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ARTICLE

Mechanism of Crack Initiation of Dissimilar Joints between 2219 Aluminum Alloy and 5A06 Aluminum Alloy

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Abstract: The crack initiation mechanism of dissimilar aluminum alloy welded joints was studied. The base metals were 2219 aluminum alloy and 5A06 aluminum alloy, while the filler wires were 2325 and 5B06. The microstructure was analyzed by optical microscope (OM), scanning electron micrograph (SEM) and energy dispersive spectroscopy (EDS). The results show that the weld hardness (HV) obtained by the 2325 is about 1000 MPa and that by 5B06 is about 800 MPa. Compared with that of the weld obtained by 2219 and 2325, the grain growth of HAZ (heat affected zone) of the weld obtained by 5A06 and 2325 is so weak that the joint softening phenomenon doesn't exist. The diffusion and segregation of Mg element and Cu element can be obviously observed in the welded fusion zone (FZ) obtained by 2325 and 5A06, and that by 5B06 and 2219. Compared with the welded joint obtained by 5B06 filler wire, the great cracking tendency can be found in dissimilar welded joint obtained by 2325 filler wire, because there is no obvious low melting eutectics in welded joint by 5B06 filler wire. Many low melting eutectics (Al_2CuMg and $CuAl_2$) are present in the welded joint by 2325 filler wire, and the Al_2CuMg eutectics are fundamental cause for the crack initiation.

Key words: aluminum alloy; dissimilar welding; welded crack

Aluminum alloy is widely used in automobile and aerospace industries for its better physical properties, chemical properties, mechanical properties and process properties than other metals[1-3]. In the aluminum alloy structure, dissimilar aluminum alloy welding can meet property requirements of the different structural positions. General welding methods of aluminum alloy mainly include friction stir welding (FSW), laser welding (LBW), tungsten inert gas shielded welding (TIG) and melt polar inert gas protection welding (MIG), which can better resolve the basic problem of aluminum alloy welding process by theoretical analysis and experimental results[4-7].

Aluminum alloy dissimilar welding has also made significant achievements [8-12]. However, due to the different physical properties between the dissimilar aluminum alloy, many defects still can be produced by dissimilar welding. For example the welding crack is one of the most significant defects and seriously affects the quality of the welded joints. At present, the welding crack has been comprehensively studied in the aluminum alloy welding fields [13-15]. But, there are few reports about the dissimilar aluminum alloy welding crack. The welding crack directly determines the quality of the welded joints in the welded structure, even it can cause a great economic loss and injures of people. Therefore, it is primary to eliminate or reduce the welding crack in order to obtain high-quality dissimilar aluminum alloy joints.

In this paper, dissimilar welded joints of Al-Mg aluminum alloy and Al-Cu high-strength aluminum alloy was studied. The microstructure and properties of dissimilar welded joints, the diffusion behavior of alloy elements, the type of eutectics and welding crack initiation mechanism were discussed. Hopefully, these researches can provide some theoretical references for eliminating dissimilar alu-

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minum alloy welding crack in the future.

1 Experiment

2219 aluminum alloy and 5A06 aluminum alloy plates were used as base metals. The dimensions of 2219 specimens was 100 mm×50 mm×5 mm and that of 5A06 specimens was 50 mm×50 mm×2 mm. 2219 aluminum alloy was overlapped butt welded with 5A06 aluminum alloy. The filler wires were 2325 filler wire and 5B06 filler wire. The welding machine was Fronius Trans Puls Synergic 2700 welder equipped with a Fanuc robot welding system. The welding parameters were base welding current (170 A), peak welding current (185 A), pulse frequency (55 Hz) and welding voltage (20 V). Table 1 and Table 2 displays the nominal chemical composition of base metals. Table 3 and Table 4 display the nominal chemical composition of 2325 filler wire and 5B06 filler wire, respectively. Fig.1 and Fig.2 show the microstructure and EDS of base metals.

