Title	Quantitative Evaluation of Solidification Brittleness of Weld Metal during Solidification by In-situ Observation and Measurement (Report V) : Correlation between Critical Strain Rate and Critical Deformation Rate Required for Solidification Crack Initiation(Materials, Metallugy & Weldability)
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Quantitative Evaluation of Solidification Brittleness of Weld Metal during Solidification by In-situ Observation and Measurement(Report V)†

— Correlation between Critical Strain Rate and Critical Deformation Rate Required for Solidification Crack Initiation —

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Abstract

Behaviors of strain rate near solidification front and mean deformation rate of specimen have been investigated using tensile cracking test with Restraint-relaxation U-form hot cracking device combined direct observation technique MISO for stainless steels. The behavior of strain rate measured by MISO technique with lapse time after start of welding corresponded to that of mean deformation rate measured by strain gauge method. Critical deformation rate required for crack initiation was appropriate for comparison of the crack susceptibilities among materials as critical strain rate required for crack initiation.

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

1. Introduction

By utilizing the MISO techique[1], the authors showed in the previous paper[2] that the critical strain rate required for the initiation of weld solidification crack is an excellent parameter to compare crack susceptibilities among materials in welding fabrication. However, direct photographing of the cracking phenomenon and film analysis by the MISO technique requires much skill and time. Therefore, it is to be desired that the parameter which is as excellent as the critical strain rate is produced without utilizing the MISO technique. The solidification cracking test under low strain rate as the same order of critical strain rate have to be used to evaluate crack susceptibility.

Self-restraint cracking test is suitable for evaluation of crack susceptibility in welding fabrication. As well known, the Houldcroft hot cracking test is useful for the solidification cracking. The strain rate for crack initiation in the Houldcroft test measured by the MISO technique was as low as critical strain rate[2]. However, this test can not be changed deformation rate and does not have a good reappearance.

On the other hand, some of the authors invented a new hot cracking device, namely Restraint-relaxation U-form hot cracking device (U-form hot cracking device)[3]. This device has the capability to deform specimen and to measure deformation rate. It is considered that the tensile cracking test with U-form hot cracking device is suitable to evaluate solidification crack susceptibility.

Therefore, the authors have intended to measure the strain rate near solidification front by the MISO technique and the deformation rate of specimen by strain gauge method during welding in tensile cracking test with U-form hot cracking device, and to compare the behaviors of these. Moreover, it has been done to investigate whether the deformation rate required for crack initiation can evaluate crack susceptibility or not.

2. Materials Used and Experimental Methods

2.1 Materials used

Commercial stainless steels were used, and their

Table 1 Chemical compositions for material used

Material	Item	Chemical composition (wt%)							
		C	Si	Mn	P	S	Cr	Ni	Mo
Stainless steel	SUS310S(A)	0.068	0.81	1.17	0.017	<0.001	24.56	19.22	0.02
	SUS310S(B)	0.052	0.75	1.12	0.016	0.001	25.02	19.15	0.01
	SUS310S(C)	0.045	0.68	1.16	0.016	0.003	24.71	19.28	0.01

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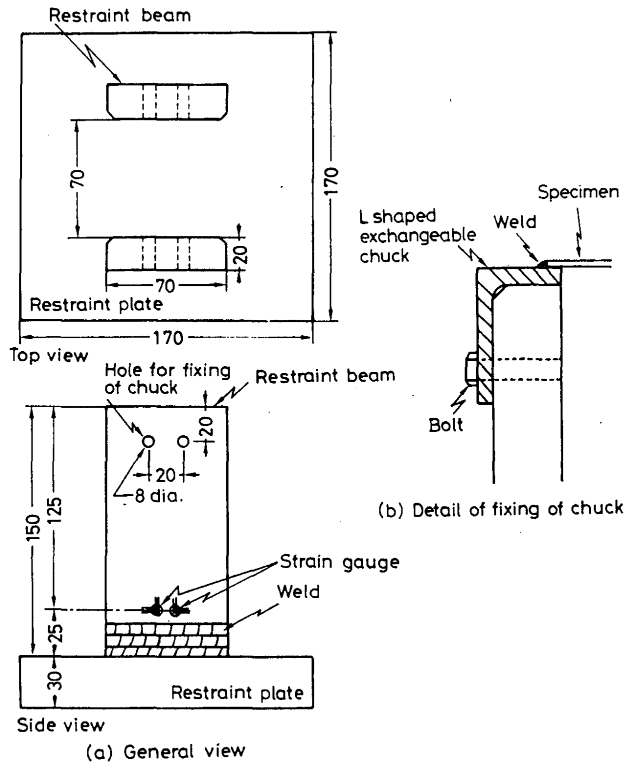


