JOURNAL OF MATERIALS SCIENCE 25 (1990) 2017–2024

Effect of microstructure on impact fracture behaviour of SUS304L SAW joint at low temperature

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The dependency of Charpy impact value (E_v) of SUS304L submerged arc weldment on test temperature and the angle (θ) between columnar structure and specimen has been studied. The distribution of E_v in the weldment was also measured. The results were summarized as follows. (1) The impact value scarcely depends on the angle θ. (2) E_v of the weld metal decreases with decreasing the test temperature because the brittle fracture occurred along to δ ferrite. (3) E_v indicated a minimum value at the weld metal and increased drastically at the fusion boundary and reached a high value at the base metal. The variation of E_v corresponds to the distribution of oxide inclusion and the change of morphology of δ ferrite. (4) At low temperature, globular type δ ferrite causes fine dimples, a discontinuous δ ferrite network causes large dimples, and continuous δ ferrite easily leads to brittle fracture along to δ.

1. Introduction

Austenitic stainless steel of Fe–18Cr–8Ni has excellent fracture toughness at low temperature and has been used as structural steel for cryogenic applications. The materials are usually used in the line pipe systems and chamber which requires a tightly closed structure, so most of the joining parts are achieved by welding. Generally, the microstructure is changed by the welding process and the fracture toughness decreases [1–3]. The autogenuous welder which usually has a high weld heat input is often adopted in order to save costs. The microstructure of weld metal becomes more coarse grain [4], than the one caused by the use of multi-pass low heat input welding, and more anisotropic, which means the microstructure or mechanical properties change with orientation between the specimen and columnar crystal. This characteristic appears in microstructure so that the columnar structure develops. The stress corrosion cracking at the anisotropic microstructure of the weld metal has been already studied [5] but there were few studies about the fracture toughness. It must be important for safety design to investigate the anisotropy and unhomogeneity of fracture toughness on weldment.

In this study, considering the practical side mentioned above, high heat input one pass submerged arc welding (SAW) was performed by using SUS304L stainless steel and it was possible to get the columnar structure which has coarse and anisotropic grain. Variation of impact value caused by decreasing the testing temperature and by changing the direction and position of the specimen in weldment has been observed in this report. Simultaneous observation of metallurgical microstructure and fracture surface by means of the scanning electron microscope (SEM) has been used to inspect the micro-fracture mechanism of the weld metal.

2. Experimental method

Base and weld metal used are SUS304L type stainless steel plate of 12 mm thickness and JISY308L electrode wire of 4 mm diameter correspondingly. Chemical compositions are shown in Table I. Butt weldment were achieved by one pass submerged arc welding at the conditions mentioned at Table II. The purpose of applying the high heat input one pass welding was to get anisotropic columnar microstructure and delete the heat effect from the following weld pass. The direction of the welding columnar structure was inspected by means of the etch pit method [5]. Fig. 1 indicates the half size Charpy impact specimen used which were sampled from the position as shown in Fig. 2. The angle (θ) between the longitudinal of the specimen and columnar structure are 0, $\pi/4$, and $\pi/2$

TABLE I Chemical compositions of base metal, electrode wire, and weld metal used

	Composition (wt %)								
	C	Si	Mn	P	S	Ni	Cr	N	O
Base metal (SUS304L)	0.017	0.52	0.92	0.032	0.003	10.53	18.43	0.0270	0.0012
Electrode wire (JIS Y308L)	0.014	0.56	1.87	0.024	0.017	9.81	19.64	0.0200	0.0028
Weld metal	0.040	0.66	1.22	0.035	0.009	9.40	18.40	0.0220	0.0520

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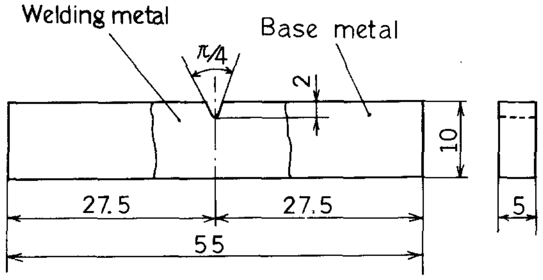


Figure 1 Charpy impact specimen used. (Dimensions in millimetres.)

radians. The notch positions of Charpy specimen were changed in order to measure the distribution of impact value from the centre of the bead to the base metal.

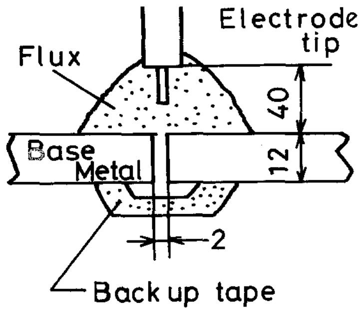
The impact test was performed by means of 294 J (30 kgf·m) class Charpy impact testing machine at temperatures of 293 and 77 K. Fractography by scanning electron microscope (SEM) was also performed to observed the fracture surface.

