 9{\cdot}8$ MPa. Specimens of $Fe_3Al$/Q235 diffusion welded joints were prepared and examined. The microstructure close to the interface was observed by means of SEM. The phase constituents and fine structure were analysed by means of XRD and TEM.

## 3. Results and discussion

### 3.1 *X-ray diffraction analysis at the diffusion welded interface of $Fe_3Al$/Q235*

Figure 1 shows secondary electron micrographs of the diffusion welded joint of $Fe_3Al$/Q235 dissimilar materials.

**Table 1**. Chemical composition and thermophysical properties of $Fe_3Al$ intermetallic compound.

| Chemical composition (wt%) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Fe | Al | Cr | Nb | Zr | Mn | B | Ce |
| 81·02 | 15·71 | 0·78 | 1·93 | 0·28 | 0·1 | 0·01 | 0·15 |

| Thermophysical properties | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Structure | Ordering temperature (°C) | Young's modulus (GPa) | Melting point (°C) | Coefficient of heat expansion ($10^{-6}$·$K^{-1}$) | Density (g·$m^{-1}$) | $s_b$ (MPa) | $d$ (%) | HRC |
| $DO_3$ | 540 | 140 | 1540 | 11·5 | 6·72 | 455 | 2 | 29 |

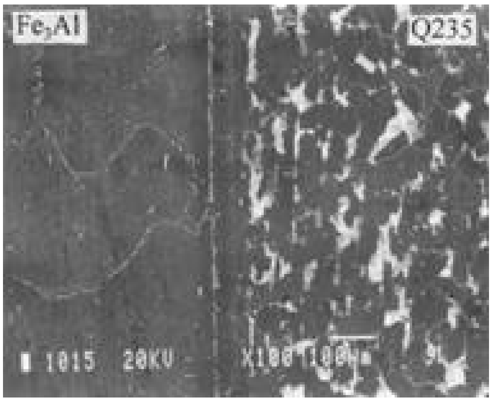


**Figure 1.** Secondary electron micrograph of the joint close to the interface of $Fe_3Al$/Q235.

Results indicate that the interface of $Fe_3Al$ intermetallic compound and Q235 steel exhibit diffusion characteristics and are joined well. Microstructure from the $Fe_3Al$ side stretches into Q235 side crossing the interface continuously and at the interface mesh well with each other. There are smaller columnar grains in the diffusion transition zone, most of which are equiaxed grains because the diffusion of alloy elements causes the transitional zone multi-alloying.

Iron and aluminum can form a series of Fe–Al intermetallic compounds with different properties depending on the aluminum content. X-ray diffraction analysis in the region adjacent to the interface both in $Fe_3Al$ and Q235 phases was conducted in order to further clarify the phase constituents and the results are shown in figure 2.

As shown in figure 2, there are three phases at the diffused interface of $Fe_3Al$/Q235 and they are $Fe_3Al$ intermetallic compound, $a$-Fe (Al) solid solution and brittle phase FeAl. FeAl is mainly formed on the $Fe_3Al$ side with high aluminum content and large brittleness. So the area adjacent to interface within $Fe_3Al$ matrix is the weakest part among the whole interface. $a$-Fe (Al) solid solution has B2 type *bcc* lattice. This is because the fraction of aluminum atoms reduce with decrease in aluminum content. The change from FeAl to $Fe_3Al$ to $a$-Fe (Al) is attributed to a transfer of the aluminum atoms from unstable interstitial sites in the iron lattice to a more stable (and ordered) B2 structure in which they occupy specific iron lattice sites (Fair and Wood 1994).