Fig. 1 Shape and size of U-form hot cracking device used.

chemical compositions are shown in **Table 1**. The thickness of all materials is 2mm.

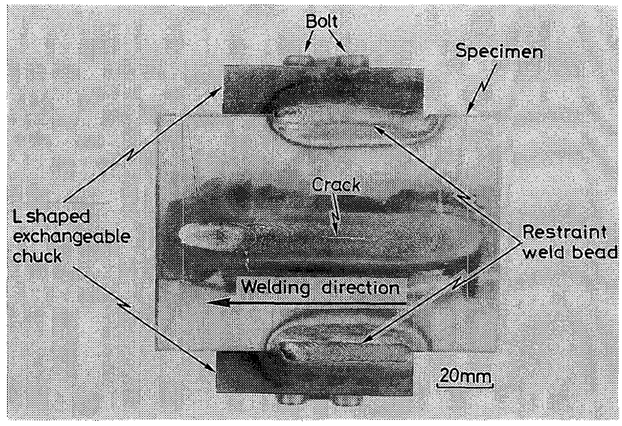
2.2 Tensile hot cracking test

As mentioned above, tensile hot cracking test with restraint-relaxation U-form hot cracking device (U-form hot cracking device) was used to measure the deformation rate for crack initiation and propagation.

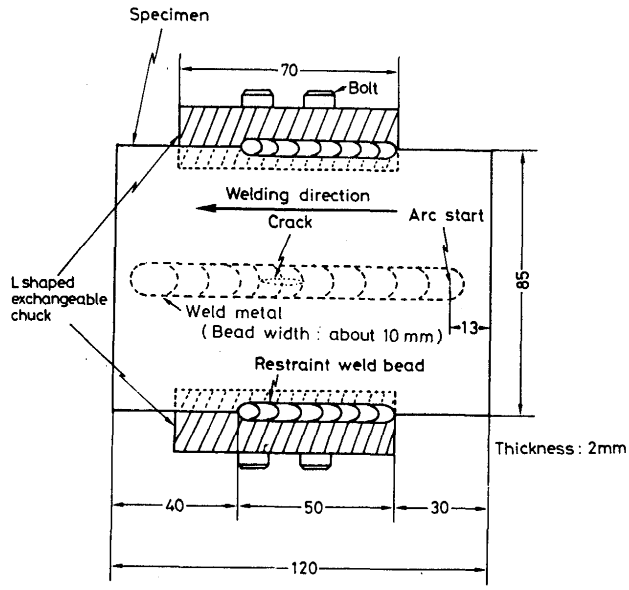
The shape and size of U-form hot cracking device used are shown in **Figure 1**. This device consists of one restraint plate and two restraint beams, and is made of 80kgf/mm^2 class high strength steel because of its high yield strain. Maximum load and maximum of initial deflection at the top of the beams are 20KN and 5mm, respectively. The specimen was welded to L-shaped steel fixed on the device by bolts and nuts as shown in Fig. 1 (b). Deflection of the beam was measured by strain gauges stuck near the root of the beam.

Configuration of specimen used is shown in **Figure 2**. At first, the two beams were deformed by compressive force with C-clamp, to produce initial deflection at the top of the beams. The welding for chucking specimen to L-shaped steel fixed on the device was done with GTAW (without filler metal) under conditions of 100A, 15V (DCEN) and 0.83mm/s.

