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A New Fracture Analysis of Weld Cracks by Means of Recrystallization Method†

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Abstract

Recrystallization method is applied to fracture analysis of weld cracks in weldable high strength steels, i.e. hydrogen-induced cold crack, stress-relief crack and solidification crack. In this method, cracked specimen is heat-treated to recrystallize intense plastic deformed region around the crack, and then recrystallized grain size at crack surface and recrystallized zone width are measured and utilized as factors to identify the type of crack and stress condition. It is shown that recrystallization behavior is different among hydrogen-induced cold crack, stress-relief crack and solidification crack. Thus, recrystallization method as fracture analysis is available when crack surface is inadequate for execution of electron microfractography due to its oxidization or contamination. It is also shown as regards hydrogen-induced cold crack that magnitude of restraint stress is reflected on recrystallization behavior.

KEY WORDS: (Fractography) (Recrystallization) (Cold Cracking) (Hot Cracking)

1. Introduction

As well known, microfractography with scanning or transmission electron microscope is very useful for fracture analysis, and thus widely used. However, one of disadvantages of electron microfractography is that it is very sensitive to posterior damage of fracture surface, e.g. oxidization and contamination, etc. Thus electron microfractography is sometimes helpless against crack or fracture occurring during fabrication or operation.

Under such situation as oxidization or contamination covers fracture surface, X-ray diffraction technique of the fracture surface is a useful method[1], where distribution of residual stress or half-value width near the fracture surface is utilized to estimate the fracture mode. However, X-ray diffraction apparatus is not necessarily widely used, and demands skill to some extent. Another disadvantage of X-ray diffraction technique is that the size of X-ray beam is not generally small enough, and thus spatial resolving power is insufficient.

In recent years, recrystallization method[2-8] has been developed for fracture analysis, where distribution of plastic strain around the tip of crack or notch is evaluated from recrystallized grain size after heat treatment and related to fracture mode. By means of this method, COD under large-scale yielding[3], relations between plastic deformed zone size and growth rate of fatigue crack[2-5], absorbed energy in Charpy impact test[6], and so on have been well analyzed. Since gauge length in measurement of plastic strain, so to speak, is considered to be approximately recrystallized grain size[9], this method corresponds to semi-microfractography in a sense.

This method demands only a furnace, a series of metallographical treatments and an optical microscope. Moreover, plastic deformed zone is well seized visually as recrystallized zone.

Therefore, this method must be very valuable for analysis of cracks in the following two ways; (i) identification of weld crack whose fracture surface is inadequate for electron microfractograph due to its oxidization or contamination, and (ii) estimation of plastic strain and thus magnitude of stress which is not necessarily possible in electron microfractograph. In this paper, applicability of recrystallization method is studied to hydrogen-induced cold crack, stress-relief crack and solidification crack in steel weldment which were made with several cracking tests.

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2. Materials Used and Experimental Procedures

Base metals used were weldable high strength steels HT50 (JIS SM50), HT60 (SM58Q) and HT80, where the figure behind HT gives the ultimate tensile strength in kg/mm^2. The chemical compositions and mechanical properties of these base metals are shown in **Table 1**, in which those of deposited metal of electrodes are also included.

Hydrogen-induced cold cracking, stress-relief cracking, and solidification cracking were made by means of various weld cracking tests, e.g. the TRC test[10], fillet weld cracking test, the Varestraint test[11], and so on. Besides, tensile test was carried out for base metal, synthetic HAZ and weld metal in root pass of HT60 and HT80 in order to quantitatively evaluate the relation between plastic strain and recrystallized grain size. The diameter and the length of the parallel portion of the tensile test specimen was 3 and 10 mm respectively. The synthetic HAZ was made with high-frequency heating apparatus, where the peak temperature and the cooling time from 800 to 500°C was selected to 1350°C and 7 sec respectively. The weld metal specimen was machined from actual root pass made from the matching electrode to the base metal with heat input of 17 kJ/cm.

The specimen after the testing was heat-treated in an electric furnace for recrystallization, the condition of which was 700°C x 3 hr in argon atmosphere. Recrystallized grain size of ferrite was measured with optical microscope in magnification of 400 after the etching with Nital.

3. Experimental Results and Discussion

3.1 Characteristic of recrystallization of weld zone

Relation between true strain and recrystallized grain size obtained from tensile specimens is shown in **Fig. 1 (a)** and **(b)** for HT60 and HT80 respectively. The true strain is logarithmic strain in other words, and further equal to equivalent plastic strain. It is noteworthy that the relation in the synthetic HAZ is similar to that in the base metal in either HT60 and HT80. However, the relation in the weld metal is somewhat different from that in the base metal or the synthetic HAZ, especially in HT80. Moreover, Fig. 1 shows that minimum true strain necessary for recrystallization in the synthetic HAZ is also nearly equal to that in the base metal, the value of which is about 0.05 in either HT60 and HT80. However, minimum true strain necessary for recrystallization in the weld metal is higher than that in the base metal or the synthetic HAZ, the value of which is about 0.15 in HT60 and about 0.2 in HT80.

