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GTA Welds of Iron-Aluminide Based Alloys

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Abstract: The weldability of two Fe_3Al-based intermetallic alloys and one Fe-16%Al-based (atom fraction) alloy has been investigated for gas tungsten arc (GTA) welding on sheets with a thickness of 2 mm. The results indicated that pre-heating and post-annealing treatment were important procedures for retarding cold crack initiation and the proper selection of filler could effectively improve the weldability. For the same alloys with the same welding filler, it is better to choose lower welding current, in another word, lower heat input.

Key words: iron-aluminide; gas tungsten arc welding; weldability; filler

The ordered Fe-Al alloys, in particular those having DO_3 (Fe_3Al) and B2 (FeAl) structures are of high commercial interest because of their excellent resistance to oxidation, low density, high corrosion resistance, in addition to a good mechanical strength at intermediate temperature compared to the majority of the iron- or nickel-based alloys. It has been confirmed that proper alloying (such as with Cr, B) and thermomechanical process (such as forging and rolling process followed by heat treatment) can significantly improve room temperature ductility and mechanical strength within intermediate temperature [1, 2]. These make iron-aluminides attractive candidates for structural applications.

Studying the welding behavior of Fe-Al based alloys is an integral part of developing them as engineering materials, because joining by conventional welding is an important means of fabricating engineering materials into structural components. Limited work has been conducted in this field. Electron beam (EB) and gas tungsten arc (GTA) welding processes had been investigated by Goodwin and David etc [3, 4]. The weldability of Fe_3Al-type alloys of the sheets with a thickness of 0.76 mm was found to be very sensitive to the welding condition. Moreover no weld fillers have been reported. The present work investigates the weldability of Fe-Al based alloys with a thickness of more than 2 mm. The effect of the filler on the weldability is also discussed. It shows that defect-free welds with reasonably good tensile properties at room temperature can be made by GTA welding, and that a novel filler for the welding of Fe-Al alloy was found.

1 Experimental Procedure

The compositions of the alloys studied are given in **table 1**. All alloys were prepared by vacuum induction melting, and conventional pure iron, aluminum and chromium were used as raw materials. After being homogenized at 1000 ℃ for 24 h, the ingots were hot-forged between 1100 ℃ and 850 ℃, then hot-rolled into sheets with a thickness of 2 mm within 800–1000 ℃. The coupons of 500 mm×30 mm×2 mm were made from the sheets. Full-penetration GTA by one pass were made on a Miller syncrowave 351 and WSE-315 machines with the welding current of 50–80 A, welding speeds of 0.5–2 mm/min. The diameter of the filler was 2.5 mm. All GTA welding were made with argon shielding. Pre- and post-weld heat treatment were conducted at 400 ℃. The welding specimens were examined by X-ray non-destructive test with a precision of 1/50 thickness of the sheets. Specimens for optical metallography were etched with a chemical solution of $8CH_3COOH + 4HCl + 1HNO_3$ (volume fraction). The transverse tensile property tests were performed by using the MTS810 machine with a cross head speed of 2 mm/min. The dimension of the specimens is 50 mm ×10 mm.

Table 1 Compositions of the test alloys (mass fraction) %

Alloy	Al	Cr	Mo	Nb	C	Y	Fe
Fe_3Al(Cr)	15.7	5.72	—	—	—	—	Bal.
Fe_3Al(CrNbC)	16.4	5.45	—	0.94	0.030	—	Bal.
Fe-16Al(CrMoNbYC)	8.0	5.11	1.92	0.23	0.033	0.06	Bal.

2 Results and Discussion

2. 1 Filler materials for GTA welding

Fe-Al based alloys show hydrogen-induced cold cracking tendency and have high coefficient of linear expansion and low thermal conductivity which lead to a poor weldability. Iron-based alloys including Fe_3AlCr, low or middle carbon CrMo steel (named as

FCM), austenite stainless 1Cr18Ni9Ti and nickel-based alloys (Ni2, Ni82, Inconel625 and C-4) were chosen as filler materials. Ni82 and Inconel625 contain 20%Cr (mass fraction, so as the follows); C-4 contains 16%Cr and 16%Mo, and Ni2 is pure Ni. The effect of fillers on the cracking behavior of Fe-Al based alloys using GTA welding with a current of 80–120 A is shown in **table 2.**