After that, the force was unloaded. As a result, tensile force acted to the specimen. Then, test welding was done



(a) Setting specimen to L-shaped exchangeable chuck



(b) Shape and size of specimen

Fig .2 Configuration of specimen and its setting to L-shaped exchangeable chuck for tensile cracking test with U-form hot cracking device.

with GTAW(without filler metal) under conditions of 70A, 14V(DCEN) and 0.83mm/s.

Figure 3 shows the arragement of the MISO technique combined with the tensile hot cracking test using U-form hot cracking device. The behaviors of crack initiation and propagation were photographed by high speed cinecamera (about 50frames/s) through an optical microscope.

Strain and strain rate for crack intiation and propagation were measured by the MISO technique. Deformation rate was obtained from the gradient of time-deflection curve at optional time during the test welding. The maximum of deformation rate in this paper was slow, namely about 0.03mm/s. It was similar to crosshead speed of tensile hot cracking test used to measure the critical strain rate required for crack initiation[2].

Moreover, tensile hot cracking test as mentioned in the previous paper[2)] was also used to compare the strain rate for crack initiation measured by the U-form hot cracking device with the critical strain rate for crack initiation measured by this test. Details of experimental procedures were mentioned in the previous paper[2)].

3. Experimental Results and Discussions

3.1 Characteristics of solidification crack

Figure 4 shows appearance of solidification cracks of SUS310S(C) tested under various initial deflection(d_0). Crack does not occur with the $d_0 = 1.7$mm. All of cracks are initiated at the region of center of weld bead in restraint weld bead and are longitudinal crack. Crack length increases together with d_0, and then the tip of crack reaches the crater with $d_0 = 3.0$mm(Fig.4(d)).

Figure 5 shows the behaviors of deflection d during the test welding. The deflection decreases together with lapse time under d_0 of 1.7, 2.0 and 2.5mm. Moreover, after t = 95s, it increases slightly. And, with $d_0 = 3.0$mm, the deflection decreases till the finish of welding. These behaviors will be explained later. The time of crack initiation is between t = 60s and 70s. So the mean deformation rate $\dot{d}$ at t = 70s are shown in this figure. The value of $\dot{d}$ increases together with d_0. The change of $\dot{d}$ is sensitive to compare with that of d_0.

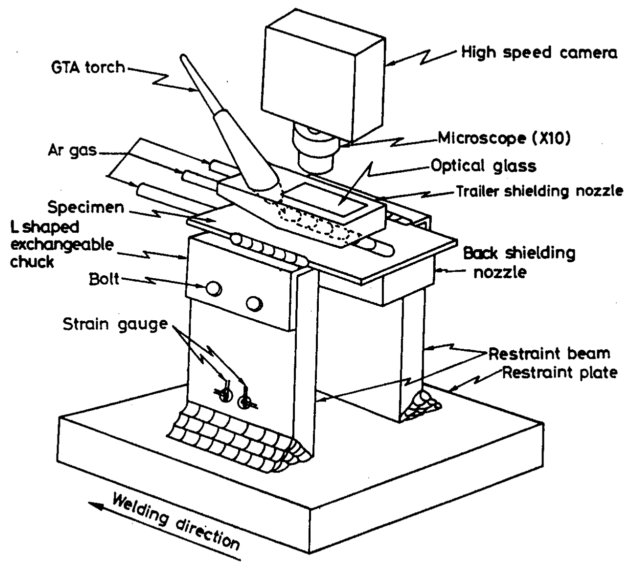


Fig .3 Shematic illustration of device for MISO technique utilizing tensile cracking test with U-form hot cracking device.

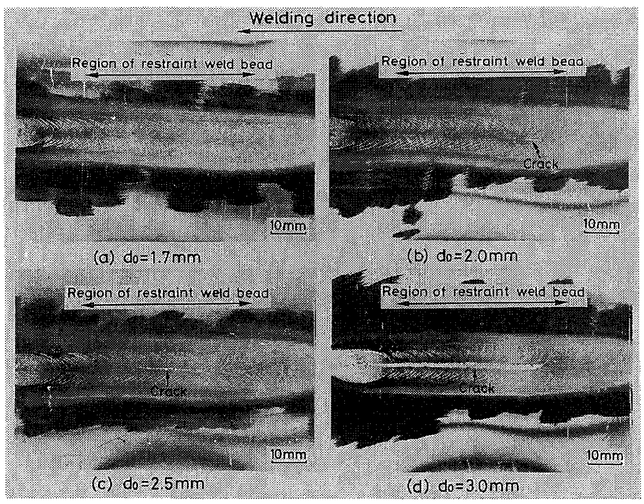


Fig .4 Appearance of cracks in tensile cracking test with U-form hot cracking device.