Other characteristics of recrystallization are seen in **Fig. 2**, which gives recrystallized macrostructures of tensile specimens of HT60. Banded recrystallization owing to rolling texture is observed in the base metal and the synthetic HAZ, and arched un-recrystallized zone owing to segregation band during solidification is observed in weld metal. It is ambiguous for the present whether these arose from dependence of recrystallization or plastic deformation on chemical heterogeneity.

3.2 Hydrogen-induced cold cracking

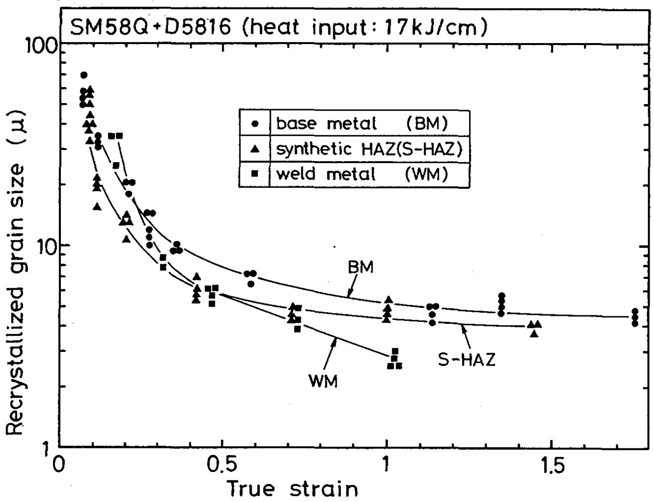
3.2.1 TRC test

The TRC test[10] which was devised by Suzuki, et al. in order to evaluate the susceptibility of root cracking was applied to HT60 with y-groove. Electrode used was low hydrogen type JIS D5816 which matched HT60 in strength, and heat input was selected to 17 kJ/cm without preheating. Applied stress σ was selected to 54, 72 and 96 kg/mm^2, and the resultant fracture time was 0.05, 70 and 119 min respectively. The recrystallized transverse macrostructures are shown in **Fig. 3**, where recrystallized zones are seen darkly because of oblique lighting. The root cracks in $\sigma = 54$ and $72\ kg/mm^2$, Fig. 3(a) and (b), occurred in HAZ at first and then grew into weld metal,

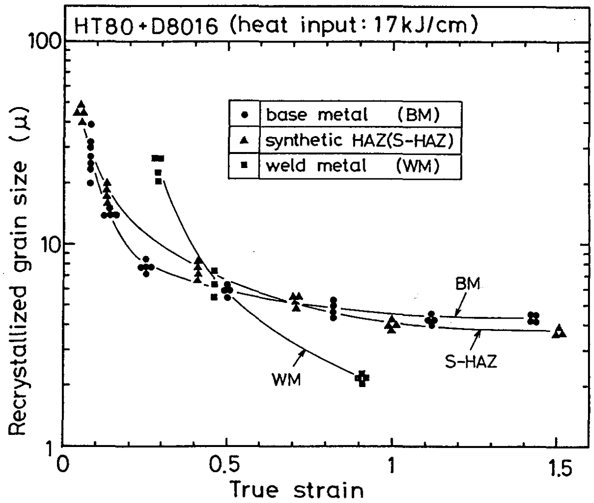
Table 1 Chemical compositions and mechanical properties of base metals and deposited metals.

Material		Composition (wt. %)											Thickness	Yield strength	Tensile strength
		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	(mm)	(kg/mm^2)	(kg/mm^2)
Base metal	HT50(SM50A)*1)	0.15	0.33	1.35	0.024	0.004	-	-	-	-	-	-	22	37	55
	HT50(SM50A)*2)	0.14	0.33	1.37	0.022	0.016	-	-	-	-	-	-	12	38	55
	HT50(SM50B)*3)	0.15	0.45	1.29	0.018	0.015	-	-	-	-	-	-	100	34	53
	HT50 (SM50) *4)	0.18	0.43	1.54	0.027	0.021	-	-	-	-	-	-	25	-	-
	HT60(SM58Q)	0.14	0.22	1.30	0.022	0.004	-	0.17	-	0.07	0.04	-	31	56	66
	HT80*5)	0.12	0.25	0.88	0.011	0.003	0.24	0.05	0.69	0.39	0.04	0.001	32	81	85
	HT80*6)	0.09	0.28	0.85	0.013	0.004	0.24	0.05	0.75	0.42	0.04	0.001	34	75	83
Electrode	D5016(matching HT50)	0.07	0.45	1.06	0.013	0.007	-	-	-	-	-	-	4(Dia.)	51	58
	D5816(matching HT60)	0.08	0.48	1.10	0.013	0.007	-	0.53	-	0.17	-	-	4(Dia.)	57	67
	D8016(matching HT80)	0.05	0.52	1.47	0.012	0.006	-	2.57	0.18	0.50	-	-	4(Dia.)	77	86

