Title	Quantitative Evaluation of Solidification Brittleness of Weld Metal during Solidification by In-Situ Observation and Measurement (Report IV) : Effect of Grain-Boundary Sliding on Strain-Rate Dependence of Critical Strain Required for Solidification Crack Initiation(Materials, Metallurgy & Weldability)
Author(s)	Matsuda, Fukuhisa; Nakagawa, Hiroji; Tomita, Shogo
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Quantitative Evaluation of Solidification Brittleness of Weld Metal during Solidification by In-Situ Observation and Measurement (Report IV)†

– Effect of Grain-Boundary Sliding on Strain-Rate Dependence of Critical Strain Required for Solidification Crack Initiation –

Fukuhisa MATSUDA*, Hiroji NAKAGAWA**, Shogo TOMITA***

Abstract

Tensile hot cracking test, Trans-Varestraint cracking test and simulated hot ductility test have been carried out for stainless steels and Inconel alloy. The aim of this work is to investigate the next three phenomena from grain-boundary sliding. Namely: (1) the critical strain required for solidification crack initiation increases with an increase in strain rate. (2) the strain rate dependence increases with a decrease in crack susceptibility, and (3) the critical strain in the high strain rate is more sensitive to compare the crack susceptibilities among materials than that in the low strain rate.

Grain-boundary sliding has occurred at solidification grain-boundary of weld metal during solidification under the condition of low strain rate. Then, these phenomena in the above have been explained from the view point of contribution of grain-boundary sliding to total strain of weld metal.

KEY WORDS: (Solidification) (Hot Cracking) (Stainless Steel) (GTA Welding)

1. Introduction

The authors showed in the previous paper[1)] that the critical strain required for the initiation of weld solidification crack increases with an increase in strain rate, and that the tendency is noticeable in materials of low crack susceptibility. Therefore, the cracking test with high strain rate was confirmed to be useful for the comparison of crack susceptibilities among materials[1)], although the critical strain rate required for the initiation of the crack is alternative excellent criterion in the sense that the rate is as slow as that in actual welding fabrication. However, the reason for this strain rate dependence of the critical strain has not been clear.

In the field of hot workability, it is well known[2, 3)] that flow stress and ductility increase with an increase in strain rate, and that generally grain-boundary sliding is one of major reasons for these strain rate dependences. Also in the field of creep, the importance of grain-boundary sliding is widely accepted. Moreover, one of the authors revealed concerning the ductility-dip cracking in welding of Fe-36%Ni alloy[4)] that grain-boundary sliding causes the formation of cavity at grain-boundary, and that high strain rate makes the ductility trough unclear because of the reduction of grain-boundary sliding. According to these references, the dependence of ductility on strain rate is considered to be directly correlated to the dependence of grain-boundary sliding on strain rate.

All these references above mentioned are concerned with the ductility below solidus temperature. However, there are a few reports[5,6)] showing that flow stress increases with strain rate by compression test in solid-liquid coexistent temperature. However, study on the grain-boundary sliding in solid-liquid coexistent state has not been done until now.

Therefore, the purpose of this paper is to study whether grain-boundary sliding occurs or not within brittleness temperature range during weld solidification, and whether it has a strain-rate dependence or not if it occurs. In general, grain-boundary sliding is usually measured quantitatively by making marking line on the surface of specimen[4)].

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* Professor
** Research Instructor
*** Graduate Student of Osaka Univ.

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However, it is impossible to make marking line on the surface of weld metal during solidification. Therefore, hot ductility test was done in solid-liquid coexistent temperature for the specimen with marking lines to assess the extent of grain-boundary sliding quantitatively.

2. Materials Used and Experimental Methods

2.1 Materials used

Commercial austenitic stainless steel (SUS310S) and Inconel alloy 600 were used, and their chemical compositions and thickness are shown in **Table 1**.

Table 1 Chemical compositions of materials used.