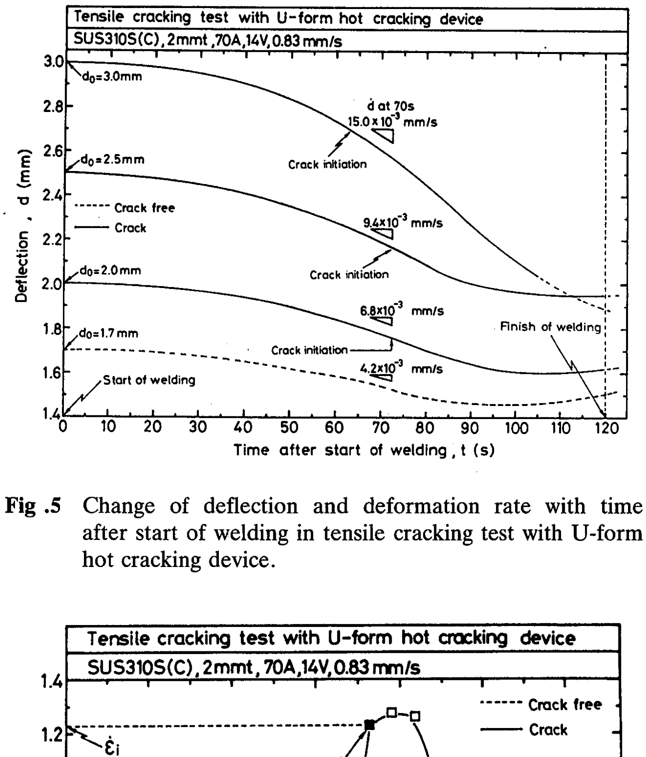


Fig .5 Change of deflection and deformation rate with time after start of welding in tensile cracking test with U-form hot cracking device.

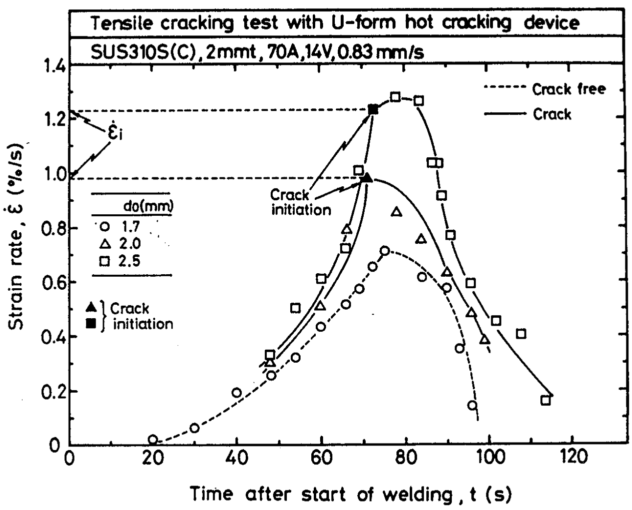


Fig .6 Relation between time after start of welding, t and strain rate, $\dot{\varepsilon}$ (d_0 = 1.7, 2.0, 2.5mm).