Code in parentheses is the designation of Japanese Industrial Standard (JIS)
*1): applied to non-restraint T type cracking test and controlled restraint fillet weld cracking test
*2): applied to non-restraint T type cracking test and Varestraint test
*3): applied to bead-on-plate cracking test
*4): applied to fatigue crack test
*5): applied to tensile test
*6): applied to stress-relief cracking test

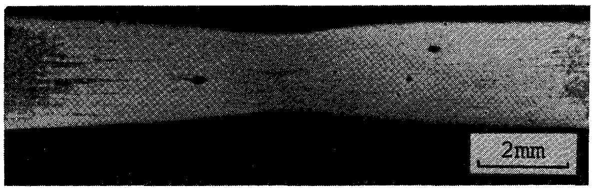


(a) HT60

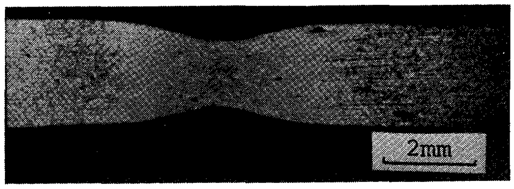


(b) HT80

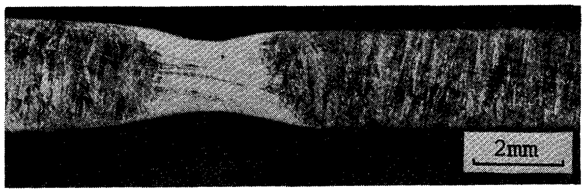
Fig. 1 Relation between true strain and recrystallized grain size in tensile test specimen of weld zone



(a) base metal



(b) synthetic HAZ

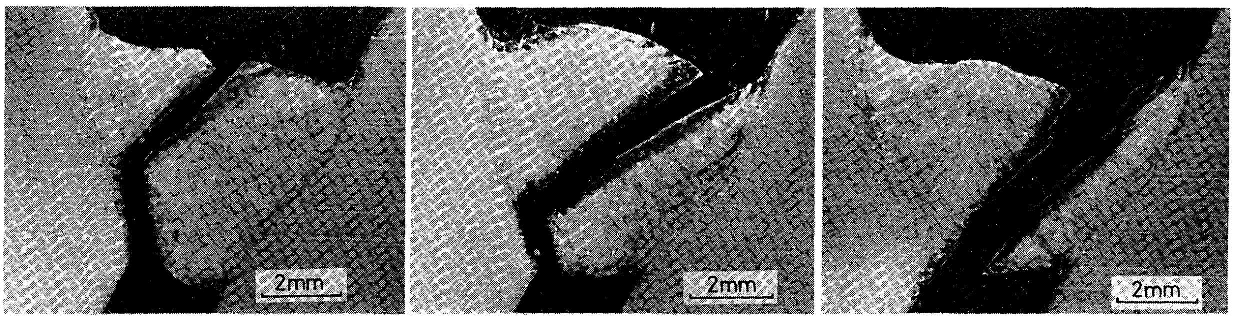


(c) weld metal

Fig. 2 Recrystallized macrostructure of tensile test specimens of HT60

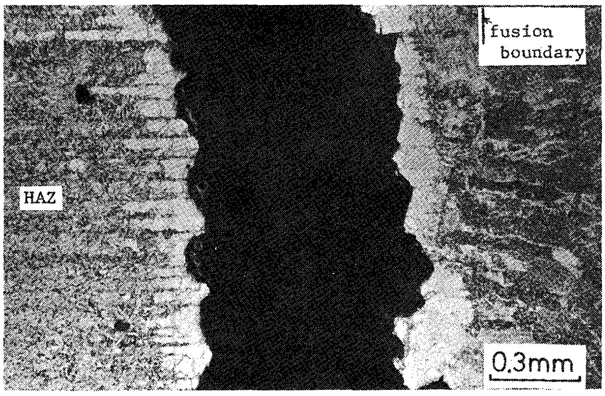
whereas the crack in $\sigma = 96\ kg/mm^2$, Fig. 3(c), occurred in weld metal in shear mode instantaneously at completion of loading. A tendency is observed as a whole that the recrystallized zone width gradually increases from the root, namely vicinity of the bottom of weld metal, toward the surface of weld metal.