3. Results and discussion

3.1. Microstructure of weldment

The microstructure of SUS304L SAW weldment are shown in Fig. 3a, b, c and d. The matrix of weld metal is austenite (symbolized by γ) and the network structure is δ ferrite. Some investigators [6, 7] indicated that δ ferrite in SUS304 weld metal could be classified as vermicular and lacy type. In this study, the morphology of the δ ferrite are classified to vermicular, lacy, and globular. Vermicular type has a curved boundary and forms a network. Lacy type has a straight boundary and forms a group of parallel lines. The morphology of the globular type is spherical or ellipsoidal. Fig. 3a indicates the microstructure of the weld bead centre. A columnar crystal has grown at the fusion boundary and has been combined at the bead centre. The morphology of most of the δ phase is vermicular type and a little lacy δ ferrite also exists. Fig. 3b shows a microstructure at the point separating 2.5 mm from bead centre. The directionability of the δ ferrite network are observed in this figure. Fig. 3c indicates the fusion boundary. Many globular δ ferrite exists at the boundary of the columnar crystal. Variation of the δ

TABLE II Submerge arc welding condition

Flux type	Bonded flux (WEL SUB F-8*)
Base metal	SUS304L Thickness 12 mm
Electrode	JIS Y308L 4 mm wire
Figure of weld groove	
Voltage	39 V
Current	670 A
Speed	6.33 mm sec^{-1}
Heat input	41.3 kJ cm^{-1}

*Nippon Welding Rod Co., Ltd.

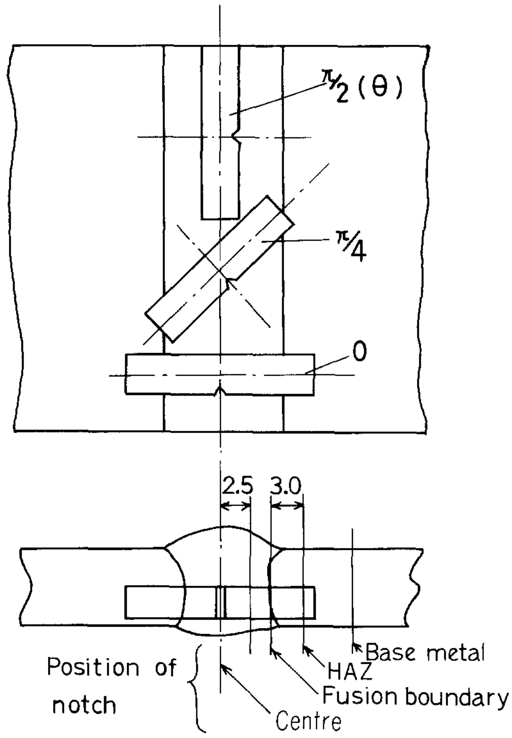


Figure 2 Sampling position of specimen. (Dimensions in millimetres.)

ferrite figure has a strong effect on the fracture toughness at low temperature which will be referred to in a later paragraph. Fig. 3d shows the microstructure of SUS304L base metal. It seems that fine globular inclusion exists in the γ matrix of the weld metal but in base metal. Observing carefully, using an X-ray microanalyser, the spherical inclusion contained oxygen, silicon and manganese, on the other hand blocky inclusions contained oxygen and aluminium components, so these inclusions are Mn-silicate and Al_2O_3, respectively. Comparing with MIG welding which had been studied by the effect of oxide on fracture toughness by Kamiya *et al.* [8], aluminium type oxide exists more in SAW weld metal than in MIG weld metal. The total volume fraction of oxide has a great influence on the ductile fracture.

Next, the direction of columnar crystal was inspected by etch pit method. Fig. 4 shows the pits appearing at the surface cutting normally to the longitudinal columnar crystal. Judging from these pits, most of the crystal has (1 0 0) orientation and good alignment.

3.2. Results of impact test

The relationship between the impact value and the direction of columnar structure is shown in Fig. 5. The direction means the angle between the longitudinal direction of the columnar structure and the specimen (see Fig. 2), which is symbolized by θ. Effect of θ on the impact value is small at both temperatures, 293 and 77 K. On the other hand the impact value of the weld metal decreases to half of the value in the base metal. The impact value decreased 30 or 40% with decreasing the testing temperature from 293 to 77 K at the weld metal but there is no change at the base metal.