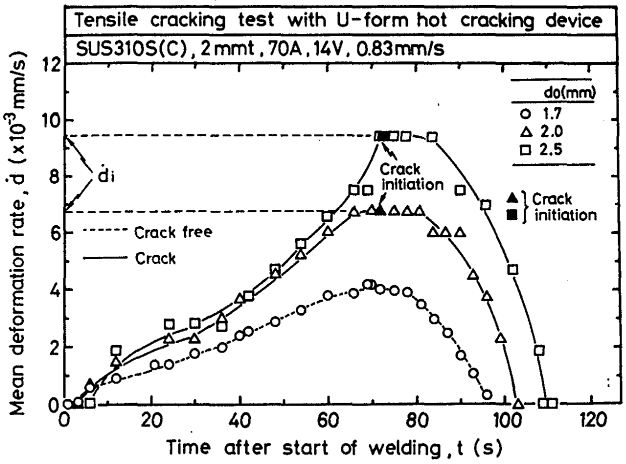


Fig .7 Relation between time after start of welding, t and mean deformation rate, $\dot{d}$ (d_0 = 1.7, 2.0, 2.5mm).

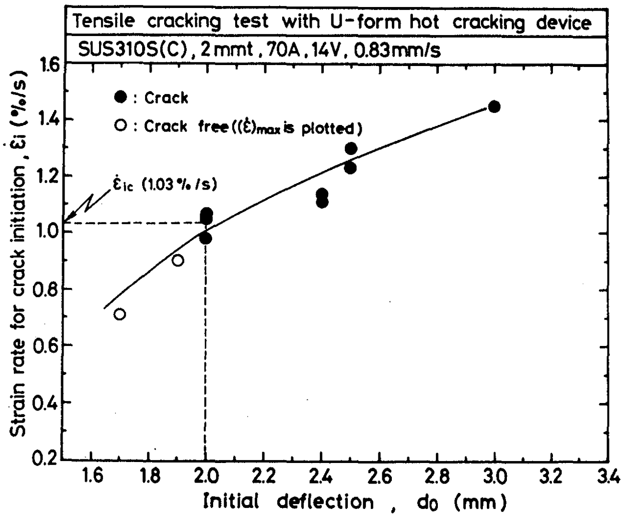


Fig .8 Relation between initial deflection, d_0 and strain rate for crack initiation, $\dot{\varepsilon}_i$.

3.2 Behaviors of strain rate measured by MISO technique and deformation rate measured by strain gauge mathod

Figure 6 shows the behavior of strain rate $\dot{\varepsilon}$ near solidification front during the test welding for SUS 310S(C). The strain rate $\dot{\varepsilon}$ increases together with lapse time, and it reaches nearly a maximum at the crack initiation. The strain rate for crack initiation is designated as $\dot{\varepsilon}_i$. In the case of crack free, it reaches a maximum at about t = 70s. After that, $\dot{\varepsilon}$ decreases together with lapse time. Moreover, value of $\dot{\varepsilon}$ increases together with d_0.

Figure 7 shows the behavior of mean deformation rate during the test welding for SUS310(c) under the same condition as Fig. 6. The mean deformation rate $\dot{d}$

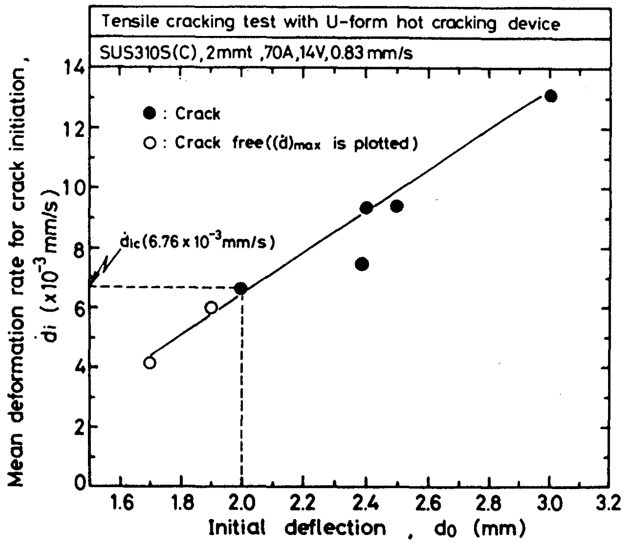


Fig .9 Relation between initial deflection, d_0 and mean deformation rate for crack initiation, $\dot{d}_i$.

increases together with lapse time, and it reaches a maxinum at the crack initiation. The mean deformation rate for crack initiation is designated as $\dot{d}_i$. In the case of crack free, it also reaches a maximum at about t = 70s. After that, $\dot{d}$ decreases together with lapse time. The value of $\dot{d}$ increases together with d_0. Therefore, it is concluded that the behavior of $\dot{\varepsilon}$ corresponds to that of $\dot{d}$.

