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Solidification crack susceptibility of aluminum alloy weld metals

LIU Ren-pei(刘仁培)[1], DONG Zu-jue(董祖珏)[2], PAN Yong-ming(潘永明)[2]

1. College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China;

2. Harbin Research Institute of Welding, Harbin 150080, China

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Abstract: The susceptibilities of the three aluminum alloys to solidification crack were studied with trans-varestraint tests and tensile tests at elevated temperature. Their metallurgical characteristics, morphologies of the fractured surface and dynamic cracking behaviors at elevated temperature were analyzed with a series of micro-analysis methods. The results show that dynamic cracking models can be classified into three types. The first model has the healing effect which is called type A. The second is the one with deformation and breaking down of metal bridge, called type B. The last one is with the separation of liquid film along grain boundary, called type C. Moreover, the strain rate has different effects on crack susceptibility of aluminum alloys with different cracking models. ZL101 and 5083 alloys belong to type A and type C cracking model respectively, in which strain rate has greater effect on eutectic healing and plastic deformation of metal bridge. 6082 alloy is type B cracking model in which the strain rate has little effect on the deformation ability of the liquid film.

Key word: aluminum alloy; weld metal; susceptibility; weldability; solidification crack; cracking models; dynamic cracking models

1 Introduction

The weldability of the metal has great effect on designing welding structures and their later performance in practice. Consequently, the following factors have to be considered when evaluating weldabilites of weld metal and base metal. They are welding operability, arc stability, susceptibility to porosity of weld metal, weld-metal fluidity, strength, fatigue properties, weld-metal oxidation resistance, corrosion resistance, the resistance of weld metal to solidification cracking and so on. Of these properties, the resistance of weld metal to solidification cracking has been paid much attention to, especially for aluminum alloy[1−5].

Solidification cracking appears in the solid–liquid coexistence zone of which temperature is in the range immediately above the solidus. The crack may occur when solidifying weld metal undergoes large tensile stress during its solidification. Much work has been carried out on this subject. Among them, cracking theories, the influence of weld metal composition, and the effects of welding conditions have been emphasized[6−13].

It has been noticed that the susceptibility of solidification crack is related to the shape of solidifying ductility curve of material during solidification. It is also known that the strain rate has effects on the shape of the solidifying ductility curve, therefore may affect the susceptibility of material to solidification crack[1−3, 6, 11]. But further research work about the mechanism of the effects has seldom been reported. In this paper, the effects of strain rates on the susceptibility of solidification crack were investigated. This indicates that the extent of the effect is not the same for different materials, and the mechanism of the effect was also discussed.

2 Experimental

Three aluminum alloys, ZL101, 5083 and 6082, were used as test materials. Their chemical composition are listed in Table 1.

The susceptibilities of these three alloys to solidification crack were conducted with Varestraint Testing Machine of HHRL-1 on which the tested planes can be bent with both fast speed and slow speed respectively. The machine was developed by Harbin Welding Institute and the test procedures were the same as those illustrated in Ref.[1].

Welding parameters for the test were as follows:

Corresponding author: LIU Ren-pei; Tel: +86-25-84895790; Fax: +86-25-84892951; E-mail: lrp_msc@nuaa.edu.cn

Table 1 Composition of aluminum alloys used in test(mass fraction, %)

Material designation	Mg	Si	Zn	Mn	Fe	Cr	Cu	Ni	Ti	Al
ZL101	0.36	8.03	—	0.10	0.04	—	—	—	—	Balance
5083	4.14	0.12	<0.25	0.55	0.16	0.082	<0.1	<0.05	<0.05	Balance
6082	0.90	0.93	<0.2	0.67	0.17	0.15	<0.1	—	0.076	Balance

welding process was AC TIG Welding without deposited metal; welding current was 180 A; arc voltage was 12 V; welding speed was 75 mm/min; gas flow rate was 540 L/h.

Weld metal tensile tests were conducted at elevated temperature in the vacuum chamber of ultra-high temperature microscope. The testing processes were as follows: firstly, the tensile sample of weld metal was fixed with the tensile clamps; secondly it was heated by an electron beam to a temperature at which the material was in the solid–liquid coexistence zone of three aluminum alloys, ZL101, 5083, 6082 respectively; thirdly it was stretched with both of large strain rate, 25 μm/s, and small strain rate, 5 μm/s; finally, the tensile length of sample with loading was plotted by a X-Y recorder as *P*—*L* curve of the specimen. The dynamic process of cracking at elevated temperature was video recorded, and the total strain of the specimen was measured too.

