Title	Weld Cold Cracking in HAZ of Engineering Carbon and Low Alloy Steel (Report II) : Applicability of Simulation Test for Cold Cracking of Quenching Crack Type(Materials, Metallurgy & Weldability)
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Weld Cold Cracking in HAZ of Engineering Carbon and Low Alloy Steel (Report II)†

– Applicability of Simulation Test for Cold Cracking of Quenching Crack Type –

Fukuhisa MATSUDA *, Hiroji NAKAGAWA ** and Hwa Soon PARK ***

Abstract

Thermal and mechanical testing conditions of simple simulation test to evaluate cold cracking susceptibility, which is done by notch tensile test during cooling of a simulated weld thermal cycle, are examined in order to obtain similar quenching crack behavior to that in the RRC test. The test is shown to be available to get the correlation between fracture temperature and fracture stress by applying thermal cycle similar to actual welding and tensile deformation from just above Ms temperature under different cross-head speeds corresponding to contraction rate in actual welding.

It is shown that the peak temperature for the simulation test should be set so as to liquate the grain-boundary in order to obtain nearly the same fracture stress as that in the RRC test. Moreover, it is shown that the grain-boundary liquation lowers the fracture stress and promotes the intergranular fracture.

KEY WORDS: (Low Alloy Steels) (Carbon Steels) (Tool Steels) (Cold Cracking) (Grain Boundaries) (Simulating)

1. Introduction

In the previous paper,[1] the fundamental behavior of cold cracking of the type of quenching crack was studied by means of the RRC test coupled with AE technique, and followed by metallurgical examination. Through this study, similarity and differentia of this type of cold cracking with hydrogen-induced cold cracking, intimate relation to liquated grain-boundary near fusion boundary and so on were revealed.

It is well known, however, that the RRC test is complex and troublesome in execution in spite of its high availability for such steels having low Ms point. From this viewpoint, a simple simulation test for cold cracking of quenching crack type is required to develop not only for purpose of analysis of cracking mechanism but also for the development of crack-insusceptible steel.

Therefore, in this study, a simulation test method was developed by means of notch tensile test during cooling of simulated weld thermal cycle and its applicability was investigated with regard to fracture temperature vs. fracture stress behavior, correspondence of fracture stress and microstructure comparing those in the RRC test.

2. Materials Used and Experimental Procedures

2.1 Materials used

Medium carbon Ni-Cr-Mo steel JIS SNCM439 and high carbon steel JIS SK5, which were the same materials as those used in the RRC test in the previous report,[1] were used. **Table 1** shows the chemical compositions of these steels.

Table 1 Chemical compositions of materials used.

Material	Chemical composition (wt.%)							
	C	Si	Mn	P	S	Ni	Cr	Mo
SNCM439	0.40	0.26	0.83	0.007	0.009	1.80	0.82	0.26
SK5	0.83	0.34	0.48	0.010	0.007	-	-	-

2.2 Experimental procedures

Simulation test for evaluation of quenching crack susceptibility which was developed in this investigation was done with notch tensile test method during cooling of simulated weld thermal cycle using a weld thermal simulator by means of high frequency induction heating. The thermal cycle and loading mode are shown in **Fig. 1** in relationship between temperature or displacement and time. The shape and size of the specimen is shown in **Fig. 2**. The thermal cycle shown in Fig. 1 was programmed so as to agree with that in the RRC test in the previous report[1] as accurately as possible. The conditions were; heating time to peak temperature was 12 sec, the peak temperature with its holding time of 6 sec was varied to establish the good correlation between the RRC test and the simulated test, and the cooling time from 1073 to 773K, that is, $\Delta t_{1073\text{-}773K}$ was fixed to 3.5 sec. The loading mode was applied by time-displacement control which was programmed so as to make the stress agreed with that

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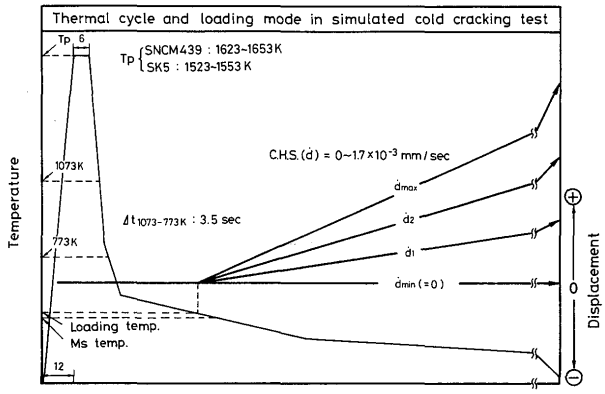


Fig. 1 Thermal cycle and loading mode in simulated cold cracking test.