Table 1 Chemical composition of 2219 (wt%)

Al	Cu	Mn	Zr	Mg	Ti	Si	Fe
Bal.	5.8~6.8	0.2~0.4	0.1~0.25	0.02	0.1~0.2	0.2	0.3

Table 2 Chemical composition of 5A06 (wt%)

Al	Cu	Mn	Mg	Zn	Ti	Si	Fe
Bal.	0.10	0.50~0.80	5.8~6.8	0.20	0.10~0.30	0.40	0.40

Table 3 Chemical composition of 2325 wires (wt%)

Al	Cu	Mn	Zr	Mg	Ti	Si	Fe
Bal.	5.8~6.8	0.2~0.4	0.1~0.25	0.02	0.1~0.2	0.2	0.3

Table 4 Chemical composition of 5B06 wires (wt%)

Al	Cu	Mn	Mg	Zn	Ti	Si	Fe
Bal.	0.10	0.50~0.80	5.8~6.8	0.20	0.10~0.30	0.40	0.40

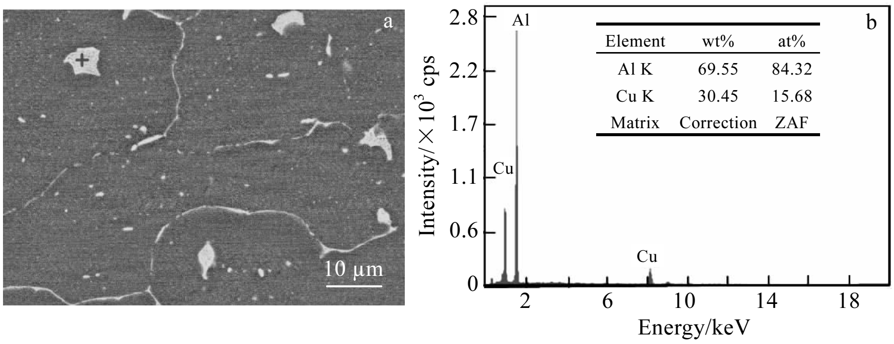

Fig.1 SEM image (a) and EDS spectrum (b) of 2219 base metals

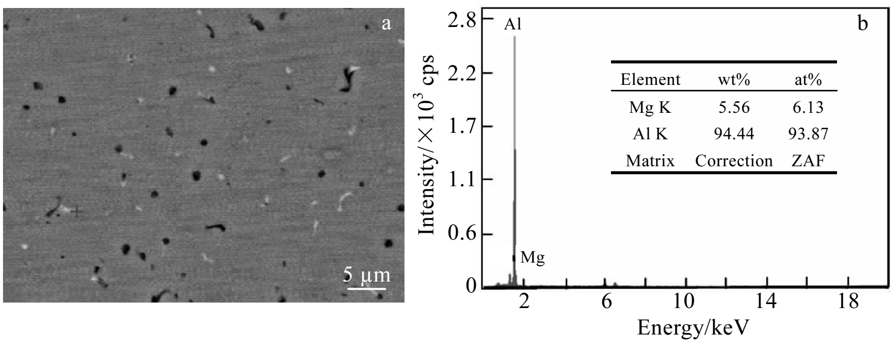

Fig.2 SEM image (a) and EDS spectrum (b) of 5A06 base metals

After welding, metallographic samples were prepared by wire-electrode cutting along the transversal direction (see Fig.3), mechanically ground and polished. Then the samples were etched for 10~20 s with Keller's etchant (1 mL HF, 1.5 mL HCl, 2.5 mL HNO_3, 95 mL H_2O). The microstructure characterization was examined by optical microscopy (OM) and scanning electron microscopy (SEM). The element diffusion and welding crack were analyzed by energy dispersive spectroscopy (EDS). The microhardness of these samples were measured by Vickers indenter under 100 g load for 15 s dwelling time, and the schematic diagram of metallographic preparation and hardness tests are shown in Fig.3.