3 Results and discussion

3.1 Effects of strain rate on susceptibility of solidification crack of materials

3.1.1 Trans-varestraint test results

Brittle temperature range(BTR) and solidifying ductility curve in BTR of 5083 and 6082 alloys were obtained with Varestraint Testing Machine of HHRL-1 shown in Fig.1. The solid lines in Fig.1 are the results of slow bending speed, the dash lines are the results of fast bending speed and the CST is the critical strain rate for temperature drop which was used to evaluate the susceptibility[1].

It can be seen from Fig.1(a) that the criterion of CST to solidification crack of 5083 Al-Mg alloy[1] increases up to 9.69×10^{-3}(%/℃) with slow bending speed from a mini value that is hard to measured with fast bending speed. 6082 alloy cracks with minimum strain (0.1%) at any strain rate, and the value of CST is too small to be measured. On the other hand, no solidification crack was found in ZL101 alloy at both fast and slow bending rates when strain is up to 2.5%, CST is so high in this case that it is also hard to be quantitatively measured. Therefore, the following results can be reached.

1) The susceptibilities of the three alloys to solidification crack are very different. The resistance

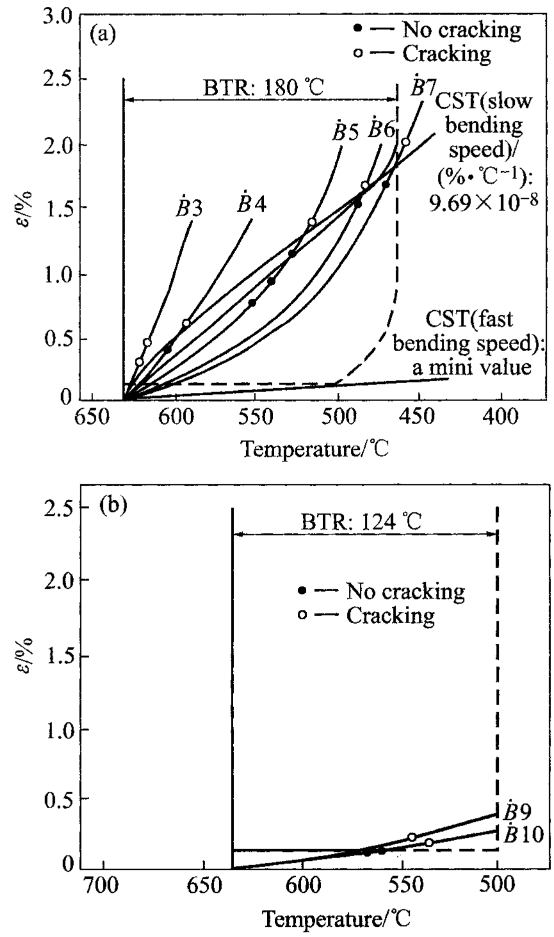

Fig.1 Brittle temperature range(BTR) and ductility curve in BTR: (a) 5083 alloy; (b) 6082 alloy

to solidification crack of ZL101 alloy is the greatest and that of 6082 alloy is the smallest, with that of 5083 alloy in between.

2) The solidifying ductility curve of 5083 alloy moves upwards with the decreasing strain rate, and the deformation ability of the alloy increases significantly with the decreasing temperature in brittle temperature range. That is to say, strain rate has greater effect on solidification crack susceptibility of 5083, resistance of solidification cracking increases when strain rate decreases. Because 6082 and ZL101 alloys are very sensitive or dull to the cracking respectively, effects of strain rates on susceptibility of cracking are hard to be indicated quantitatively by trans-varestraint test, therefore, tension tests at elevated temperatures were then conducted.

3.1.2 Results of tension test at elevated temperatures

Elevated temperature tensile tests of the ZL101 and 6082 alloys, which were obtained with two different strain rates of 5 μ m/s and 25 μ m/s, were conducted by using weld metal tensile specimens fixed by the tensile clamps in the vacuum chamber of ultra-high temperature microscope. The *P*—*L* curves of the ZL101 and 6082 alloys are shown in Fig.2.