Examples of recrystallized microstructures are shown in **Fig. 4**. In Fig. 4(a) where the root crack occurred in coarse-grained region in HAZ, the recrystallized zone is generally narrow though affected by rolling texture, and the recrystallized grain size is large. In Fig. 4(b) where the root crack grew in weld metal, the recrystallized zone is wide, and the recrystallized grain size at the crack sur-

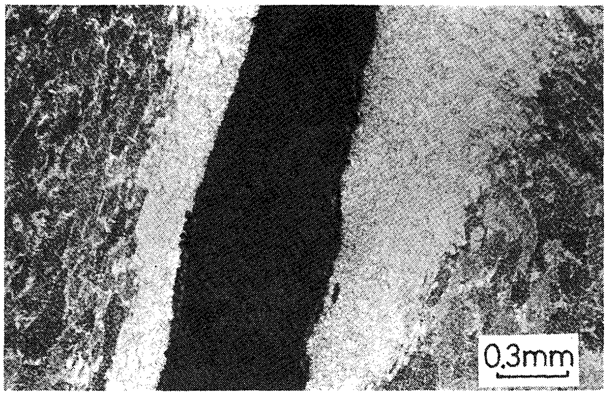


(a) $\sigma = 54\ kg/mm^2$ (b) $\sigma = 72\ kg/mm^2$ (c) $\sigma = 96\ kg/mm^2$

Fig. 3 Recrystallized macrostructure in transverse crosssection of TRC test specimen of HT60 (oblique lighting)



(a) vicinity of weld bond near bottom of weld metal



(b) weld metal

Fig. 4 Recrystallized microstructure in transverse crosssection of TRC test specimen of HT60

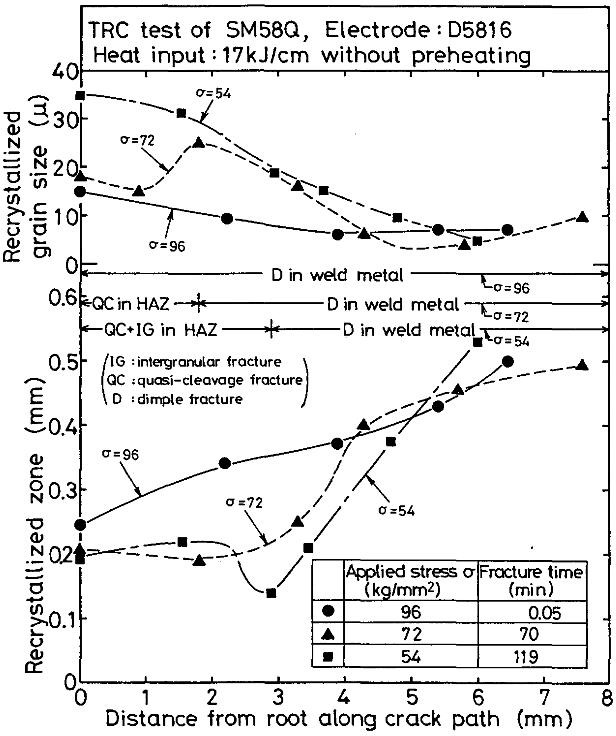


Fig. 5 Recrystallized grain size at crack surface and recrystallized zone width vs. distance from root along crack path in TRC test specimen of HT60

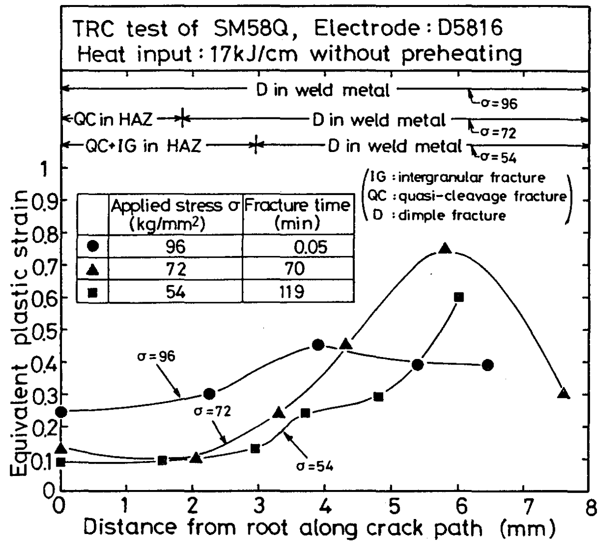
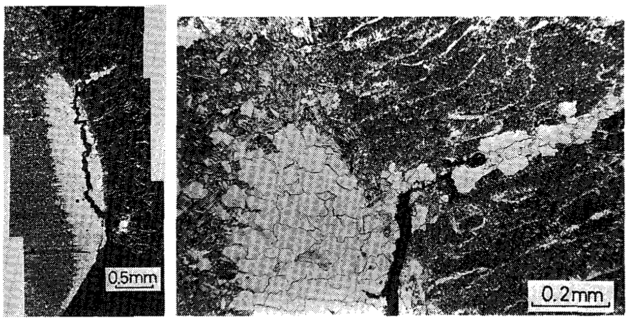