On the other hand, variation of the impact value at the region between the weld metal and base metal at

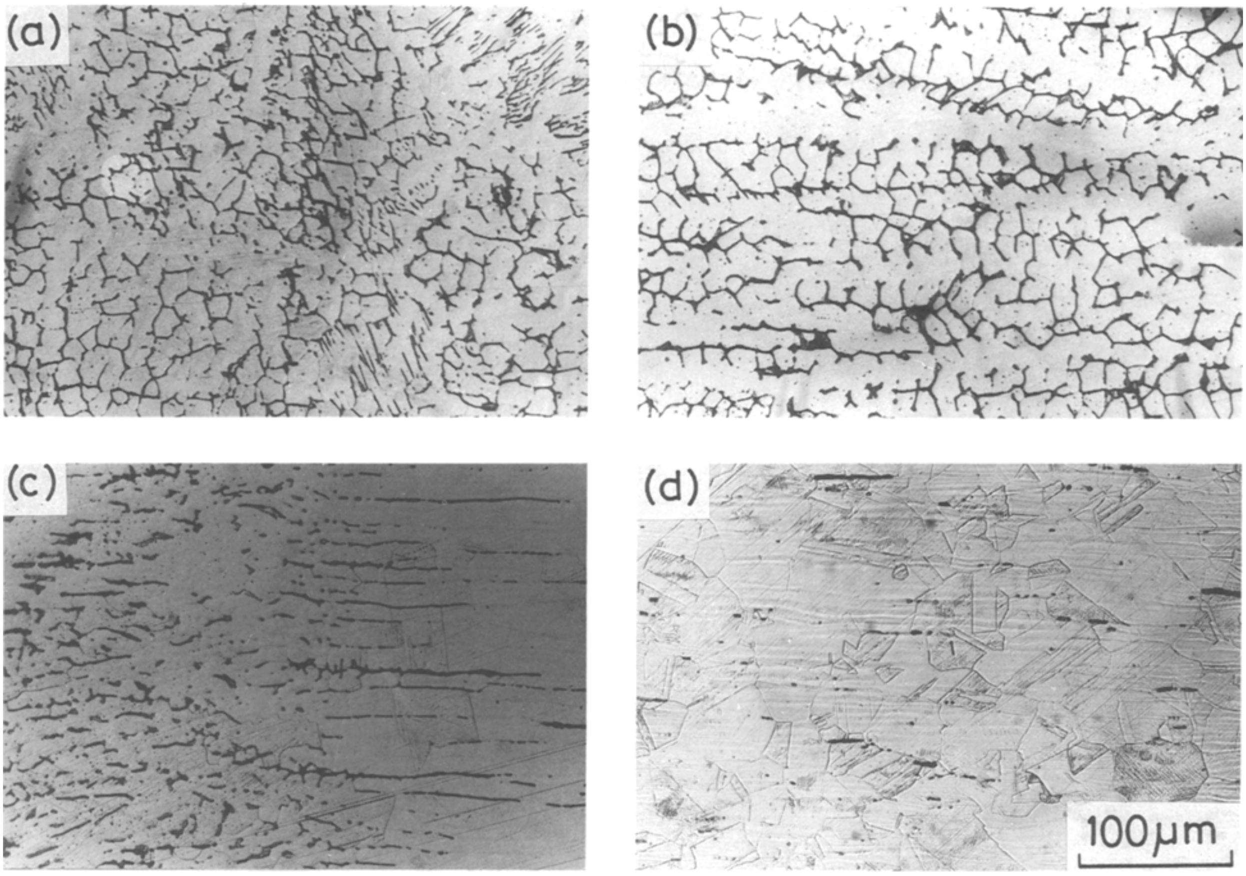


Figure 3 Metallurgical microstructure of SUS304L SAW joint, (a) Centre of weld metal. (b) Region separating 2.5 mm from centre of bead. Vermicular type δ ferrite forms directional network. (c) Epitaxial solidification occurs from fusion boundary. Morphology of δ is globular or rod-like. (d) Base metal include a few δ ferrite and no inclusions.

constant θ is shown in Fig. 6 accompanied by an illustration. The weld metal had a lower constant impact value at any temperature. The values increase drastically at the fusion boundary and reach a higher constant value in base metal. The oxide has a great effect on the phenomenon mentioned above [8]. Finally, the impact value is changed by the testing temperature conditions, and volume fraction of oxide, but constant θ.

3.3. Metallurgical microstructure and fractography

3.3.1. Base metal

Fig. 7 shows the fracture surface of the base metal at a low temperature of 77 K. Ductile fracture, which is characterized by a developing dimple pattern, is observed at both temperatures of 77 and 293 K. Few and fine inclusions in the dimple pattern referred to the good fracture toughness in the base metal.

3.3.2. Weld metal

Fig. 8 indicates the fracture surface of weld metal. At room temperature (293 K), most of the fracture surface is composed of dimple pattern regardless of θ. Considerable amount of spherical inclusions exist in centre of the dimple more than base metal. It is considered that the dimples easily initiate from these

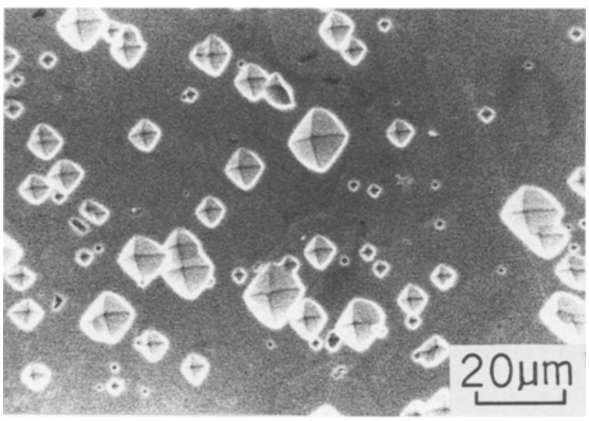


Figure 4 Shape of etch pit at the surface of normal to the columnar structure. Judging from the shape of pit, the growing direction of columnar is almost ⟨1 0 0⟩.