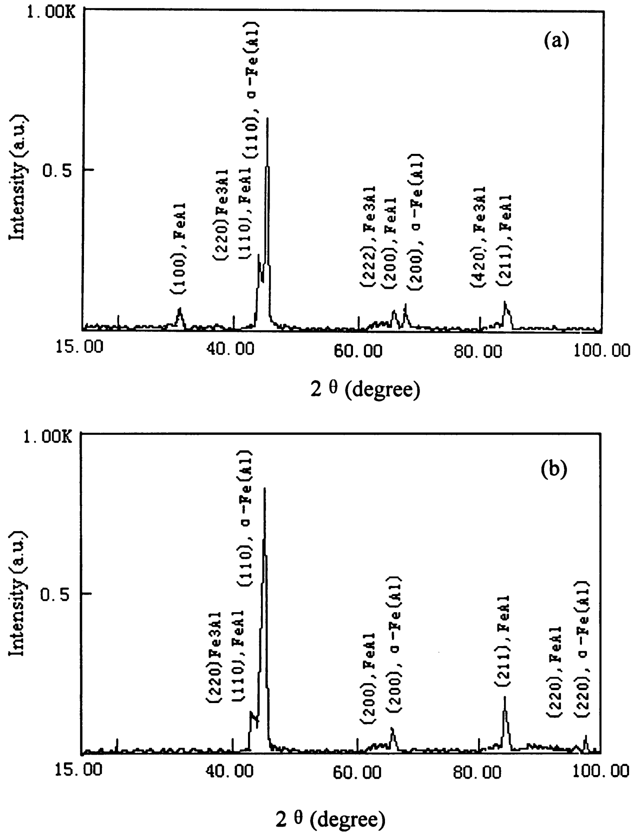


**Figure 2.** X-ray diffraction pattern of the phase at the diffused interface of $Fe_3Al$/Q235: (**a**) region inside $Fe_3Al$ phase and (**b**) region inside Q235 phase.

## 3.2 *TEM morphology at the diffusion joint of $Fe_3Al$/Q235*

For the welding of dissimilar materials, the element diffusion and phase formed at the interface of dissimilar materials are the key to decide the property of the whole diffusion joint. A thin slice was cut from the interface region by means of mini-cutting machine and then was ground into thin sample. Finally energy dispersive X-ray (EDAX) analysis of diffused element was conducted. The results are shown in figure 3.

Aluminum atom content is about 28% and iron atom content is 71% near $Fe_3Al$ matrix at the interface of $Fe_3Al$/Q235, while aluminum atom content is only 1·5% near Q235 carbon steel. There is higher concentration gradient between aluminum and iron in the base metals of $Fe_3Al$ and Q235. So aluminum atom may diffuse from $Fe_3Al$ to Q235 and iron atom from Q235 to $Fe_3Al$. Compound produced at the interface changes into $\alpha$-Fe (Al) solid solution.

There are $Fe_3Al$, FeAl phases and $\alpha$-Fe (Al) solid solution at the interface of $Fe_3Al$/Q235 according to XRD but the lattice orientation between these phases will heavily affect the whole diffused joint. TEM morphology and selected zone electron diffraction pattern of the interface are shown in figures 4 and 5.

Close to $Fe_3Al$ matrix phases are mainly $Fe_3Al$ and FeAl whose lattice orientation is $(110)_{Fe_3Al}//(011)_{FeAl}$, while there is $\alpha$-Fe (Al) solid solution whose lattice constant is 0·287 nm and cementite ($Fe_3C$) with [010] grain orientation close to Q235 carbon steel. Their lattice orientation is $[110]_{\alpha\text{-Fe(Al)}}//[010]_{Fe_3C}$. Analysis on TEM morphology indicates that these phases are composed of sub-crystal grain structure without any obvious brittle phase and micro-defects such as pore and crack. The