Fig. 6 Equivalent plastic strain at crack surface vs. distance from root along crack path in TRC test specimen of HT60



(a) low magnification (b) high magnification

Fig. 7 Recrystallization in front of growing root crack in TRC test specimen of HT60

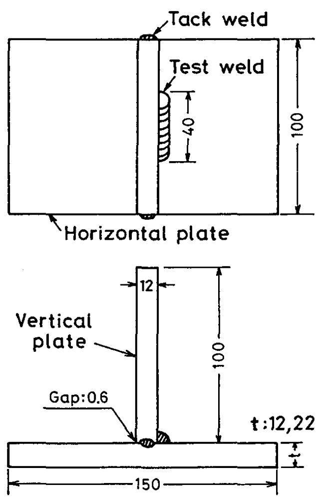


Fig. 8 Specimen configuration of non-restraint T type cracking test

face is very small. However, it is inexplicable in Fig. 4 (b) that the widths of recrystallized zones at the both sides of the crack are different each other.

Figure 5 shows dependence of mean width of recrystallized zones at the both sides of the crack and recrystallized grain size at the crack surface on the distance along the crack path from the root. Characteristic of crack surface is also written in Fig. 5 as IG, QC or D, which mean intergranular, quasi-cleavage and dimple fracture mode respectively. The recrystallized zone width gradually increases and the recrystallized grain size gradually decreases along the crack path by way of exceptions near the parts where the crack turned into weld metal from HAZ in $\sigma = 54$ and $72\ kg/mm^2$. Now it is noteworthy that the recrystallized zone width and recrystallized grain size in the range of distance from the root less than about 4 mm well reflect the magnitude of applied stress. That is to say, the specimen in $\sigma = 96\ kg/mm^2$ has the largest recrystallized zone width and the smallest recrystallized grain size. The specimen in $\sigma = 54\ kg/mm^2$ has the nearly same recrystallized zone width as that in $\sigma = 72\ kg/mm^2$, but has the largest recrystallized grain size. In other words, the higher the applied stress was loaded, more the plastic deformation developed. In the range of distance from the root more than about 4 mm, it is impossible to distinguish the magnitude of applied stress, because all the crack in this range grew in rapid shear fracture mode.

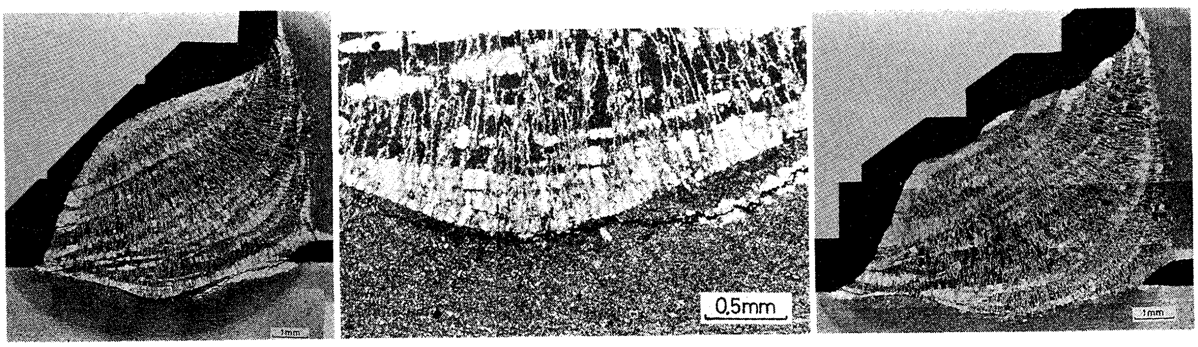
Conversion of the recrystallized grain size at the crack surface in Fig. 5 into equivalent plastic strain by the relation in Fig. 1 (a) gives **Fig. 6**, which also enable us to distinguish the magnitude of applied stress in the range of distance from the root less than about 4 mm. Comparing the equivalent plastic strain with the fracture mode in Fig. 6, it is also recognized that the equivalent plastic strain at the crack surface more than about 0.15 caused dimple fracture mode.

Besides, **Fig. 7** shows example of recrystallized microstructure where the growing root crack was suddenly arrested by removing the applied stress. There is a recrystallized zone in front of the crack tip. It may be interesting in a future subject to analyze the recrystallized zone in front of crack in order to estimate the stress condition at the cracking during fabrication or operation.