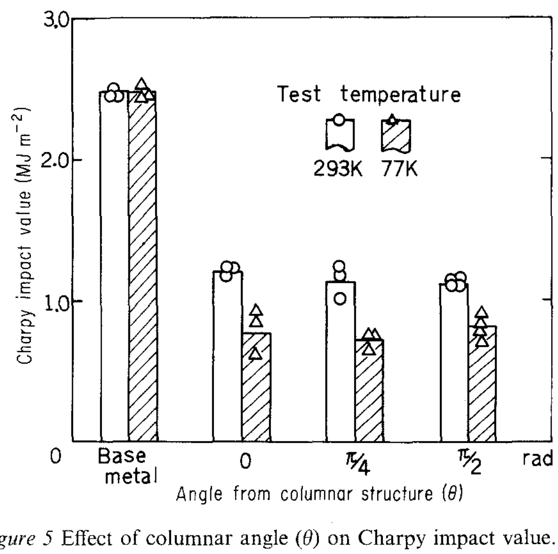


Figure 5 Effect of columnar angle (θ) on Charpy impact value.

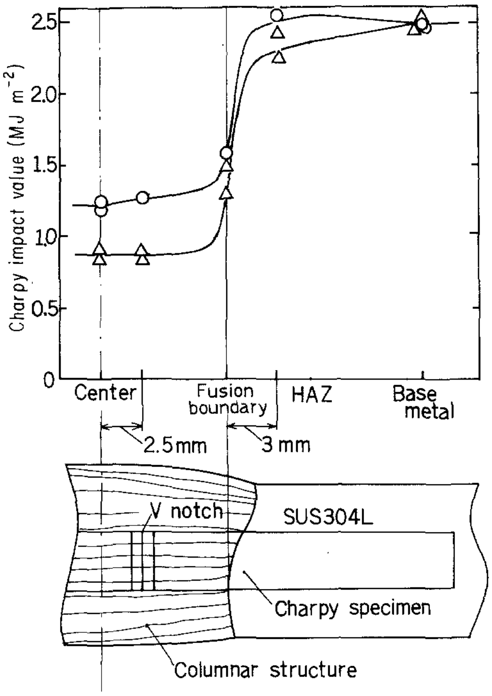


Figure 6 Distribution of impact value and schematic diagram of weldment. Test temperature (○) 293 K, (△) 77 K.

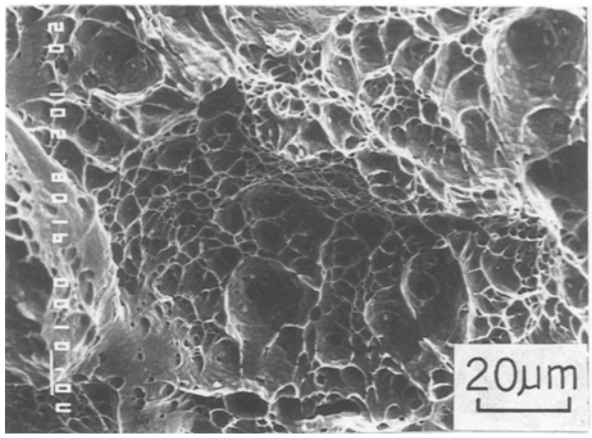


Figure 7 SEM fractography of the fracture surface of 77 K Charpy impact specimen from SUS304L base metal. Dimple reveals the ductile fracture manner at low temperature.

inclusions and toughness seems to decrease. Usually, the impact value in weldment strongly depends on the variation of oxide volume fraction as mentioned past report [8] or others [9]. Considerable amount of oxide inclusion remains after deoxidation by the flax in SAW weld metal, so the fracture toughness is inferior to MIG or TIG weldment.