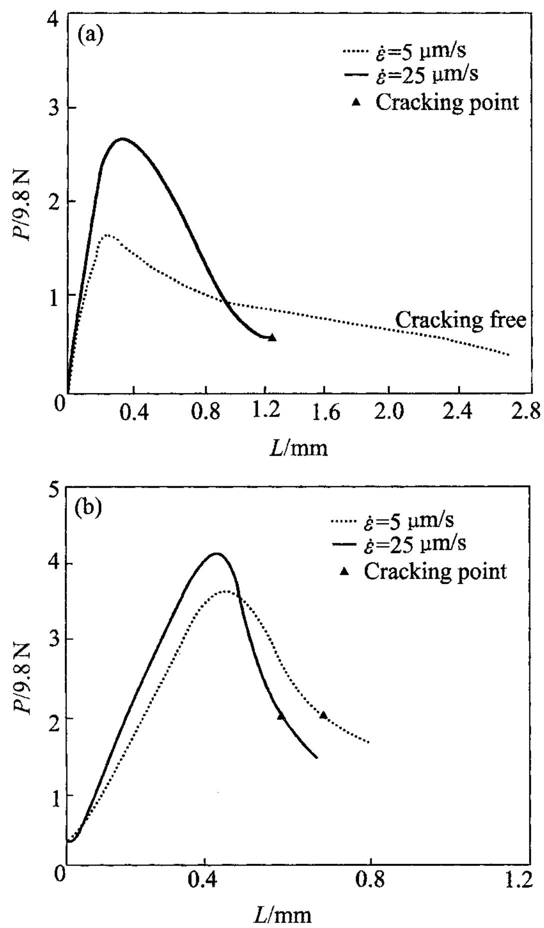

Fig.2 *P*—*L* curves obtained with elevated temperature tensile test: (a) ZL101 alloy, 580 ℃; (b) 6082 alloy, 600 ℃

It can be seen from Fig.2(a) that for ZL101 alloy, the tensile curves become smoother and have a larger plastic deformation before fracture under low strain rates than those with high strain rates. It is verified that there is a great plastic deformation in this alloy during slow speed tension at elevated temperatures. On the contrary, *P*—*L* curves of 6082 alloy at fast and slow speed tensile rates are similar (Fig.2(b)). Fracturing strains from the both tests have no obvious difference and there is no obvious plastic deformation either.

From the results of the varestraint tests and elevated temperature tensile tests, it is known that strain rates have effects on solidification crack susceptibility of aluminum alloy and that the effects are not the same for different materials. It has greater effect on the solidification crack susceptibility of ZL101 and 5083 alloys, and less effect on 6082 alloy.

3.2 Metallurgical characteristics of weld metal of different materials

The weld metals of the three aluminum alloys are of different microstructures. In ZL101 casting aluminum alloy there is more eutectics of low melting point which distributes along grain boundary in continuous net form, as shown in Fig.3(a). While in the welds of 6082 alloy there exist few low melting point eutectics which wet the whole grain boundary and appear in the form of continuous film net, as