2 Results and Discussion

2.1 Metallographic microstructure

Fig.4 shows the microstructures of welded joints obtained by 2325 filler wire. There are obvious differences in

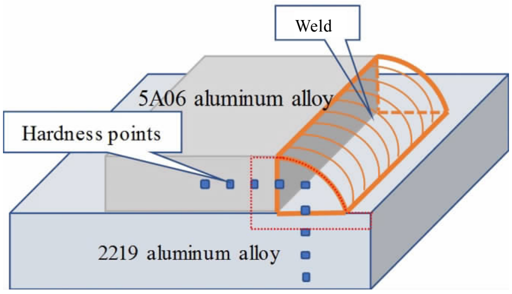

Fig.3 Schematic diagram of metallographic preparation and hardness tests

the microstructure of the HAZ by the different filler wires. When the 2325 filler wire is used, the columnar crystal grows along the direction of heat dissipation in the HAZ of the weld obtained by 2325 and 5A06 (see Fig.4a). The main reason for grain growth is that the high temperature of HAZ under welding thermal cycling is close to the melting point of weld metal in the welding process. Because the origins of base metal grains are big, the growth of grain is not obvious in the HAZ of 2219 aluminum alloy (see Fig.4b).

Fig.5 shows the microstructures of welded joints obtained by 5B06 filler wire. The microstructure of HAZ is consistent with that of the weld HAZ of 2325 filler wire (see Fig.5a and Fig.5b). However, there are significant differences in the microstructure of the weld center by the different filler wires. Compared with the microstructure of weld center obtained by 5B06 filler wire, the equiaxed grains of weld center are coarser when the 2325 filler wire is used. The grain size is determined by the grain liquid growth and grain solid growth. If a kind of metal stays for a longer period of time in the liquid phase, the grain size is bigger. In this paper, the melting point of the 2325 filler wire and the 5B06 filler wire is about 520 and 600 ºC, respectively. Hence, the grain size of the weld obtained by 2325 filler wire is bigger than that of the weld obtained by 5B06 filler wire under the same conditions of the welding process.

2.2 Diffusion behavior of Cu element and Mg element in fusion zone

Fig.6 shows the EDS linear scanning results of fusion zone (FZ) of the weld obtained by 2325 filler wire. The diffusion behavior of Cu element and Mg element on 2325-5A06 FZ is shown in Fig.6a. One can was obviously observed the mutual diffusion behavior between Mg element and Cu element in the FZ. The Mg element content gradually increases from left to right (2325→5A06). The Cu element content gradually decreases from left to right (2325→5A06). The content of Cu element and Mg element is high at the point A and point B, according to the phase diagram of this zone has $CuAl_2$ and Al_2CuMg. The diffusion behavior of element in 2325-2219 FZ is shown in Fig.6b. Because the 2325 filler wire and 2219 aluminum

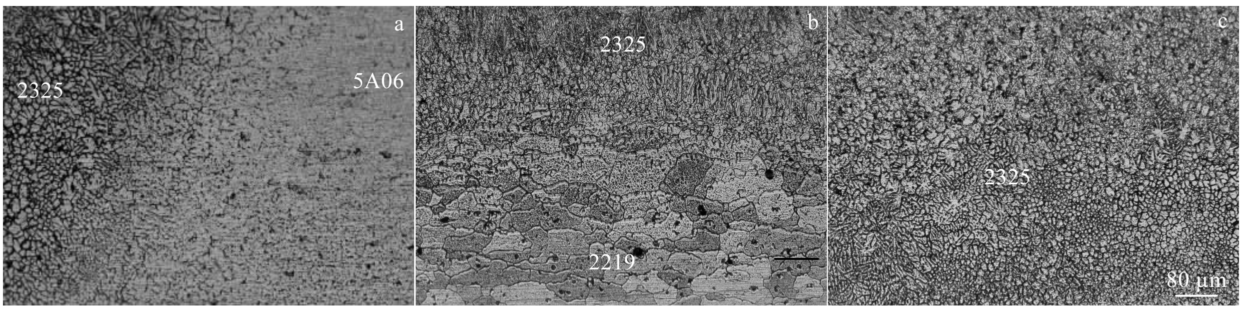

Fig.4 Typical microstructures in different zones of 2325 weld: (a) 5A06 side of fusion line, (b) 2219 side of fusion line, and (c) the center of 2325 weld