Material	Item	Chemical composition (wt%)								Thickness (mm)	Remark
		C	Si	Mn	P	S	Cr	Ni	Others		
Inconel alloy	Inconel 600 (A)	0.033	0.25	0.35	0.007	0.002	15.47	74.84	Fe:8.30, Cu:0.03	2.0	Tensile hot cracking test
	Inconel 600 (B)	0.035	0.21	0.20	0.008	0.002	15.79	74.28	Fe:8.31, Mo:0.20	3.5	Trans-Varestraint cracking test
Austenitic stainless steel	SUS310S* (A)	0.07	0.67	1.74	0.016	0.001	25.05	19.80	Mo:0.05	4.0	
	SUS310S* (B)	0.05	0.72	1.49	0.024	0.001	25.21	19.32	—	3.0	Simulated hot ductility test

*:Designation follows Japan Industrial Standard (JIS).

2.2 Tensile hot cracking test.

The shape of the specimen used was the same as that in the previous paper[1)], namely $300^l \times 100^w \times 2^t$ (mm). GTA welding was done without filler metal under the conditions of 70A, 12V (DCEN) and 0.83mm/s. Tensile deformation was applied perpendicular to the welding direction during the welding with the tensile hot cracking tester under the two kinds of crosshead speed (C.H.S.) of 0.1 and 20mm/s. Crosshead speed (C.H.S.) of 0.1mm/s was the same as that to evaluate the lower critical strain rate below which the crack can not occur as mentioned in the previous paper[1)], and 20mm/s was maximum in the tester used. Strain and strain rate applied on the specimen are shown in **Table 2**. As soon as the tensile deformation was completed, welding was stopped and the specimen was immediately removed from the chuck to prevent grain-boundary sliding during cooling after solidification.

2.3 Trans-Varestraint cracking test

The size of the specimens used were $100^l \times 100^w \times 4.0^t$ for SUS310S and $100^l \times 100^w \times 3.5^t$ (mm) for Inconel 600. GTA welding was done without filler metal under the conditions of 100A, 15V (DCEN) and 2.5mm/s. The augmented strain evaluated by $(t/2R) \times 100(\%)$ was set to 0.3%, refered to 7) and 8), where t = thickness of specimen and R = radius of block. Two kinds of augmented strain rates shown in Table 2 were applied to the specimen by controlling the falling speed of yokes.

2.4 Simulated hot ductility test

It is difficult to measure the grain-boundary sliding in the tensile hot cracking test and the Trans-Varestraint cracking test, because any marking lines to measure the sliding can not be drawn on the surface of weld metal during solidification. Therefore, simulated hot ductility test was applied.

Table 2 Testing conditions of tests used.

Testing method	Material	C.H.S. (mm/s)	Augmented strain (%)	Augmented strain rate (%/s)
Tensile hot cracking test	Inconel 600 (A)	0.1 20	2.7*	1.3* 20.8*
Trans-Varestraint cracking test	Inconel 600 (B)	—	0.3**	0.5 23.7
	SUS310S (A)	—	0.3**	0.4 24.0
Simulated hot ductility test	SUS310S (B)	0.06 6.07	—	—

*:Evaluated by MISO technique.
**:Evaluated by $(t/2R) \times 100$ (t:thickness of specimen, R:radius of bending block).

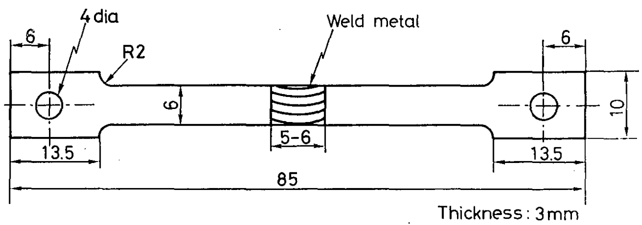


Fig. 1 Shape and size of specimen used for simulated hot ductility test.

The shape and the size of specimen used in this test is shown in **Fig. 1**, where weld metal was located in the middle of specimen. The welding was done with GTAW under the conditions of 100A, 15V (DCEN) and 1.67mm/s with Ar gas back shielding. The bead width of top and back surfaces was about 5 ~ 6mm. The surface of specimen was polished electrolytically, and some ten straight marking lines to measure the grain-boundary sliding were scratched on the surface of weld metal by a razor. The test was done with high frequency induction heating system in

Ar atmosphere. The specimen was heated with the heating rate of about 44.7°C/s up to 1340°C, which was the liquation temperature of grain boundary in weld metal, and then tensile deformation was applied under keeping the temperature with two kinds of C.H.S., namely 0.06 and 6.07mm/s, shown in Table 2. Crosshead speed (C.H.S.) of 0.06mm/s was the same as that used to evaluate the lower critical strain rate in the tensile hot cracking test in the previous paper[1].