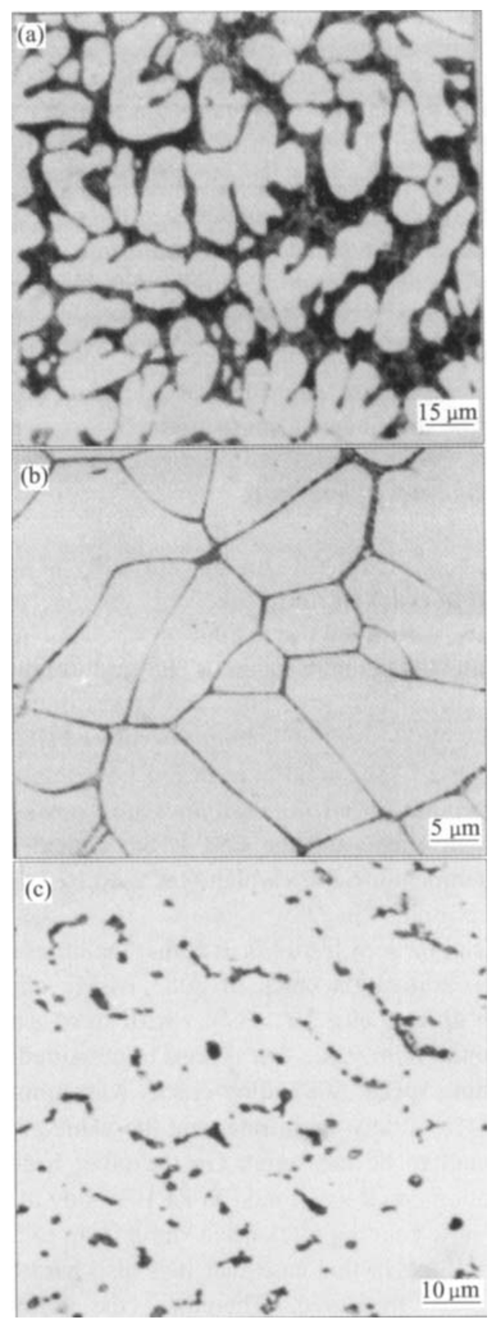

Fig.3 Microstructures of solidifying metals quenched in water: (a) ZL101 weld metal; (b) 6082 alloy, 600 ℃, quenched in water; (c) 5083 alloy, 590 ℃, quenched in water

shown in Fig.3(b). In the welds of 5083 alloy there are much less low melting point eutectics, which do not wet the grain boundary and appear in the form of strips or globular shapes along grain boundaries, as shown in Fig.3(c).

3.3 Fracture morphologies of different materials at elevated temperature

From the fractured surface of specimens after tensile tests at elevated temperature, it is found that in the fractured surface of 5083 alloy high temperature cracks there are cavities and traces of tearing formed by the breaking of metal bridges, as shown in Fig.4(a).

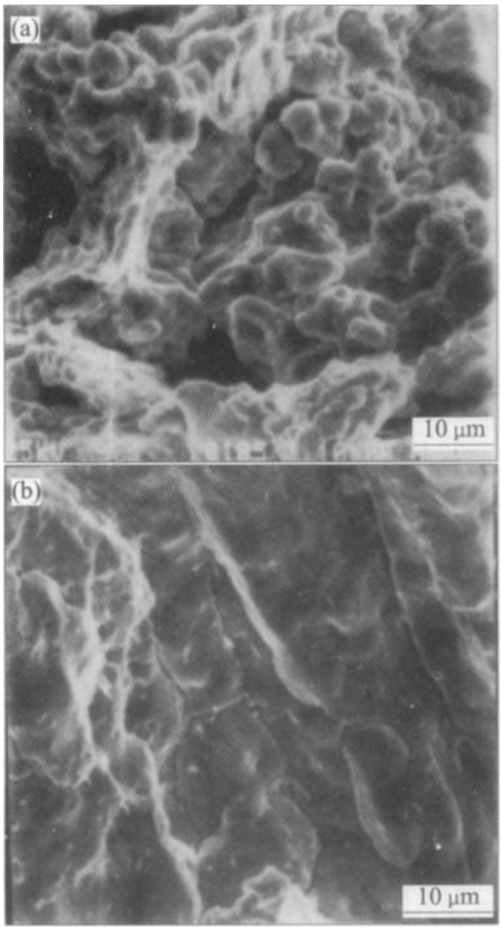

Fig.4 Fracture morphologies of weld metal at elevated temperature: (a) 5083 alloy; (b) 6082 alloy

It indicates that low melting point material does not spread along the whole grain boundary when specimen of 5083 alloy is cracking, there must be some solid connections. This coincides well with the result mentioned above. The fractured surface of 6082 alloy has smooth surface and the grain boundaries are covered with thin films. There is not any trace of tearing (Fig.4(b)). This also coincides with the results of metallographic tests.

3.4 Dynamic characteristics of elevated temperature cracking of different materials

1) Ultrahigh temperature tensile test in ZL101 alloy

During tensile test at 580 ℃, two kinds of low melting point eutectics, Al-Si and Al-Mg_2Si-$FeMgSi_6Al_8$-Si completely melt[14]. There is a great amount of liquid metal which forms a continuous channel along the grain boundaries. When specimen is stretched at a slow strain rate of 5 μm/s, a crack is firstly initiated, as shown in Fig.5(a). Liquid metal then flows in and heals it, as shown in Fig.5(b). No crack is found finally. When strain rate increases to 25 μm/s, there is not enough time for liquid metal to heal the cracks. Specimen fractures when it is stretched to1.25 mm.