At the low temperature of 77 K, brittle fracture is observed frequently in the fracture surface of the weld metal as shown in Fig. 8a-2, b-2 and c-2. It is difficult to measure quantitatively but at least 20 or 30% of the surface may be brittle. Fracture toughness of the weld metal tends to decrease with appearing brittle fracture in the weld metal. Finally, at low temperature, the

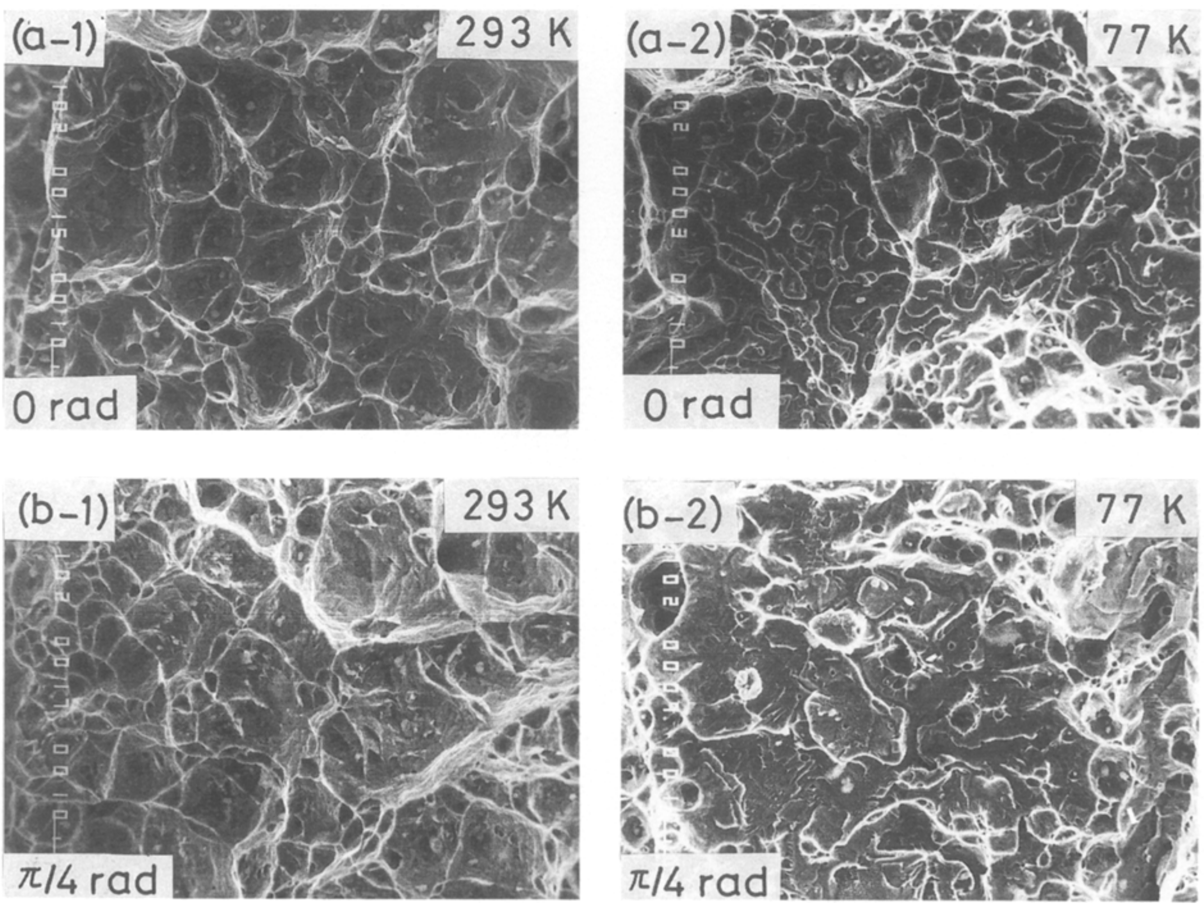


Figure 8 SEM fractography of the fracture surface of Charpy impact specimen in SUS304L SAW weld metal with several columnar angle. (a-1), (b-1), (c-1) show the fracture surfaces of 293 K impact specimen of weld metal. Dimples reveal the ductile fracture. (a-2), (b-2), (c-2) show the fracture surfaces of 77 K impact specimens of weld metal. Surfaces consist of a mixture of dimple and cleavage.

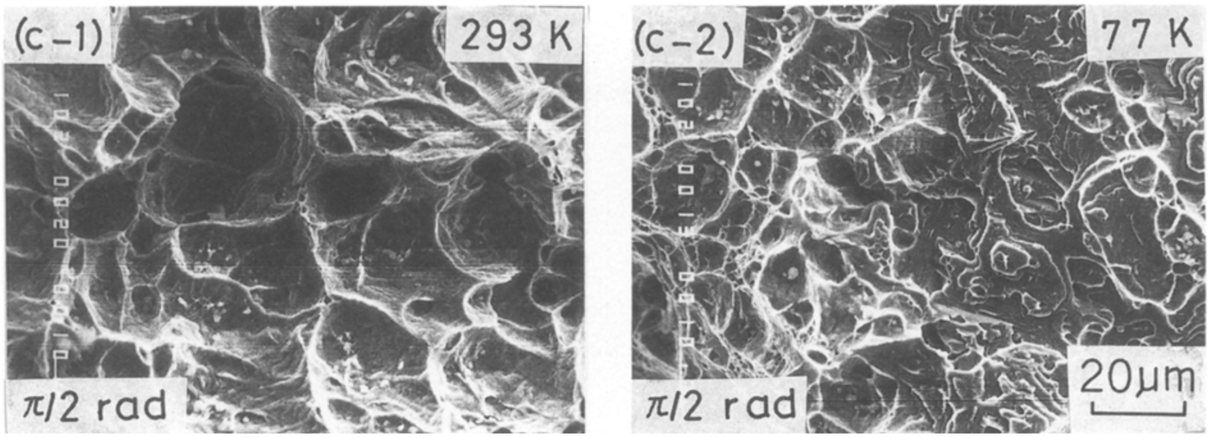


Figure 8 Continued

fracture surface is a mixture of brittle and dimple in the weld metal [10].