3.2.2 Fillet weld cracking test

At first, non-restraint T type cracking test[12,13] was applied to HT50 to make heel crack. Specimen configuration is shown in **Fig. 8**, where two horizontal plates of different thickness were alternately used. Electrode used was low hydrogen type JIS D5016 which matched HT50 in strength, and heat input was selected to 17 kJ/cm without preheating. Recrystallized macrostructures and microstructure are shown in **Fig. 9**. Heel crack which grew from the root under the weld metal occurred only in the use of 22 mm thick horizontal plate, Fig. 9 (a). Recrystallized zone width gradually decreases from the root, and finally the recrystallized zone disappears in spite of the existence of crack as clearly seen in Fig. 9 (b). In this region it is considered that the crack grew under very small restraint stress.

Now, it is worth notice in Fig. 9 (a) and (c) that recrystallization occurs at several places in the weld metal in addition to the zone around the crack. Such a phenomenon as this is not observed in Figs. 3 and 4. This recrystallization in weld metal is considered to be owing to the lower yield stress and the lower recrystallization temperature of HT50 weld metal than those of HT60 weld metal. Here, it is expected that this recrystallization in the weld metal in addition to the zone around the crack can be positively utilized in order to estimate the stress condition of weld zone. For example, comparing Fig. 9 (a) with Fig. 9 (c) where heel crack did not occur, the recrystallization area in weld metal in Fig. 9 (a) is somewhat larger than that in Fig. 9 (c).



(a) thickness of horizontal plate: 22 mm (b) bottom of weld metal in (a) (c) thickness of horizontal plate: 12 mm

Fig. 9 Recrystallized macro- and microstructure in non-restraint T type cracking test of HT50

Such a phenomenon can be also seen in the following: Controlled restraint fillet weld cracking test[14], the specimen configuration of which is shown in **Fig. 10**, was applied to HT50. Electrode used was low hydrogen type JIS D5016, and heat input was selected to 17 KJ/cm without preheating. **Figure 11** shows recrystallized macrostructures with (a) low and (b) high restraint intensities. As clearly seen, the recrystallization in weld metal in Fig. 11 (a) occurs in almost all the weld metal in addition to the zone around the crack in HAZ.

Besides, recrystallization can be also seen in the toe of weld as in Fig. 9 (a), (c) and Fig. 11 (a). So, analysis of recrystallized zone at the toe of weld may be available if toe crack becomes a problem.

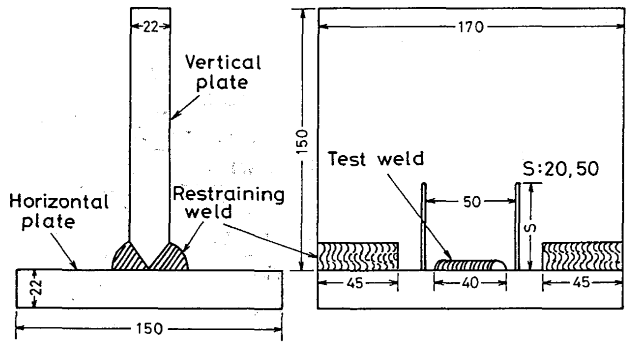
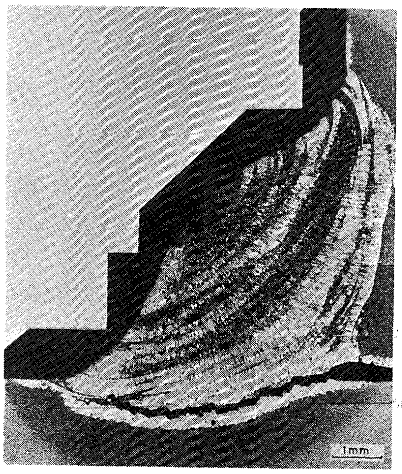
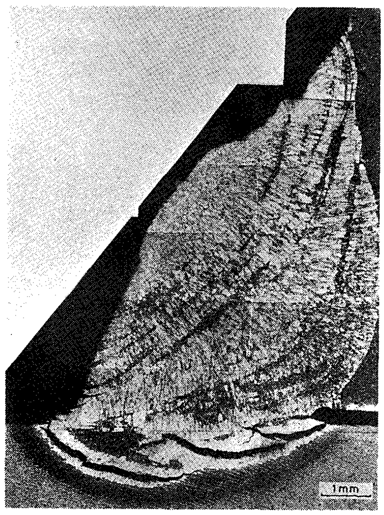


Fig. 10 Specimen configuration of controlled restraint fillet weld cracking test



(a) low restraint intensity (S in Fig. 10: 50 mm)