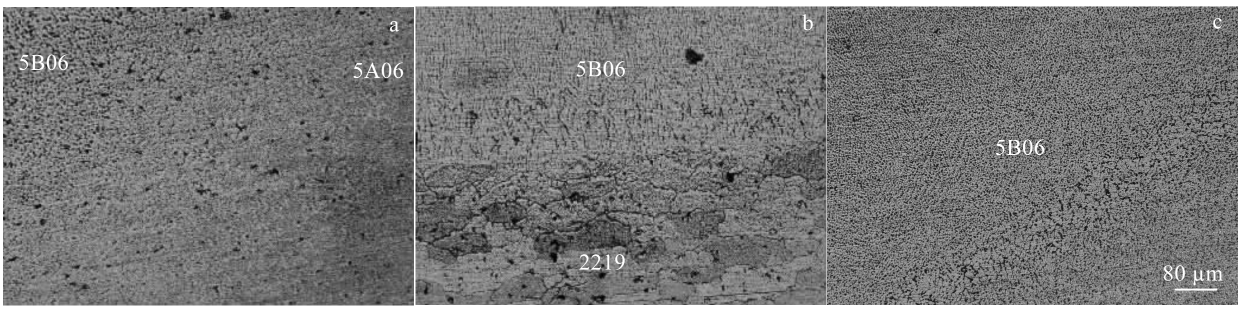

Fig.5 Typical microstructures of different zones in 5B06 weld: (a) microstructure on 5A06 side of fusion line, (b) microstructure on 2219 side of fusion line, and (c) the central of 5B06 weld

alloy have the similar chemical composition (see Table 1 and Table 2), the content of Cu element is basically stable from 2325 side to 2219 side. Fig.7 shows the EDS linear scanning results of fusion zone of weld obtained by 5B06 filler wire. The variation trend of element content is basically consistent with the linear scanning results in the FZ of weld obtained by 2325 filler wire.

2.3 Hardness test

According to the Hall-Petch relationship, the microhardness of metal material is inversely proportional to the grain size. Microstructures and alloying elements are the major factors to determine material properties. In this test, the microhardness of Al-Cu alloy is larger than that of Al-Mg alloy. The Cu element is the major component for hard aluminum alloy. Because Cu element can refine grains and accelerate the progress of aging strength, the microhardness of the weld obtained by 2325 filler wire is higher than that of the weld obtained by 5B06 filler wire. The detailed microhardness distribution of the welded joints obtained by different filler wires is shown in Fig.8.

Fig.8a shows the microhardness of the welded joint obtained by 2325 filler wire. The microhardness curve of lengthways section is shown in black line. The microhardness of weld and base metal is higher than that of HAZ. Due to the effect of weld thermal cycle, the grains and phases of the HAZ grow and break the plate initial state, so the microhardness decreases. The microhardness curve of transverse section is shown in red line. Because Al-Mg aluminum alloy can not be strengthened by heat treatment, the effect of weld thermal cycle is obvious on the microhardness. Compared with base metal, there is no apparent softening in HAZ. Fig.8b shows the microhardness of the welded joint obtained by 5B06 filler wire. The change of transverse microhardness is stabilized (see the red line) and the HAZ microhardness of lengthways is softened (see the black line).

Therefore, the composition of filler wires is the primary factor for the microhardness distribution of dissimilar aluminum alloy joints.

2.4 Mechanism of crack initiation of dissimilar aluminum alloy joints

The welded joints of 5B06 filler wire do not have exist cracks, but when the 2325 filler wire is used, the crack is observed. Hence, the following researches are focused on crack initiation mechanism. The crack of 2325 welded joint is observed by SEM and EDS, and the result is shown in Fig.9.

Fig.9 shows that the weld crack belongs to solidification crack and grows along the grain boundary. The weld fracture mode is the brittle fracture. For aluminum alloys, the existence of low melting point eutectics and residual stress is the main reason for producing the solidification crack. In this part, the effect of eutectics on crack is mainly discussed.