The fracture manner, brittle or ductile, depends on the microstructure of fractured region. In order to get the experimental proof about the relationship between microstructure and fracture manner, a fractographic method which is a combination of metallurgical microstructure and fracture surface has been used [11]. The typical results of specimen fractured at 77 K are shown in Fig. 9a, b and c. The fracture manner is related to the morphology of δ.

1. Globular type δ: fine dimples are formed at the region which include the globular type δ ferrite as shown in Fig. 9a. It is considered that the globular type δ ferrite acts as spherical inclusion and promotes the formation of dimples. Likewise, the large dimples are formed at the region of microstructure containing the discontinuous vermicular type δ ferrite as shown in Fig. 9b. It is considered that brittle crack might occur in δ ferrite at first and next internal necking was developed at the circumference of the crack and finally grew to large dimples.

2. Vermicular type δ: on the other hand, brittle fracture is frequently observed at the area of continuous vermicular type δ ferrite network, as shown in Fig. 9c. It is considered the continuously brittle cracking occurred along to the δ ferrite network. The size of brittle facet coincides with the cell size of δ ferrite network.

3.3.3. Fusion boundary

Fig. 10 shows the microstructure of fusion boundary. The morphology of δ is globular and discontinuous vermicular type, so the fracture manner of fusion boundary is almost ductile by dimple at low temperature. Consequently, the impact value at low temperature is almost the same as to one at room temperature as shown in Fig. 6. On ductile fracture by dimple, the impact value strongly depends on the oxide volume fraction [8, 9]. The fine spherical oxide exists in weld metal as shown in Fig. 10. Fig. 11 shows the quantitative variation of oxide volume fraction measured by an area analyser. Oxide volume fraction of 0.4% uniformly distributed in weld metal and

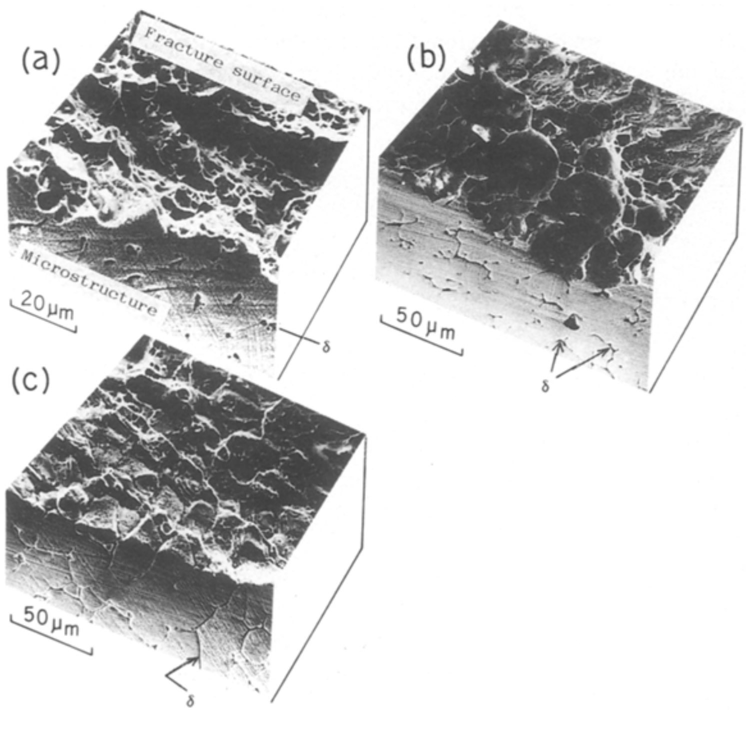


Figure 9 Combination of metallurgical microstructure and fractography. (a) Globular type δ ferrite caused fine dimple. (b) Discontinuous δ ferrite caused large dimple. (c) Continuous vermicular type δ ferrite network caused brittle fracture.