Table 2 The effect of the fillers on cracking behavior of GTA welding of Fe-Al based alloys

Welded material	Fe_3AlCr	FCM	1Cr18Ni9Ti	Ni2	Ni82	Inconel 625	C-4
Fe_3AlCr	$C^{(1,3)}$	NC	$C^{(2)}$	NC	NC	$C^{(2)}$	$C^{(2,3)}$
$Fe_3AlCrNbC$	$C^{(1,3)}$	NC	$C^{(2)}$	$C^{(2,3)}$	$C^{(2,3)}$	$C^{(1,2)}$	$C^{(1)}$
Fe-16AlCrMoNbYC	—	NC	$C^{(2)}$	—	—	—	—

Note: C—crack, NC—no crack, 1—longitudinal crack, 2—transversal crack, 3—cold crack.

The results clearly indicated the effect of fillers on welding cracking behavior in the case of thin sheet. GTA welding of Fe_3AlCr, $Fe_3AlCrNbC$ and Fe-16Al-CrMoYC alloys was produced with low or middle carbon CrMo steel——FCM filler. Hot- or cold-crack was not found by naked eye and X-ray non-destructive testing. However transversal cracking can be found with 1Cr18Ni9Ti filler, and the same for the longitudinal cracking with base metal filler. Among all tested nickel-based fillers, crack-free welds of Fe_3AlCr alloy were produced only with Ni82 and Ni2 under extreme conditions.

Table 3 summarizes the room temperature tensile strength σ_b of the GTA welding of tested alloys, which is within a range of 150−200 MPa. For FCM filler, the cracking of the welded specimens usually initiated at base metal or HAZ; however for Ni82 or C-4 filler, because of the discontinuity in structures and compositions near fusion line, the cracks were generated and subsequently propagated along this region, which resulted in low tensile strength. The investigation of fractography shows predominantly transgranular cleavage with some secondary cracks.

Table 3 The tensile strength of the GTA welding specimens at room temperature

Filler	Welded material	I / A	σ_b / MPa	Cracking zone
FCM	$Fe_3Al(Cr)$	80—120	127	Base metal
		80—120	270	Fusion zone
FCM	$Fe_3Al(CrNbC)$	80—120	222	Base metal
		80—120	211	Base metal
Ni82	$Fe_3Al(Cr)$	80—120	170	HAZ
		80—120	61	Base metal
Ni2	$Fe_3Al(Cr)$	80—120	136	Base metal
		80—120	177	HAZ

Figure 1 shows the microstructures of welded zone of Fe_3Al (CrNbC) and Fe-16Al (CrMoNbYC) alloys with FCM filler. The optical photomicrograph demonstrated a uniform crystalline microstructure at weld zone and base materials, which named epitaxial growth microstructure in accordance with base materials. The chemical compositions in FZ, HAZ and base materials analyzed by EDAX (energy dispersive analysis X-ray) varied continuously. The filler mixed completely together with base materials [5]. The X-ray diffration also showed similar phase constituents at weld zone and base materials.

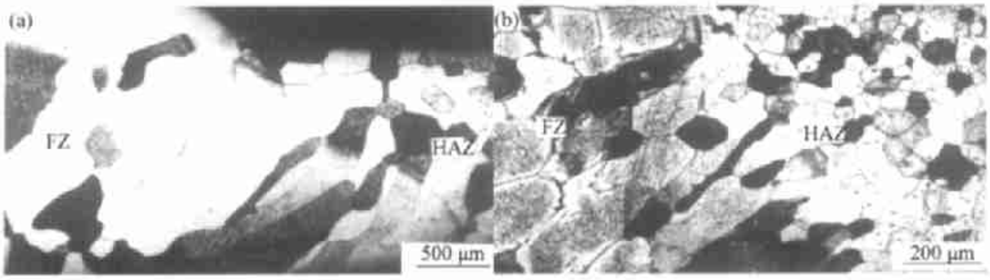

Figure 1 Microstructures of the weld zone of $Fe_3AlCrNbC$ (a) and Fe-16AlCrMoNbYC (b) alloys, FZ—fusion zone, HAZ—heat affect zone.