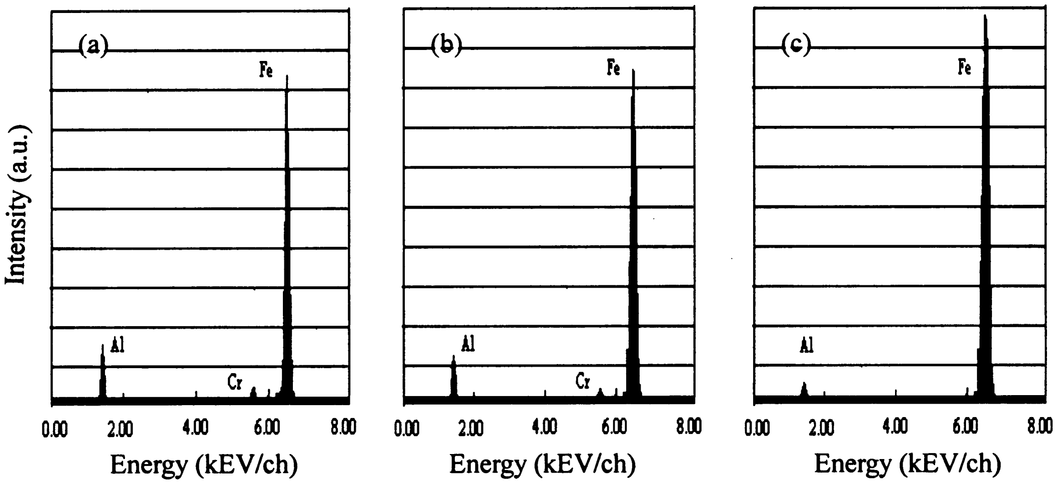


**Figure 3.** The energy dispersive curve of diffused element at the interface of $Fe_3Al$/Q235 (**a**) on $Fe_3Al$ side of the joint, (**b**) mid region of the interface and (**c**) Q235 steel side of the interface.

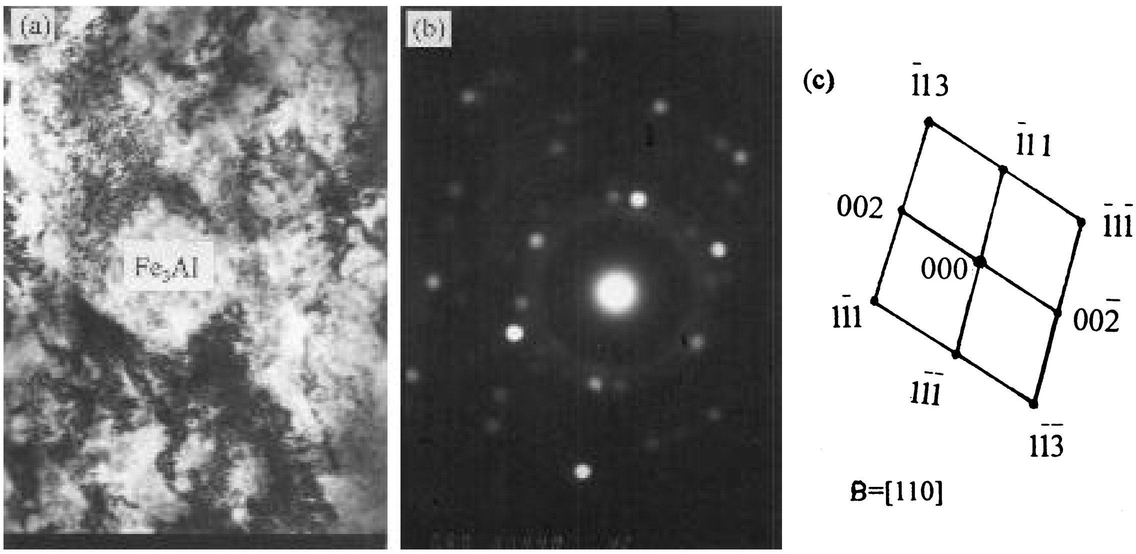


**Figure 4.** The fine structure feature of $Fe_3Al$ in the $Fe_3Al$/Q235 diffused joint: (**a**) TEM morphology, (**b**) electron diffraction pattern and (**c**) schematic index diagram.