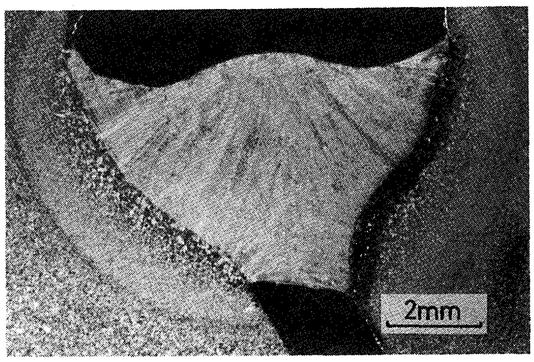


(b) high restraint intensity (S in Fig. 10: 20 mm)

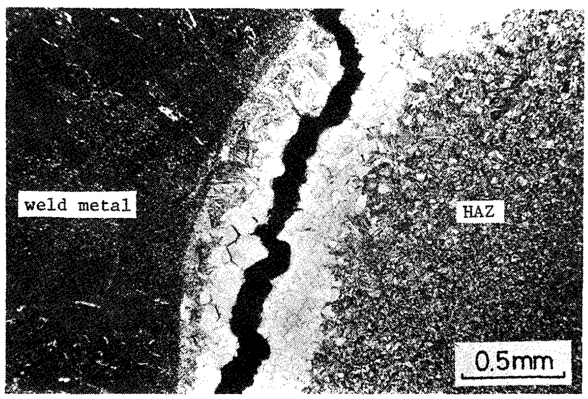
Fig. 11 Recrystallized macrostructure in controlled restraint fillet weld cracking test of HT50

3.3 Stress-relief cracking

Stress-relief (SR) cracking test was performed for HT80, the specimen configureation was Tekken type with oblique y-groove. Electrode used was low hydrogen type JIS D8016 which matched HT80 in strength, and heat input was selected to 17 kJ/cm with 150°C preheating. The specimen after welding was taken into an electric furnace for stress relief, the conditions of which were heating rate of 150°C/hr, holding in 600°C x 1 hr and furnace cooling.



(a) macrostructure (oblique lighting)



(b) microstructure

Fig. 12 Recrystallized macro- and microstructure in transverse crosssection of test specimen of stress-relief crack in HT80

Recrystallized macrostructure and microstructure are shown in **Fig. 12.** SR crack occurs along coarse-grained region in HAZ, and is accompanied with recrystallized zone of nearly constant width (about 0.3 mm) along the crack path. Mean recrystallized grain size is 32 μm independent of location along and perpendicular to the crack path. The characteristic of recrystallization of SR crack seems to be somewhat larger width in spite of the larger grain size in comparison with that of hydrogen-induced cold crack.

3.4 Solidification cracking

Bead-on-plate cracking test was done for HT50 sheet of 150 mm in length, 50 mm in width and 3 mm in thickness which was cut from original plate of 100 mm thickness. TIG-arc welding was utilized without filler metal, and welding conditions were; welding current of 140A, arc voltage of 13V, and welding speed of 150 mm/min. The welding was started from an edge, and thus solidification cracking occurred from the edge and grew following the TIG-arc.

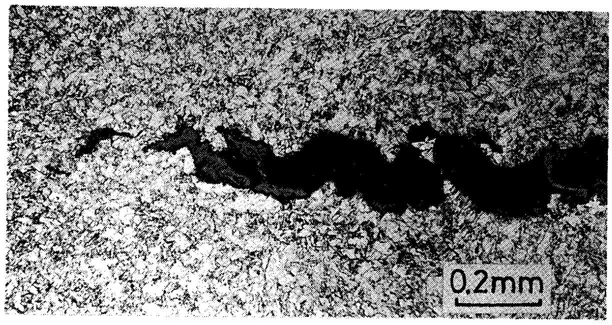
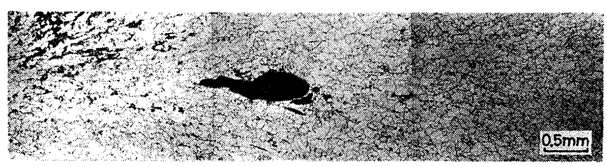
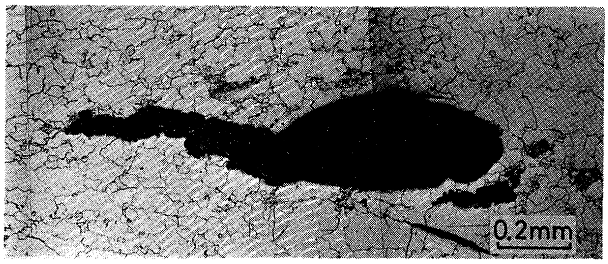


Fig. 13 Absence of recrystallization around solidification crack in bead-on-plate cracking test of HT50



(a) low magnification



(b) high magnification

Fig. 14 Recrystallized microstructure around solidification crack in the Trans-Varestraint test of HT50

Figure 13 gives microstructure around the tip of solidification crack after the heat treatment for recrystallization, which shows absence of recrystallized zone around the crack. Of course, plastic deformation must occur prior to the formation of solidification cracking, but the stored energy will be too small to recrystallize the plastic deformed zone, because the plastic strain will not be so large and/or will be easily recovered owing to extremely high temperature.