The deformation due to grain-boundary sliding and the total deformation of weld metal along the tensile direction was measured by optical microscope in X400 utilizing the marking lines. **Figure 2** shows the fracture surface of specimen at the testing temperature. The fractograph showed a feature of smooth intergranular fracture caused by grain- boundary liquation.

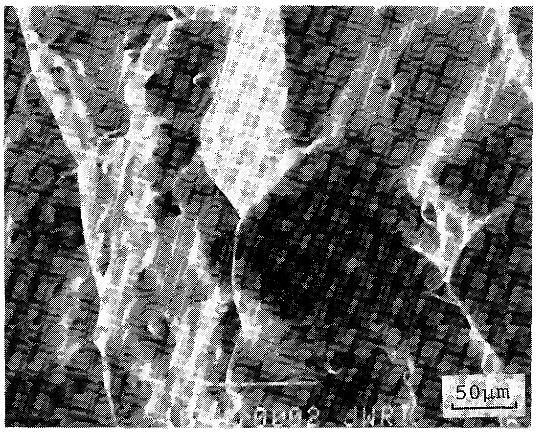


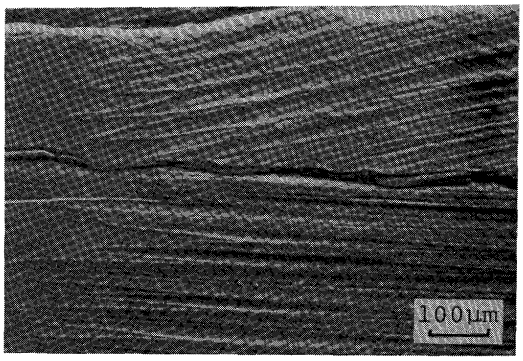
Fig. 2 Fracture surface of weld metal after simulated hot ductility test (SUS310S(B), C.H.S. = 6.07mm/s, 1340°C).

3. Experimental Results and Discussion

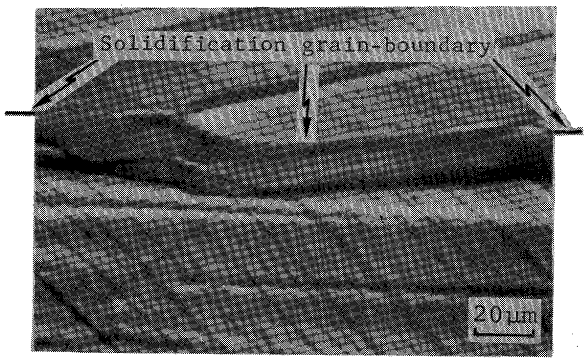
3.1 Observation of grain-boundary sliding in weld soldification cracking test

Figure 3 shows the surface of weld metal within weld solidification brittleness temperature range (BTR) of Inconel alloy 600(A) tested by the tensile hot cracking test with C.H.S. = 0.1mm/s (strain rate = 1.2%/s). Columnar grain-boundaries at solidification, which is hereafter called solidification grain-boundary, is observed with solidification substructure and many slip bands after solidification. It is noticed that the surface of weld metal shows a difference in level at the solidification grain-boundary. This means grain-boundary sliding occurred at the solidification grain-boundary.

However, with the C.H.S. = 20mm/s (strain rate = 21%/s), such obvious difference in level on weld metal surface was not observed at solidification grain-boundary as shown in **Fig. 4**.

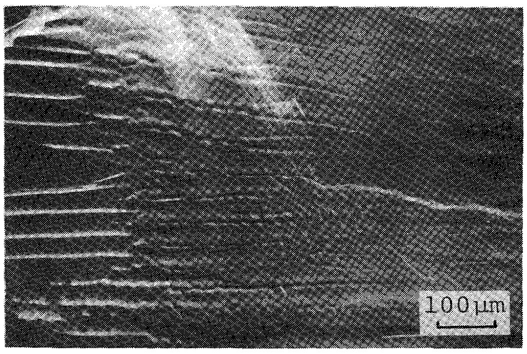


(a) low magnification



(b) high magnification

Fig. 3 Surface of weld metal of Inconel 600(A) with tensile hot cracking test under the condition of C.H.S. = 0.1mm/s.