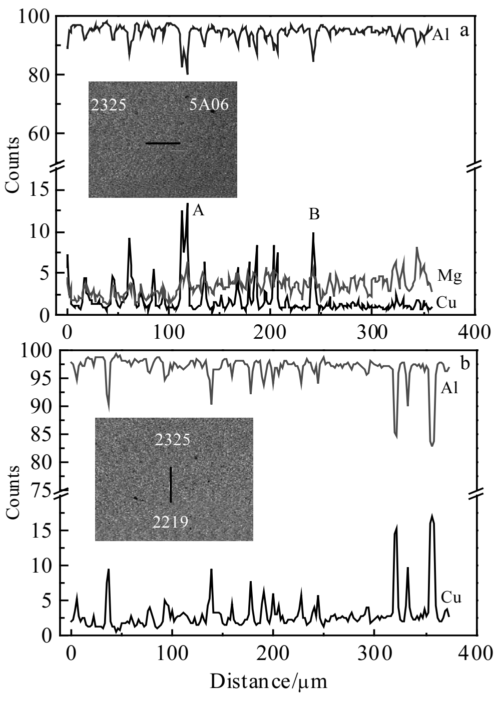

Fig.6 EDS line scanning results of the vicinity of 2325 fusion zone: (a) 2325-5A06 and (b) 2325-2219

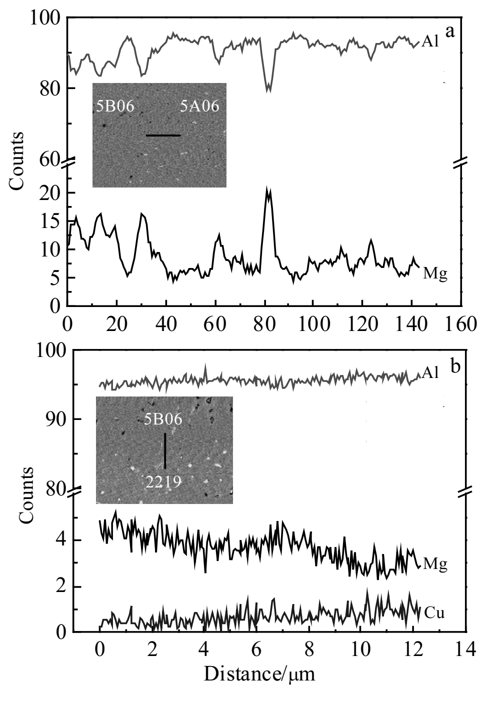

Fig.7 EDS line scanning results of the vicinity of 5B06 fusion zone: (a) 5B06-5A06 and (b) 5B06-2219

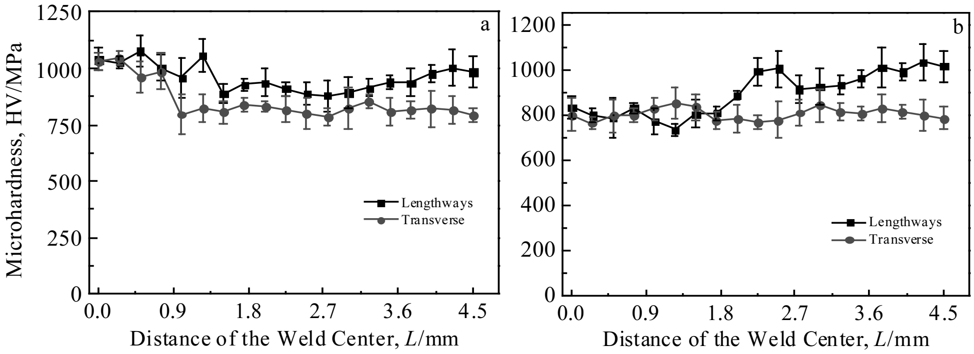

Fig.8 Microhardness distribution of 2325 welded joint (a) and 5B06 welded joint (b)