The behaviors of $\dot{\varepsilon}$ and $\dot{d}$ can be explained as follows. At the start of welding, mean strength of specimen is reduced by welding. Since the tensile force due to return of deflected restraint beams has been larger than the mean strength of specimen, tensile displacement begins to increase. However, an increase in tensile displacement means a decrease in deflection as mentioned in the principle of this device[3]. So the tensile force gradually decreases, because the restraint condition of the specimen is gradually relaxed during the test welding.

However, $\dot{\varepsilon}$ and $\dot{d}$ increase till about t = 70s as shown in Fig. 6 and 7. That is, it is suggested that the reduction of mean strength of specimen exceeds that of tensile force till about 70s.

On the other hand, when the test welding is proceeded, $\dot{\varepsilon}$ and $\dot{d}$ will decrease due to recovery of strength of weld metal and HAZ at the behind of molten pool. It is shown in the behaviors of $\dot{\varepsilon}$ and $\dot{d}$ after about 70s. After that, if the force due to thermal shrinkage of specimen exceeds the tensile force, the values of $\dot{\varepsilon}$ and $\dot{d}$ will change negative quantity. It is shown in the curve of d after about 95s under d_0 = 1.7mm in Fig. 5.

3.3 Correlation between critical strain rate and critical deformation rate for crack initiation

As mentioned in the previous paper[2], it is worth

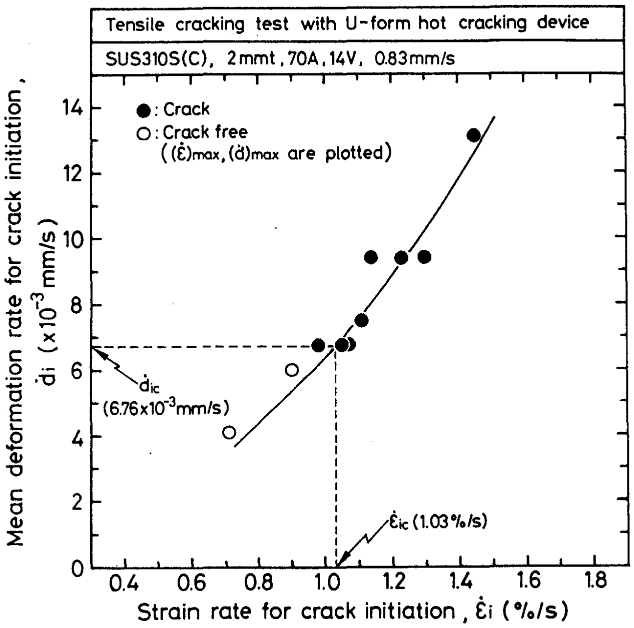


Fig .10 Relation between strain rate for crack initiation, $\dot{\varepsilon}_i$ and mean deformation rate for crack initiation, $\dot{d}_i$.

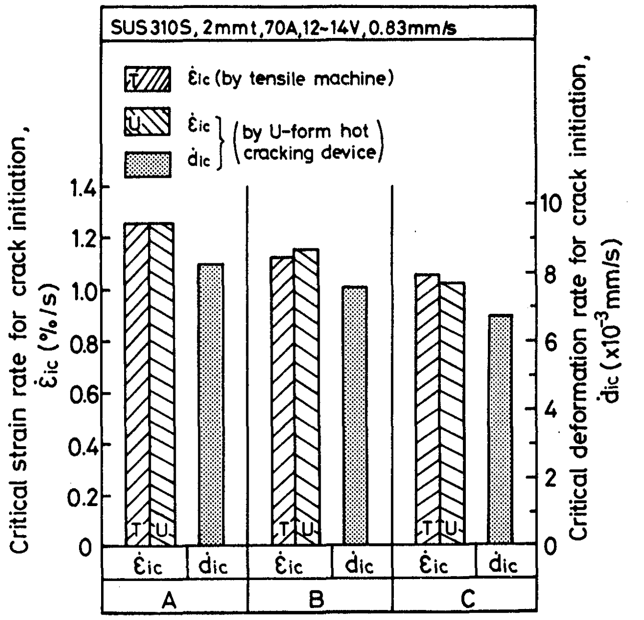


Fig. 11 Relation between critical strain rate for crack initiation, $\dot{\varepsilon}_{ic}$ and critical deformation rate for crack initiation, $\dot{d}_{ic}$.