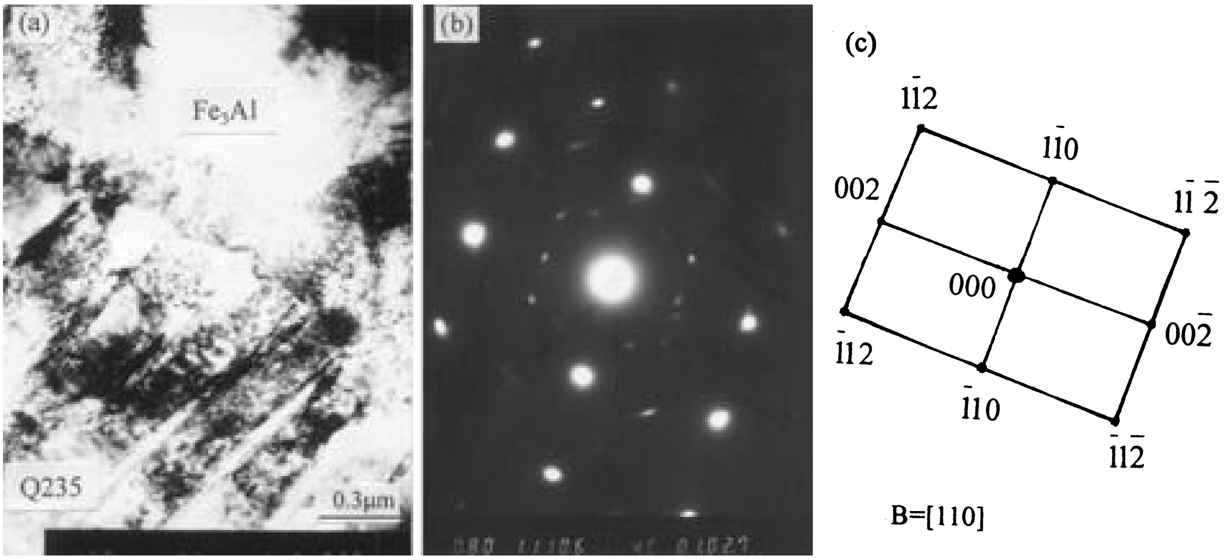


**Figure 5.** The fine structure feature at the interface of $Fe_3Al$/Q235: (**a**) TEM morphology, (**b**) electron diffraction pattern and (**c**) schematic index diagram.

results show that the interface of $Fe_3Al$/Q235 is combined compactly, which is favourable to improve the ability to resist cracking.

## 4. Conclusions

There are three phases in the $Fe_3Al$/Q235 diffusion joint and they are $Fe_3Al$ with $DO_3$ type body centred cubic (*bcc*) structure, FeAl with B2 type *bcc* structure and *a*-Fe (Al) solid solution. Diffused element aluminum atom content decreases from 28% to 1·5% during the gradual transfer from $Fe_3Al$ to Q235. The lattice orientations are $(110)_{Fe_3Al}//(011)_{FeAl}$ and $[110]_{a\text{-Fe(Al)}}//(010)_{Fe_3C}$. The phases at the diffused interface of $Fe_3Al$/Q235 are composed of sub-crystal grain structure without an obvious brittle phase or micro-defects such as pore and crack, which is favourable to improve the ability to resist cracking.

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## References

David S A and Zacharia T 1993 *Welding J.* **72** 201
David S A *et al* 1989 *Welding J.* **68** 372
Ding Chenggang, Chen Chunhuan and Yin Yansheng 2000 *Welding* **6** 16
Fair G H and Wood J V 1994 *J. Mater. Res.* **29** 1935
Gao Dechun *et al* 2000 *Acta Metall. Sinica* **36** 87
He Kangsheng and Cao Xiongfu 1986 *Welding of dissimilar metals* (Beijing: China Machine Press) p. 134
Mckameey C G *et al* 1991 *J. Mater. Res.* **6** 1779
Rabin B H, Wright J K, Wright R N and Sellers C H 1994 *J. Mater. Res.* **9** 1384