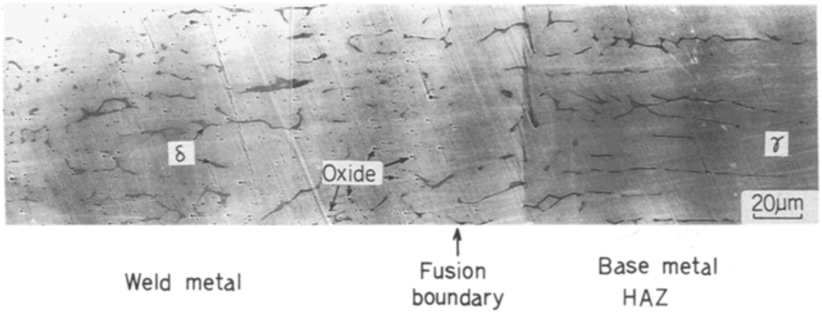


Figure 10 Morphology of δ ferrite and oxide distribution at fusion boundary.

discontinuously changes at fusion boundary to lower level of 0.05% in the base metal. The fracture occurred in base metal as well as in weld metal. Consequently, fusion boundary indicated intermediate impact value between weld and base ones at both temperatures.

3.3.4. Fracture mechanism of δ ferrite

The crack propagation path was investigated in more detail in order to clarify the micro mechanism of brittle fracture.

A typical result is shown in Fig. 12a, b and c. Brittle fracture is shown in Fig. 12a which indicate that part of the surface consists of many steps like the contour lines. Fig. 12b shows the cross section of the brittle crack covered by nickel plating. The darker part in this figure indicates δ ferrite. It is evident that the brittle fracture propagates along to δ ferrite network. Most of δ ferrite observed in this study is classified as the vermicular type, judging from the detail as shown in Fig. 3a and b. It is said that the longitudinal direction of δ is close to (1 0 0) direction that is the growing direction of ferrite dendrite. If the longitudinal direction of δ ferrite is equal to (1 0 0), the flat cleavage occurs, but actually the direction is a little leaning from (1 0 0) as shown in the illustration. The crack propagates in a zigzag mode as shown in Fig. 12c. Consequently, the continuous δ easily leads to brittle fracture and makes the toughness decrease. Additionally, impact values scarcely depend on θ, so that the probability of initiation of brittle fracture is almost the same at any θ, as shown in Fig. 8a-2, b-2 and c-2.

Fig. 13 schematically indicates the morphology and fracture mechanism of δ ferrite in weld metal at low temperature. Vermicular type δ ferrite network develops not only parallel to the growing direction of columnar structure but also to normal. The brittle fracture along to δ occurs in both directions of parallel and normal to the columnar as shown in Fig. 13a. In other words, the probability of an initiation of brittle fracture and impact value scarcely depends on θ.

On the other hand, as shown in Fig.13b, most of the globular or rod-like δ ferrite in the fusion boundary exists parallel to the columnar structure and fracture occurs in a ductile manner normal to the cell structure.

4. Conclusion

Effects of test temperature, columnar angle (θ), and sampling position on the impact value have been studied on SUS304L SAW weldment. Furthermore, the micro fracture mechanism has been discussed experimentally. The results were summarized as follows.

1. Impact value scarcely depends on the columnar angle (θ) at room temperature (293 K) and 77 K.
2. Impact value of weld metal decreases with decreasing the test temperature, which is caused by the brittle fracture occurring in δ ferrite.
3. Impact value indicated minimum value in weld metal and increased drastically at the fusion boundary and reached a constant high value in base metal.
4. At low temperature, the morphology of δ ferrite

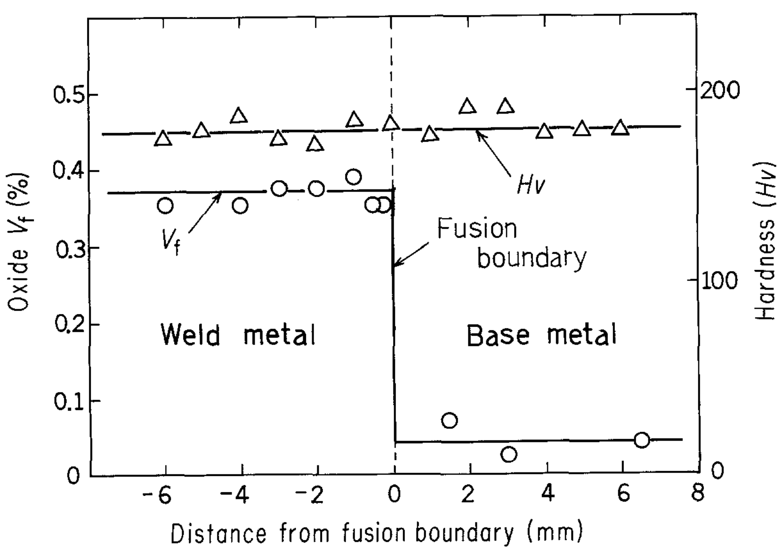


Figure 11 Oxide volume fraction drastically changes at fusion boundary. The variation corresponds to one of impact value.