Then, the Trans-Varestraint cracking test[11] was done for HT50 plate of 9 mm in thickness, where 4% augmented strain was applied. Conditions of TIG-arc welding were; welding current of 150A, arc voltage of 13V, and welding speed of 150 mm/min. An example of recrystallized microstructure around the crack is shown in **Fig. 14,** where recrystallized zone extends over the wide range around the crack, and moreover recrystallized grain size is independent of the distance from the crack. Thus, these mean that the plastic strain causing the recrystallization was not the strain causing the occurrence of the solidification crack, and that this plastic strain was accumulated during cooling after the cracking by continuance of enforced bending after the occurrence of crack.

3.5 Others

In the above mention, only weld cracks were discussed. However, this recrystallization method must be available for crack or fracture occurring during operation of welded structure, e.g. brittle fracture, fatigue fracture, and so on in order to identify and analyze the fracture mode and stress condition. For example, **Fig. 15** shows recrystallized macrostructure of fatigue-fractured welded joint of HT50, where the fatigue fracture occurred near bond from the toe. Magnifying the recrystallized zone, the recrystallized grain size was larger and the recrystallized zone width was smaller than those in hydrogen-induced crack.

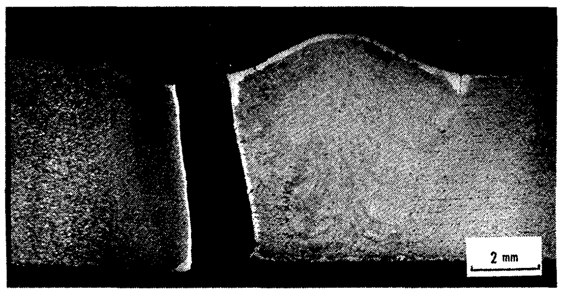


Fig. 15 Recrystallized macrostructure around fatigue fracture in electron beam weld of HT50

Finally, one problem must be emphasized here. The specimen for observation of recrystallized microstructure is usually prepared with mechanical cutting machine. This cutting makes very wide plastic deformed zone and thus wide recrystallized zone. An example is shown in **Fig. 16**, where the width of recrystallized zone extends to about 800 μm from the cutting plane. Therefore, if the plane parallel to the cutting plane is observed, insufficient metallographic polishing causes incorrect information about recrystallized zone.

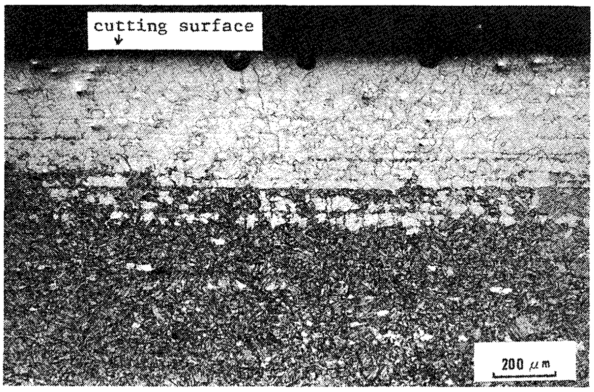


Fig. 16 Recrystallization owing to mechanical cutting with thin grindstone

4. Conclusion

Availability of recrystallization method in fracture analysis of weld cracks was discussed. Main conclusions obtained are as follows:

(1) Distributions of recrystallized grain size or equivalent plastic strain at the crack surface and recrystallized zone width are different with one another among types of weld cracks, e.g. hydrogen-induced cold crack, stress-relief crack and solidification crack. Stress-relief crack has somewhat larger recrystallized zone width in spite of the larger recrystallized grain size in comparison with that of hydrogen-induced cold crack. Solidification crack has not recrystallized zone. Moreover in hydrogen-induced cold crack, the magnitude of restraint stress is reflected on recrystallization behavior around the crack.

(2) Especially as regards hydrogen-induced cold crack in HT50 weldment, the degree of recrystallization in whole weld metal in addition to the recrystallized zone around the crack gives important information about the stress condition.

(3) Thus, this recrystallization method can be utilized enough for identification and analysis of cause of weld cracks, even if the crack surface is inadequate for electron microfractography due to its oxidization or contamination.

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