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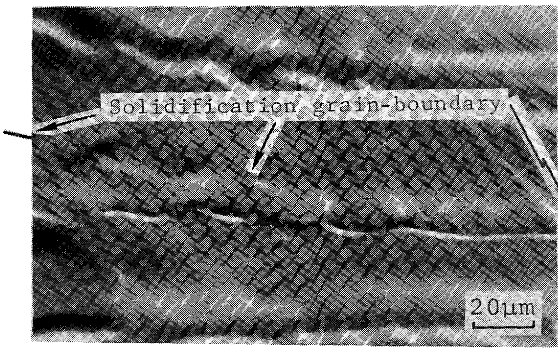


(b) high magnification

Fig. 4 Surface of weld metal of Inconel 600(A) with tensile hot cracking test under the condition of C.H.S. = 20mm/s.

Figure 5 shows the surface of weld metal within BTR of SUS310S(A) tested by the Trans-Varestraint cracking test with the low strain rate (0.4%/s). A difference in level at the solidification grain-boundary was observed, namely solidification grain-boundary sliding occurred.

However, with the high strain rate (24.0%/s), such difference in level on weld metal surface was not observed obviously at solidification grain-boundary as shown in **Fig. 6**.

Therefore, it is confirmed that grain-boundary sliding occurs at solidification grain-boundary during solidification under the condition of low strain rate.

3.2 Quantification of grain-boundary sliding in grain-boundary liquation temperature

Figure 7 shows the surface of weld metal tested with C.H.S. = 0.06mm/s, where the straight lines are the scratches made to observe the grain-boundary sliding, and grain-boundary sliding is clearly observed as in (b). EDX analysis on this grain-boundary showed an increase of Cr content as seen in solidification grain-boundary[9], and thus confirms that this grain-boundary was liquated.

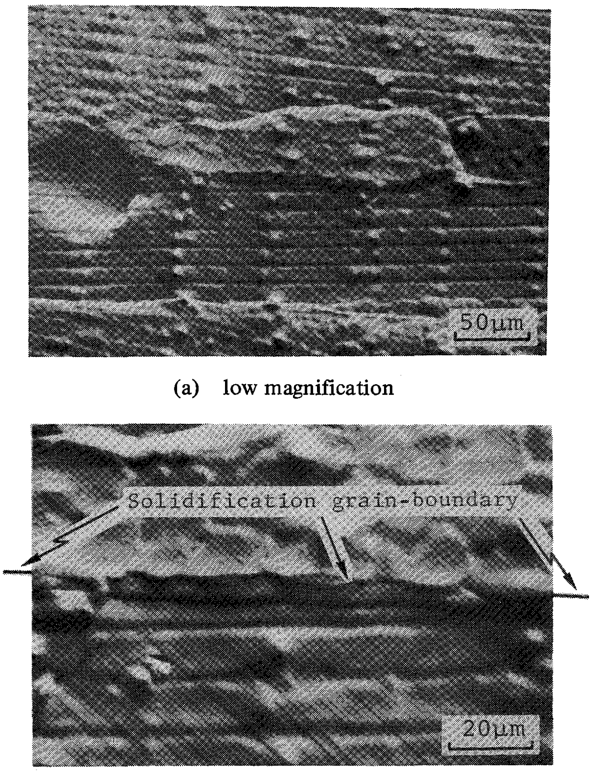
Figure 8 shows the surface of weld metal tested with C.H.S. = 6.07mm/s. Grain-boundary sliding hardly occurred.

Therefore, it is understood that the behavior of the grain-boundary sliding at the liquated grain-boundary is the same as that at solidification grain-boundary mentioned in 3.1.