noting that critical strain rate required for crack initiation $\dot{\varepsilon}_{ic}$ is sensitive to compare crack susceptibilities among materials under the low strain rate. The deformation rate at critical strain rate measured by the MISO technique has been designated as critical deformation rate. The authors have tried to investigate the relation between critical strain rate and critical deformation rate.

Figure 8 shows the relation between d_0 and strain rate for crack initiation $\dot{\varepsilon}_i$ for SUS310S(c). Open marks indicate maximum value of $\dot{\varepsilon}$ $((\dot{\varepsilon})_{max})$ under crack free. The value of $\dot{\varepsilon}_i$ increases together with d_0. An increase in d_0 also means an increase in $\dot{\varepsilon}$ during the test welding as shown in Fig. 6. That is, $\dot{\varepsilon}_i$ increases together $\dot{\varepsilon}$. This tendency corresponds closely to that mentioned in the previous paper[2].

Therefore, lower strain rate below which solidification crack can not occur, namely the strain rates for crack initiation under $d_0 = 2.0$mm correspond to critical strain rate required for crack initiation $\dot{\varepsilon}_{ic}$[2]. The average of these is 1.03%/s from this study and 1.06%/s from tensile hot cracking test. These two agree well.

Figure 9 shows the relation between d_0 and the mean deformation rate for crack initiation $\dot{d}_i$ for SUS310S(c) under the same condition as Fig. 8. Open marks indicate maximum value of $\dot{d}((\dot{d})_{max})$ under crack free. The value of $\dot{d}_i$ also increases together with d_0. This tendency corresponds to that shown in Fig. 8. The critical deformation rate, namely the average of $\dot{d}_i$ under $d_0 =$ 2.0mm, is 6.76mm/s. The relation between $\dot{\varepsilon}_i$ and $\dot{d}_i$ is shown in **Figure 10**. Open marks indicate $(\dot{\varepsilon})_{max}$ and $(\dot{d})_{max}$ as mentioned above. This has a good correlation.

Figure 11 compares $\dot{\varepsilon}_{ic}$ with $\dot{d}_{ic}$ among three materials. The marks of T and U indicate $\dot{\varepsilon}_{ic}$ measured by tensile hot cracking test and measured by U-form hot cracking device, respectively. These two agree well. The value of $\dot{\varepsilon}_{ic}$ decreases in alphabetical order. In other word, crack susceptibility increases in alphabetical order. The tendency of $\dot{d}_{ic}$ corresponds to that of $\dot{\varepsilon}_{ic}$.

Therefore, it is concluded that $\dot{d}_{ic}$ is as excellent as $\dot{\varepsilon}_{ic}$ and these are sensitive parameters for crack susceptibility among the materials. The value of $\dot{d}_{ic}$ can be easily measured as lower $\dot{d}_i$ below which crack can not occur.

4. Conclusion

Strain rate near solidification front was measured by the MISO technique and also mean deformation rate of specimen was measured by strain gauge method in tensile test with U-form hot cracking device. Correlation strain rate with mean deformation rate was studied.

Main conclusions obtained are as follows:

(1) The behavior of strain rate near solidification front corresponds to that of mean deformation rate of specimen.

(2) The strain rate and the mean deformation rate required for crack initiation increase together with the initial deflection.

(3) The lower strain rate required for crack initiation measured under the initial deflection below which the crack does not occur agree with critical strain rate required for crack initiation which is excellent parameter to compare crack susceptibilities among

materials.

(4) The critical deformation rate at the lower strain rate required for crack initiation mentioned (3) is as excellent as the critical strain rate to compare crack susceptibilities among materials.

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