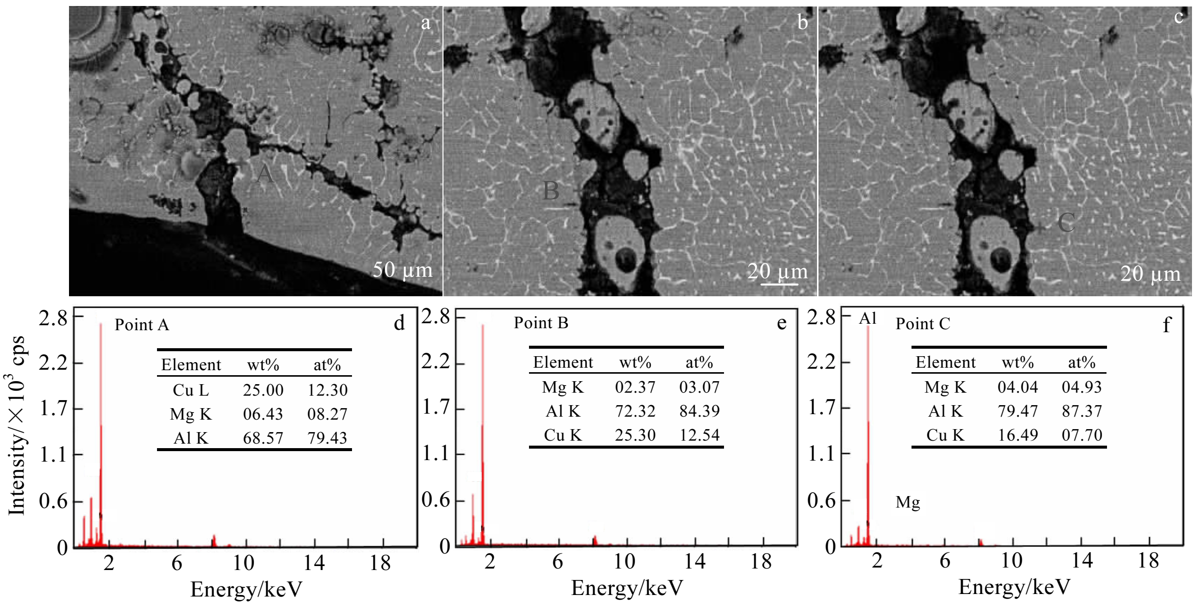

Fig.9 SEM images (a~c) and EDS analysis (d~f) of microstructure on the two side of crack

According to the result of EDS line scanning (see Fig.6a), there are many $CuAl_2$ eutectics and Al_2CuMg eutectics on the scanning-path. The Al_2CuMg eutectics or the cooperation of Al_2CuMg eutectics and $CuAl_2$ eutectics maybe play a dominant role in crack initiation process. In this text, because the crack can not be observed in weld and FZ obtained by 2325-2219 base, it is concluded that crack initiation is not caused by the single $CuAl_2$ eutectics.

In order to identify the cause of crack initiation, the composition on the two sides of the crack was analyzed by EDS, and the result is shown in Fig.9. It can be seen from Fig.9 that there are lots of Al_2CuMg eutectics distributed on the grain boundary, grain interior and the two side of the crack. The Cu content of 2325 filler wire is higher and Mg content of 5A06 filler wire is higher. Based on Fick's law, during the welding process，Mg element is spread from 5A06 base metal to 2325 weld and Cu element is spread from 2325 weld to 5A06 base metal. Due to the diffusion of the elements, the Al_2CuMg eutectics (melting point is about 507 ºC) and $CuAl_2$ eutectics (melting point is about 548 ºC) are produced in the fusion zone of the 5A06 side. During the process of weld solidify, the weld volume is shrunk. At the same time this process is prevented by un-melted metal around the weld, and then the tensile stress is formed in the weld. In this paper, at the beginning of the weld solidification, the temperature was higher, and there was more quantity of liquid metal. When the grain began growth, the inter-grain pores were presented under the shrinkage stress. But the liquid metal also could freely flow, so the inter-grain pores were filled with enough liquid metal, and it