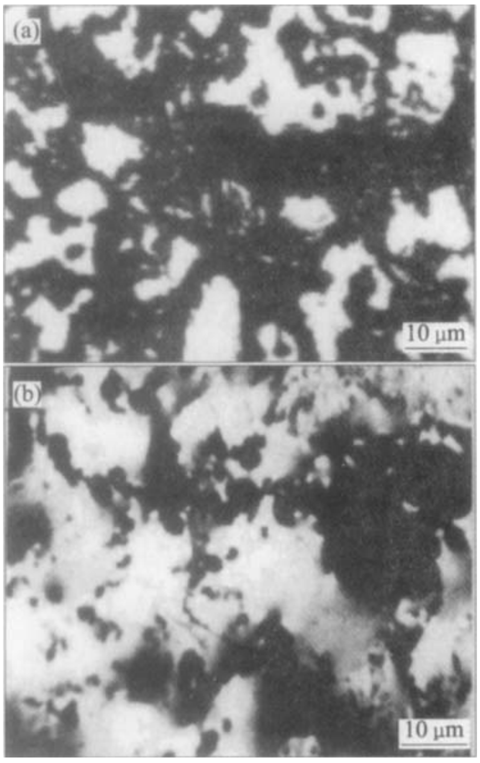

Fig.5 Elevated temperature cracking morphologies(580 ℃) of ZL101 alloy: (a) Initiated crack; (b) Healing cracks

2) Ultrahigh temperature tensile test in 5083 Al-Mg alloy

Tests were also conducted at 590 ℃ for 5083 Al-Mg alloy, at which all of low melting point eutectics melt. Cracking proceeds are as follows: at the beginning of tensile test, solid metal bridges between grains deformed first, and the liquid metal around the metal bridges deform as well, then cavities appear at grain boundary. The cavities expand into micro cracks along grain boundary with further deformation. When the strain exceeds the reserved ductility of the metal bridges, the bridges break, which leads to micro-crack forming and then the specimen fracturing. Cracks of 5083 alloy at high temperature are shown in Fig.6.

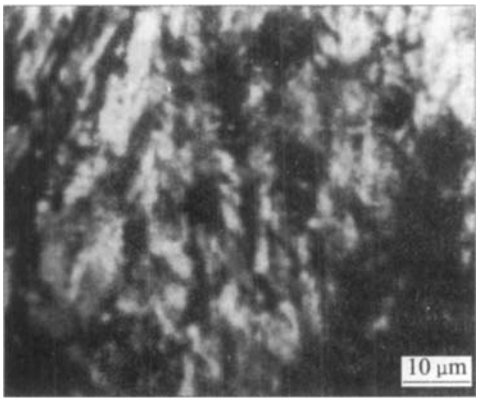

Fig.6 Elevated temperature cracking morphology (590 ℃) of 5083 alloy

3) Ultrahigh temperature tensile test in 6082 alloy

When 6082 alloy is loaded at 600 ℃ at which low melting point eutectics totally melt, grains are surrounded by a thin layer of liquid films and there is no connection of metal bridge between grains. Fracture happens along grain boundary when tensile strain is loaded. Only a small strain is needed to break the liquid films either at fast or at slow bending speed because it has rather low strength and ductility, as shown in Fig.7.

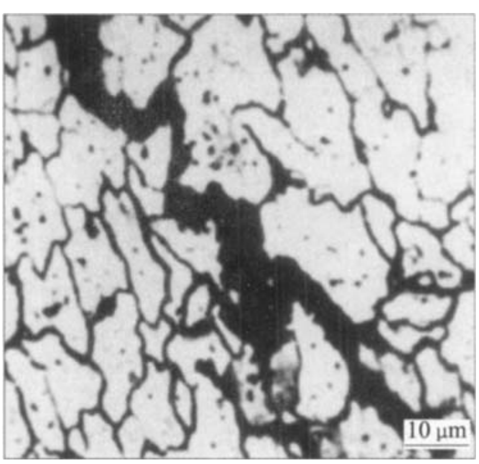

Fig.7 Elevated temperature cracking morphology (600 ℃) of 6082 alloy

3.5 Classification of materials and cracking models

The cracking mechanisms of the three aluminum alloys can be classified into three models shown in Fig.8, according to their metallurgical characteristics, morphologies of fractured surface and dynamic cracking behaviors at elevated temperature.

The first cracking model has healing effect, called type A cracking model for short. The condition for this model is that there exists a great amount of low melting point eutectic along grain boundary forming a continuous channel. When the alloy is tensile loaded at elevated temperatures, liquid surface B—B' which is perpendicular to the main stress firstly stretches apart. Since the low melting eutectic is in the form of continuous network, and the welding molten pool acts as a liquid source, the liquid metal flows into the cracks through the widen channel to heal the cracks, as shown for type A cracking model in Fig.8. The solidification of ZL101 alloy is thus of this model.