Table 3 shows the contribution of grain-boundary sliding evaluated, where St means the total deformation of weld metal which was measured from the displacement of gauge length of 4.5mm, Sgb means the deformation due to grain-boundary sliding parallel to the tensile direction which was measured as the sum of the sliding at the all grain-boundary within the gauge length, and γ means the contribution defined as Sgb/St. The value of γ is 0.2 and less than 0.03 in C.H.S. of 0.06 and 6.07mm/s, respectively, and this strain rate dependence agrees with that in creep[10]. By the may, the values of γ are about 0.3 at 900°C in bicrystal of cupper[11] and about 0.5 at 100 ~ 300°C in Cu, Fe, Cd, Sn, Al and Al alloy[12]. The value of γ in the C.H.S. of 0.06mm/s in Table 3 is a little lower than these γ values, but it may be regarded that the easiness of grain-boundary sliding is similar to that in creep, considering that the strain rate in this study is fairly higher than in creep.

3.3 Discussion of dependence of critical strain on strain rate

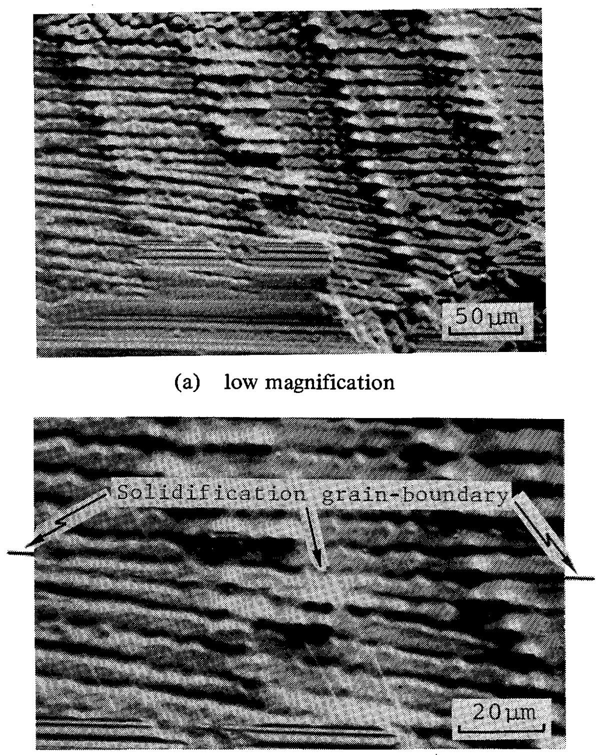
It is well known in the fields of creep and hot working



(a) low magnification

(b) high magnification

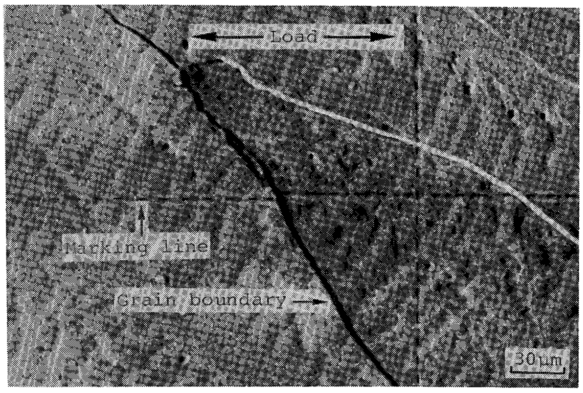
Fig. 5 Surface of weld metal of SUS310S(A) with Trans-Varestraint cracking test under the low strain rate (0.4%/s).



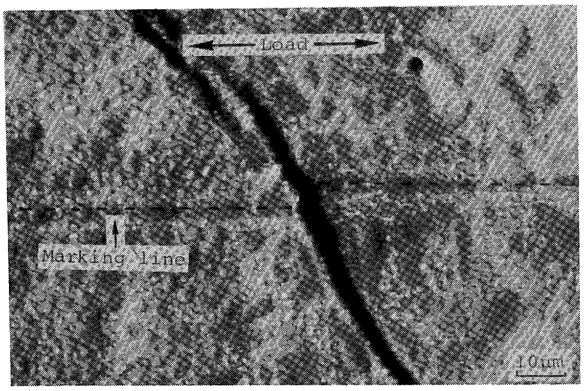
(a) low magnification

(b) high magnification

Fig. 6 Surface of weld metal of SUS310S(A) with Trans-Varestraint cracking test under the high strain rate (24.0%/s).