The microstructure of weld zone with nickel-based filler is shown in **figure 2**. A distinct boundary zone was generated between fusion zone and base materials. The microstructures of fusion zone exhibited dendritic features, and EDAX showed macro-segregation at fusion zone indicating discontinuous composition distribution. X-ray diffraction confirmed that the fusion zone is consisted of phases of Fe_3Al and Ni_3Al, which were different from base materials. The difference in the compositions and phase structures of fusion zone and base materials led to a distinct boundary zone. Santella et al. in their work on weldability of Ni_3Al alloy containing 10%Fe (atomic fraction) found that two phases existed side by side and a clear boundary zone was formed [6, 7]. Microanalysis in the weld fusion zone showed that aluminum was segregated to the interdendritic regions, while nickel enrichment was found at dendrite cores, and they were actually two phases. The boundary zone was found to be the weak performance locations, which should be expected to be similar to our test.

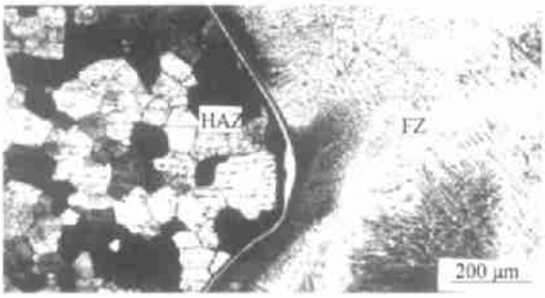

Figure 2 The microstructures of the weld zone with Nickel-based filler, FZ—fusion zone, HAZ—heat affect zone.

2.2 The effect of weld processing parameters on cracking behavior of weld zone of thin sheet GTA welding

(1) The effect of weld current.

The basic criterion for selecting welding parameters was a low heat input for equivalent weld penetration. The tests indicated that Fe_3Al based alloys can be successfully welded using GTA welding process with FCM filler by using lower welding current or lower heat input. It is found that the base metal filler (Fe_3AlCr) was more susceptible to the welding process. $Fe_3AlCrNbC$ alloy was successfully welded by using lower current with smaller distortion of weld zone. In contrast, longitudinal hot cracking or solidification cracking occurred by using higher welding current. Argon shielding can reduce oxidation and enhance weld-pool fluidity which improved microstructures and welding formability. The decrease in welding current is of particular advantage to the welding of Fe-16Al (CrMoNbYC) alloy. Optical photomicrograph shows that the width of HAZ decreased, the grain growth from base metal to fusion zone was weakened by using lower welding current, and fine grain was obtained. The shape of grains at fusion zone varied in accordance with the welding current. Coarse equiaxed grains initiated at high current for low weld-pool temperature gradient. At lower current, higher weld-pool temperature gradient and lower overheating led to the occurrence of columnar grains.

There is no refined precipitated phase in Fe_3AlCr, therefore the decrease in welding current is even more important. In general, niobium and zirconium may be deleterious to the welding properties of the alloys. But niobium or zirconium carbide reduces the producing of low melting eutectic compositions. High-temperature strength is an important factor of enhancing the resistance to HAZ cracking [7]. The test shows that the addition of Nb and C to Fe_3AlCr can improve high-temperature strength, $Fe_3Al(CrNbC)$ alloy has better weldability than Fe_3AlCr. As for Fe-16Al (CrMoNbYC), the precipitated phase may not act as an effective nucleation agent for refining the fusion zone microstructure, crack seems to propagate along the interface of the precipitated phase and matrix at high current, therefore it is necessary to control the heat input.

(2) The effect of pre- and post-weld heat treatment.

Pre- and post-weld heat treatment significantly affects the weldability of Fe-Al based alloys. **Figure 3** gives the dependence of thermal conductivity (λ) and the coefficient of linear expansion (a_l) of Fe_3Al alloy and mild steel on temperature. It indicated that Fe_3Al alloy had lower thermal conductivity and higher coefficient of linear expansion than those of mild steel.

The lower thermal conductivity is of disadvantage for heat diffusion of weld zone through the base metal, and higher coefficient of linear expansion led to fusion zone and HAZ a big shrinkage during cooling. Higher thermal stress during welding may lead to hot crack. Pre-weld heat treatment decreases temperature gradient and thermal stress, and prevents the hot cracking.