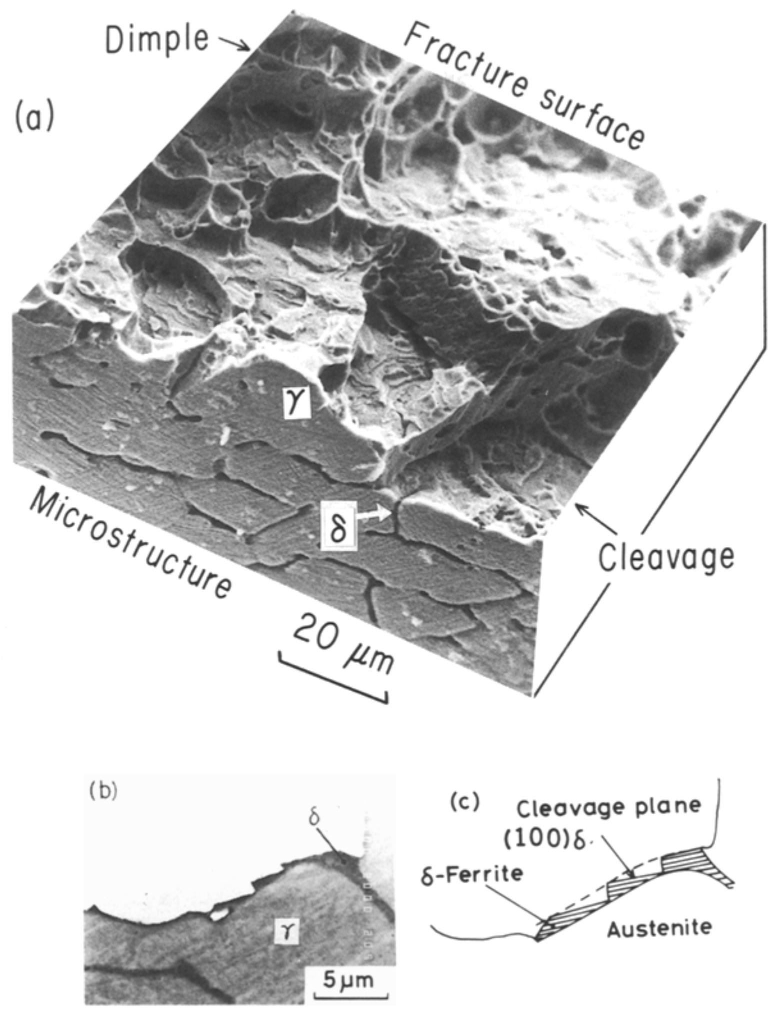


Figure 12 Combination of metallurgical microstructure and fractography by SEM. (a) Brittle fracture easily occurred at outline of δ ferrite network and the brittle fracture surface consists of many steps, like contour lines. (b) Crack propagates in zigzag along to δ ferrite. (c) Cleavage plane coincides with (1 0 0) plane of δ ferrite.

has a strong effect on the fracture mode. Globular and discontinuous vermicular type δ ferrite causes the ductile fracture by dimple. On the other hand, continuous vermicular type δ ferrite network easily lead to the brittle fracture.

Acknowledgement

The authors acknowledge the valuable advice of the late Professor T. Enjo and his members at the Japan Welding Research Institute of Osaka University. The authors also wish to express thanks to F. Sugawara, H. Echigoya and F. Ashihara for their experimental assistance and also thanks to Akita Prefectural Institute of Industrial Technology for the technical support.

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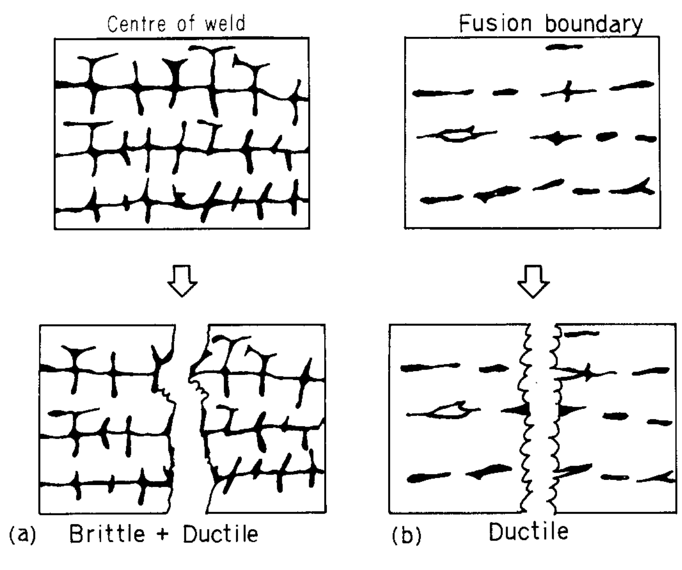

Figure 13 Schematic view of fracture at low temperature. (a) Morphology of δ ferrite is vermicular network at centre of weld metal. Fracture manner is composite of brittle and ductile. (b) Morphology of δ ferrite is rod or globular at fusion boundary. Fracture manner is ductile.

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Received 1 March
and accepted 24 July 1989