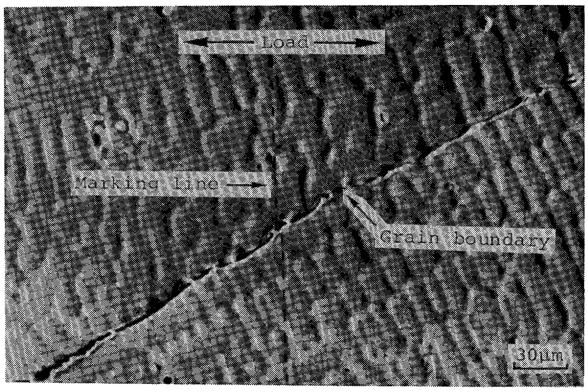


(a) low magnification

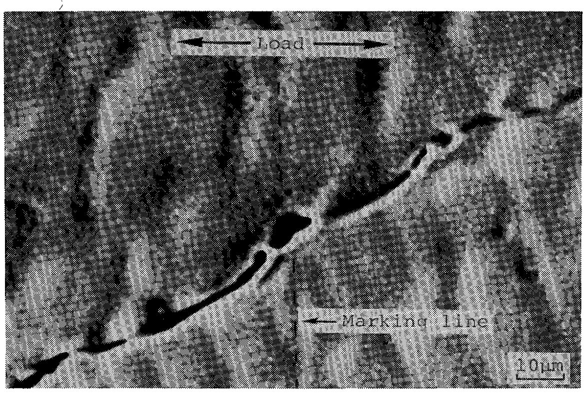


(b) high magnification

Fig. 7 Surface of weld metal of SUS310(B) with simulated hot ductility test under the condition of C.H.S. = 0.06mm/s.



(a) low magnification



(b) high magnification

Fig. 8 Surface of weld metal of SUS310(B) with simulated hot ductility test under the condition of C.H.S. = 6.07mm/s.

Table 3 Effect of strain rate on contribution of grain-boundary sliding to total deformation in solid-liquid region.

C.H.S. (mm/s)	Total deformation St (μm)	Deformation due to grain-boundary sliding Sgb (μm)	Contribution of Sgb to St (Sgb/St) γ
0.06	140	29.1	0.2
6.07	>140	<4.2	<0.03

that (i) grain-boundary sliding is usually proportional to total strain[12], (ii) the contribution of grain-boundary sliding to total strain decreases with stress[10], and (iii) flow stress increases with strain rate [13-15]. Therefore, the relationship between grain-boundary sliding and total strain can be expressed follows:

$$\epsilon_{gb} = \gamma(\dot{\epsilon})\epsilon_T \tag{1}$$

where ϵ_{gb} is the strain due to grain-boundary sliding, ϵ_T is total strain and $\gamma(\dot{\epsilon})$ is the proportional constant decreasing with strain rate $\dot{\epsilon}$.

In the previous paper, the strain in the weld metal was measured by the MISO technique and the gauge length in the MISO technique was chosen from 0.9 ~ 1.7mm[1]. Generally, there are several grains in this gauge length as shown in **Fig. 9**. This means the strain measured by the MISO technique corresponds to ϵ_T in Eq. (1). Therefore, when solidification crack occurs, it is regarded ϵ_T in Eq. (1) has just become the critical strain required for crack initiation, ϵ_i. And ϵ_{gb} has just become the critical grain-boundary sliding, ϵ_{gbc}.

Therefore, just at the initiation of solidification crack, Eq. (1) is rewritten as follows:

$$\epsilon_{gbc} = \gamma(\dot{\epsilon})\epsilon_i \tag{2}$$

Namely, the critical strain, ϵ_i measured by the MISO technique is expressed as follows:

$$\epsilon_i = \epsilon_{gbc}/\gamma(\dot{\epsilon}) \tag{2'}$$

Equation (2)′ means that ϵ_i increases with an increase in $\dot{\epsilon}$, because $\gamma(\dot{\epsilon})$ decreases with the increase in $\dot{\epsilon}$.