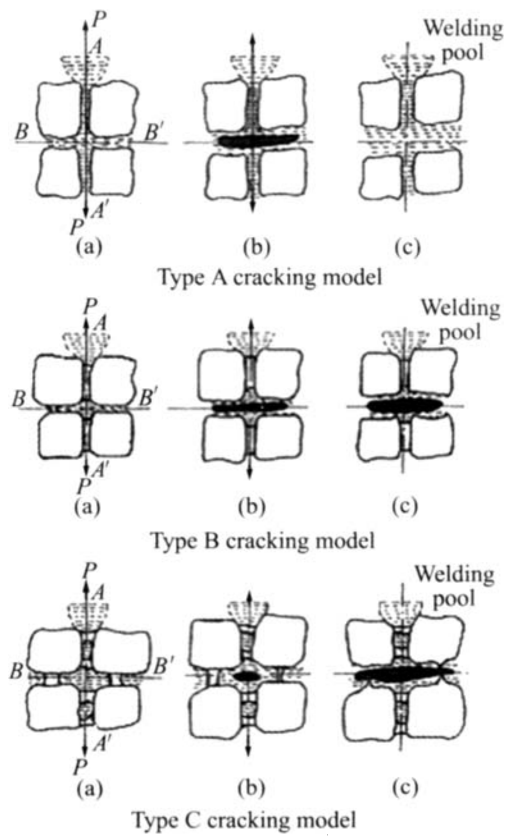

Fig.8 Cracking models of solidification crack

The second model is with the separation of liquid film along grain boundary, called type B for short, as shown in Fig.8. The condition for this model to set up is the low melting point eutectics cover most of the grain boundary in the form of thin films. But the amount of the eutectic is not enough to link up the liquid metal of welding molten pool. A thin layer of liquid film with low ductility in a direction of B—B', that is perpendicular to the acting force P can be separated under small strain. The separation gap which can not be filled completely with liquid metal leads to forming cracks, and only liquid film or eutectic is found on the fractured surface. The solidification cracking of 6082 alloy is for this model.

The third is the cracking model with deformation and breaking down of metal bridge, or type C for short, as shown in Fig.8. In this model, there is little low melting point eutectic distributing un-continuously along grain boundary. Connections of metal bridges exist between grains. Metal bridges on surface B—B' are stretched under the action of tensile force. At the same time, liquid metal encircled by the bridges also deforms. The resistance of liquid metal to deformation is weak and is not strong enough to transit the strain so that fissures occur first in the liquid film, then the metal bridges break and micro-cracks appear. Tearing traces can be seen on the fractured surface. The solidification cracking of 5083 alloy is this model.

3.6 Mechanism of effect of strain rate on solidification crack susceptibility

The alloy of type A cracking model, Z101, has a large amount of low melting point eutectics forming continuous channels within solid-liquid coexistence zone. As the low melting point liquid metal can flow and the grains can fully shift at low strain rate there is enough time for liquid metal to flow to fill in and heal the cracks even when cracks occur during deforming. The slower the strain rate is, the greater the healing effect is, and the lower the susceptibility to solidification cracking, and vise versa is.

The alloy of type C cracking model, 5083 alloy, has low melting point liquid metal spreading discontinuously along grain boundary with some solid metal bridges which block the flowing of the liquid metal. The metal bridges are strong enough to withstand a certain level of stress and to transmit the stress to the grains. When stretched, not only the metal bridges, but also the grains deform. Cracks occur only when the metal bridges are broken. Creeping deformation of this type of materials at elevated temperature appears as plastic deformation of the metal bridges and grains. Under slow strain rate, it is good for the movement of dislocation and release of stress[15]. Therefore, the slower the strain rate is, the longer fracture time is and the more plastic deformation develops. With higher fracture strain, the susceptibility to solidification cracking is lower.

The alloy of type B cracking model, 6082 alloy, has few low melting point substances between grains, which separate the grains in the form of thin films. Under this condition, it is difficult for liquid films to flow and for grain to shift. At the same time the liquid films between grains are not strong enough to bear high level of stress and can not transmit the deformation to solid grains, which makes it almost impossible for plastic deformation to form before fracture. As a result, the metal separates along liquid film. The strength of grain boundary is determined by the surface tension of liquid film because strain rate has little effect on surface tension of liquid film, and also has little effect on crack susceptibility of this model.