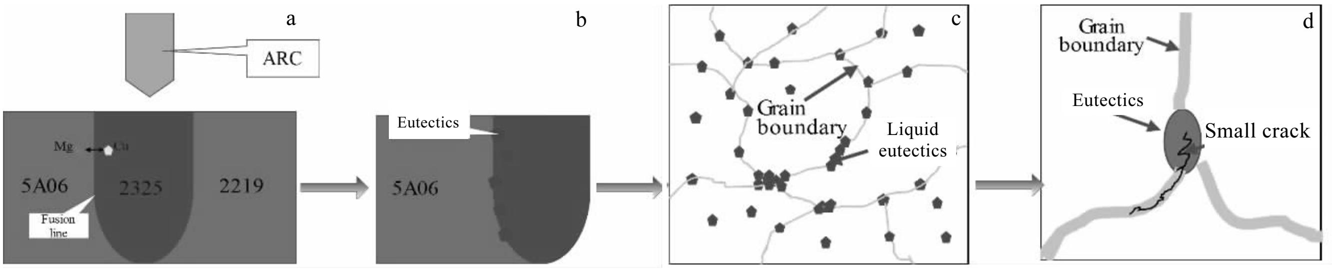

Fig.10 Schematic diagram of crack initiation: (a) the diffusion of alloy element, (b) eutectics production, (c) weld solidification, and (d) small cracks

would not produce cracks. This process is called "the healing". During the process of metal crystallization, more pure metal were crystallized, and the impurities which were gathered in the grain boundary, and to the formation of low melting point eutectic. At the terminal stages of solidification, the Al_2CuMg liquid eutectics were formed on the grain boundary. At this point, the Al_2CuMg liquid eutectics were pulled and formed pores by tensile stress. The pores could not be filled with extra liquid metal, so the crack was formed in inter-grain, which was the weld solidification crack.

From the above, low melting point eutectics are the main cause of the crack initiation for the 2219/5A06 dissimilar welded joints. Fig.10 shows the crack initiation process of the welded joints: (a) base metal melts and alloy element diffuses; (b) the vicinity of the weld fusion zone produces eutectics, (c) the eutectics are last solidified; (d) under the tensile stress, the grain boundary produces some small cracks; (e) solidification cracks are produced when the weld metal is completely cooled (see Fig.9).

3 Conclusions

1) According to microhardness test, when the different filler wires are used, the microhardness (HV) of the dissimilar welded joints has significant differences. The microhardness of the weld obtained by 2325 is about 1000 MPa and that of 5B06 is about 800 MPa. The HAZ of 5A06 base metal does not be softened and that of grains shows obvious growth. The HAZ of 2219 base metal exhibits an obvious softening phenomenon.

2) The diffusion and segregation of Mg and Cu can be obviously observed in the vicinity of 2325-5A06 fusion zone and 5B06-2219 fusion zone by EDS element line scanning. Compared with the weld of 5B06 filler wire, the weld of 2325 filler wire is more likely to produce cracks. The Al_2CuMg eutectics are the fundamental cause of the crack initiation for the dissimilar welded joints.

3) The joint will inhibit the crack initiation of dissimilar joints between 2219 aluminum alloy and 5A06 aluminum alloy when we use 5B06 or other (non-Aluminum copper alloy) filler metals.

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2219/5A06 异种铝合金焊接裂纹萌生机理

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摘　要：采用 OM、SEM、EDS 及显微硬度实验，对不同焊丝获得的 2219/5A06 异种接头的软化微观形貌与裂纹萌生机理进行分析。结果表明： 5A06 侧 HAZ 晶粒长大不明显未发生软化现象，2219 侧 HAZ 发生较明显的软化；通过 EDS 线扫描分析可知，2325-5A06、5B06-2219 的熔合线附近发生了明显的 Mg、Cu 扩散行为， 2325-2219、5B06-5A06 的熔合线附近元素扩散行为不明显；与 5B06 焊缝相比，2325 焊缝裂纹倾向更大，因为 5B06 焊缝不存在明显的低熔点共晶相，而 2325 焊缝存在大量的低熔点共晶 Al_2CuMg 和 $CuAl_2$，Al_2CuMg 共晶的存在是致使其产生裂纹的根本原因。硬度测试结果表明：2325 焊缝的硬度(HV)约为 1000 MPa，5B06 焊缝的硬度(HV)约为 800 MPa。

关键词：Al 合金；异种焊接；焊接裂纹

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