Moreover, the reasons why the dependence of ϵ_i on strain rate increased with decreasing crack susceptibility and ϵ_i evaluated in high strain rate was more sensitive for the comparison of crack susceptibilities among materials

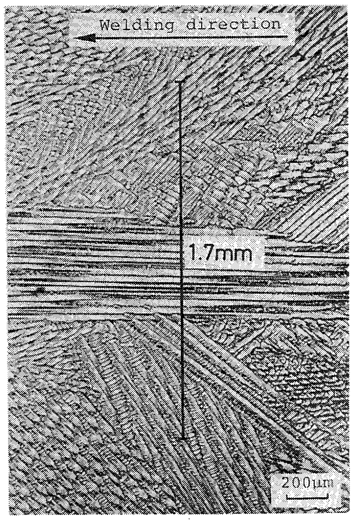


Fig. 9 Solidification structure in the center of weld bead (Inconel 600, 70A, 12V, 0.83mm/s).

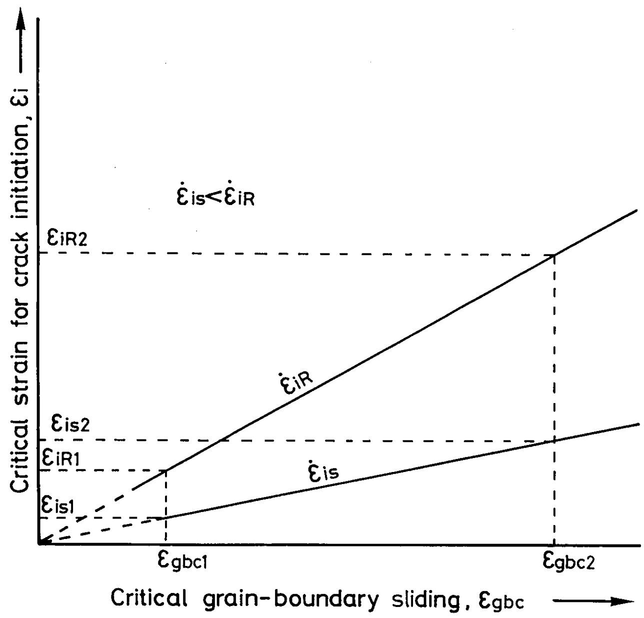


Fig. 10 Illustration of relation between critical grain-boundary sliding and critical strain.

than that in low strain rate can be explained as follows: The relationship between ϵ_{gbc} and ϵ_i is illustrated in **Fig. 10**, where a crack susceptible material having ϵ_{gbc1} and a crack insusceptible material having ϵ_{gbc2} are compared. Suppose that the two materials are tested with two strain rates, $\dot{\epsilon}_{iR}$ and $\dot{\epsilon}_{iS}$ (R: rapid, S: slow) to measure the critical strain ϵ_i by MISO technique. According to Eq. (2)′, the gradient of ϵ_i vs ϵ_{gbc} in $\dot{\epsilon}_{iR}$ is steeper than that in $\dot{\epsilon}_{iS}$. That is, the difference between ϵ_{iR2} and ϵ_{iS2} is bigger than that between ϵ_{iR1} and ϵ_{iS1}, meaning that the strain rate dependence of critical strain is noticeable in crack insusceptible material. Then, it is easily understood from Fig. 10 that the difference between ϵ_{iR2} and ϵ_{iR1} is bigger than that between ϵ_{iS2} and ϵ_{iS1}, meaning that the critical strain measured in a high strain rate is more sensitive for the comparison of crack susceptibilities among materials.

Therefore, all the strain-rate dependence of solidification cracking can be explained from the view point of the contribution of grain-boundary sliding to total strain of weld metal during welding.

4. Conclusion

Effect of grain-boundary sliding on strain-rate dependence of critical strain required for the initiation of weld solidification cracking was studied with the tensile hot cracking test, the Trans-Varestraint cracking test and the simulated hot ductility test for stainless steel and Inconel alloy. Main conclusions obtained are as follows:

(1) Under low strain rate condition, grain-boundary sliding occurs obviously within BTR. On the contrary, under high strain rate, it hardly accurs.

(2) The reasons why the critical strain increases with increasing the strain rate, the dependence of critical strain on strain rate increases with decreasing crack susceptibility, and the critical strain in high strain rate is more sensitive for the comparison of crack susceptibilities among materials than that in low strain rate can be explained from the view point of contribution of grain-boundary sliding to total strain of weld metal during welding.

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