4 Conclusions

1) Solidification cracking models are dissimilar for different aluminum alloys. The dynamic cracking models can be classified into three types. The first one has healing effect, in which it is possible to be free of cracks, such as casting aluminum, ZL101 alloy. The second is the one with deformation and breaking down of metal bridge, such as 5083 aluminum alloy. In the third model there is the separation of liquid film along grain boundary, such as 6082 alloy, which has a higher susceptibility to solidification crack.

2) It is found that strain rate has different effects on crack susceptibility of aluminum alloy with different cracking models. ZL101 and 5083 alloys are of type A and C cracking model respectively, in which strain rate has a greater effect on eutectic healing and plastic deformation of metal bridges. So it has a greater effect on the solidification crack susceptibility. 6082 alloy is type B cracking model in which the strain rate has little effect on the solidification crack susceptibility, because the strain rate has little effect on liquid film.

References

[1] DONG Zu-jue, PAN Yong-ming. Quantitative evaluation of solidification crack susceptibility in welding low alloy pressure vessel steels[J]. Welding Journal, 1986(4): 4−5.(in Chinese)

[2] NAKATA K, MATSUDA F. Evaluation of ductility characteristics and cracking susceptibility of Al alloys during welding[J]. Trans of JWRI(Japanese Welding Research Institute), 1995, 24(1): 83−94.

[3] MATSUDA F, NAKAGAWA H, TOMITA S. Quantitative evaluation of solidification brittleness of weld metal during solidification by in-situ observation and measurement (Report III)--Effect of strain rate on minimum ductility required for solidification crack initiation in carbon steels, stainless steels and inconel alloy[J]. Trans of JWRI(Japanese Welding Research Institute), 1986, 15(2): 297−305.

[4] MATSUDA F. Assessment of solidification cracking test for aluminum alloy welds[J]. Transactions of JWRI (Japanese Welding Research Institute), 1982, 11(1): 67−77.

[5] MATSUDA F, NAKATA K. New self-restrained solidification crack susceptibility test for electron-beam welding of aluminum alloys—taper-shaped hot cracking test[J]. Transactions of JWRI (Japanese Welding Research Institute), 1982, 11(1): 141−143.

[6] ARATA Y, MATSUDA F. Solidification crack susceptibility of Aluminum alloy weld metals (Report II)−Effect of straining rate on cracking threshold in weld metal during solidification[J]. Trans of JWRI, 1977, 6(1): 91−104.

[7] KIM H T. Solidification cracking susceptibility of high strength

aluminum alloy weldment[J]. Scripta Materialia, 1996, 34(7): 1139—1145.

[8] KIM H T, NAM S W. Study on the solidification cracking behaviour of high strength aluminum alloy welds: effects of alloying elements and solidification behaviours[J]. Journal of Materials Science, 1996, 31(11): 2859—2864.

[9] BROOKS J A, DIKE J J. Modeling weld solidification cracking behavior in aluminum alloys-analysis of fracture initiation[A]. ASM Proceedings of the International Conference: Trends in Welding Research[C]. Pine Mountain, Georgia: ASM International, 1998. 695—699.

[10] ARATA Y. Solidification crack susceptibility in weld metals of fully austenitic stainless steels(report II)[J]. Transaction of JWRI(Japanese Welding Research Institute), 1977, 6(1): 91—104.

[11] DING Hao, FU Heng-zhi. Influence of drawing rate on formation of hot cracking of aluminum alloys in directional solidification process[J]. Material Science and Technology, 1996, 4(2): 76—80.

[12] VAROL I, BAESLACK W A III, LIPPOLD J C. Characterization of weld solidification cracking in a duplex stainless steel[J]. Materials Characterization, 1997, 39(2—5): 555—573.

[13] SHANKAR V, GILL T P S, MANNAN S L, SUNDARESAN S. Solidification cracking in austenitic stainless steel welds[J]. Sadhana, Academy Proceedings in Engineering Sciences, 2003, 28(3—4): 359—382.

[14] LIU Ren-pei. A Study of Hot Cracking of Aluminum Alloys[D]. Harbin: Harbin Research Institute of Welding, 1989.(in Chinese)

[15] HA Fu-kuan. Micro Theory of Mechanics Properties of Metals[M]. Beijing: Science Press, 1983.(in Chinese)

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