The basic requirements for the initiation of cold cracking or delayed cracking are sufficient hydrogen level, a susceptible microstructure, and tensile stress in the weld. The hydrogen-induced cracking of Fe_3Al based alloys in vapor environment is one of the main reasons of cold cracking [8]. The rupture ductility transformation temperature (RDTT) of Fe_3Al based alloys is about 300 ℃ [9], and absorbed hydrogen-induced cracking of Fe_3Al can be restrained over 200 ℃. Raising heat treatment temperature from 200 ℃ to 400 ℃ led to better weldability and restrained cold cracking.

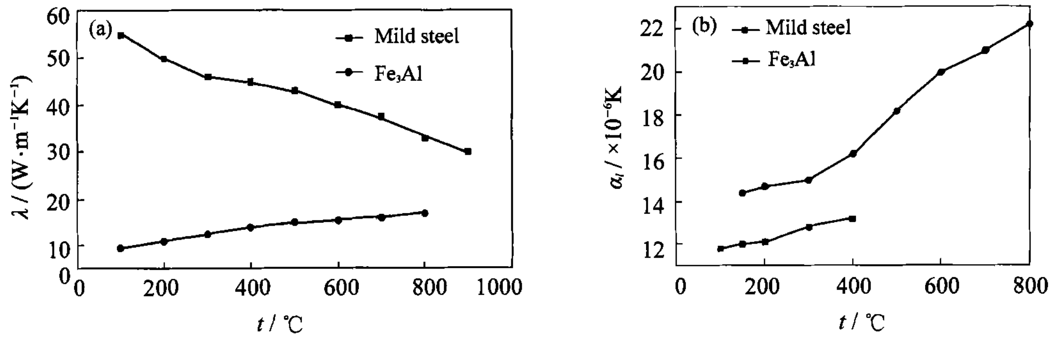

Figure 3 Thermal conductivity λ (a) and coefficient of linear expansion α_l (b) of mild steel and Fe$_3$Al vs temperature t.

The proper pre-weld heat treatment temperature is about 400 ℃.

Fe$_3$AlCr alloy filler has the same thermal conductivity and coefficient of linear expansion as Fe$_3$Al alloy, so Fe$_3$AlCr alloy is also sensitive to hydrogen, and cold cracking exists at HAZ and fusion zone. For FCM filler, the weld zone and base metal have similar structures, their compositions varied continuously with epitaxial grains. The expansion of weld zone of the filler may be less than that of the weld zones of other fillers. Fe$_3$Al(CrNbC) alloy has successfully welded without any pre- and post-weld heat treatment.

(3) Optimum welding parameters.

In order to obtain a better crack-free GTA weld, appropriate treatments need to be employed. The Optimized heat treatment procedure was pre- and post-weld heat treatment at 400 ℃ for 2 h, and cooling in furnace. The optimized weld processing parameters used to produce full-penetration GTA welds were as follows: arc voltage, 8 – 15 V; welding current, 50 – 80 A; arc travel speed, 0.5 – 2 mm/s; arc efficiency, estimated to be 70%; upper Ar flow, 20 L/min; lower flow, 10 L/min.

All of the tested alloys were successfully welded with FCM filler with the optimum welding parameters. Specially, Fe-16Al(CrMoNbYC) alloy can be welded by using low current. Fe$_3$Al (CrNbC) alloy also was successfully welded with base materials filler. In a word, Fe$_3$Al(CrNbC) alloy has good weldability, and Fe-16Al(CrMoNbYC) alloy has poor weldability except with proper processing parameters and FCM filler.

3 Conclusions

(1) In GTA welding, the weldability of Fe-Al based alloys is closely related to filler materials. Fe-Al based alloys have been successfully welded with low or middle carbon CrMo steel filler. The compositions of the weld zone and base materials varied continuously within the epitaxial grains. Because of the distinct difference in composition and phase constituent between the weld zone and base materials, Fe-Al based alloys have poor weldability when welded with nickel-based filler materials.

(2) The addition of Nb, C to Fe$_3$Al based alloys refined the microstructures of fusion zone and HAZ, enhanced the cold cracking resistance and weldability. The weldability of coarse grain Fe$_3$AlCr alloy was not as good as that of Fe$_3$AlCrNbC alloy. The delayed cold cracking can be restrained through proper pre- and post-weld heat treatments.

(3) The weld processing parameters, especially welding current, significantly affect the weldability of GTA welding. During the full-penetration welding, the decrease of weld current or weld heat input improves the resistance to cracking.

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