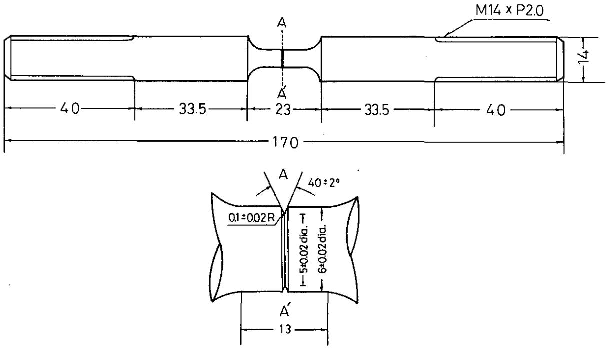


Fig. 2 Configuration of notch tensile test specimen in the simulated cold cracking test.

in the third step in the RRC test as acculately as possible. The loading mode, that is, at first the displacement was fixed to the origin from the start to the time when the temperature was cooled just above the Ms temperature, and then was increased under different cross-head speeds which are in the same order of contraction rate in actual welding under one-dimensional heat flow.[2)]

3. Experimental Results and Discussions

Figure 3 shows an example of the behavior of stress during the simulation test. At first, the stress gradually increased during the cooling from peak temperature with the contraction of specimen, then decreased noticeably due to martensitic transformation, and then increased again in the rate depending on the cross-head speed used and finally fractured at the time depending on the cross-head speed. This time can be easily converted to temperature. Therefore, it is thought that the behavior of the restraint stress in the RRC test was simulated well by the loading mode, hereafter this simulation test is called "Simulated Cold Cracking Test".

Figure 4 shows the relationship between fracture temperature and fracture stress in SNCM439. Peak temperature used were 1623, 1643 and 1653K. At the temperature above 1653K, the specimen was nearly fully melted. The result with the RRC test was also included for comparison in Fig. 4. At first, it is seen that the fracture stresses in 1623K are the highest as a whole. Well, it should be noted in the comparison of results in 1643 and 1653K that the temperature difference of 10K in such rapid heating cycle is out of control. It may be reasonable from the comparison of triangular and rectangular marks that the results obtained in 1643 and 1653K should be put in the same category. It is noticeable that some of these data designated by asterisk showed fairly lower fracture stress than those without asterisk. These microstructures, which were etched with aqueous solution of saturated picric acid including surface reagent, compared in **Fig. 5** mean that the grain-boundaries in the specimen

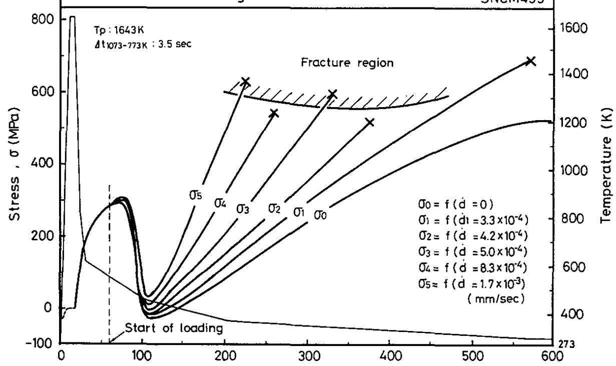


Fig. 3 An example of behavior of stress during simulated cold cracking test in SNCM439.

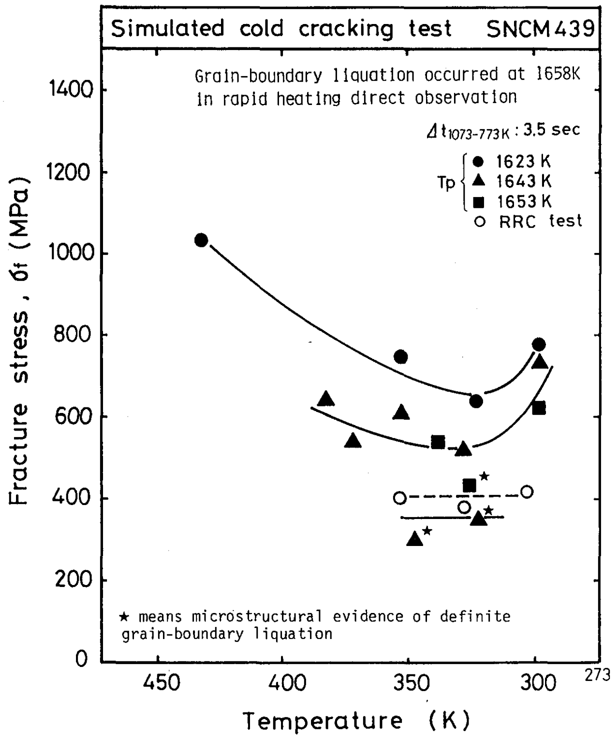
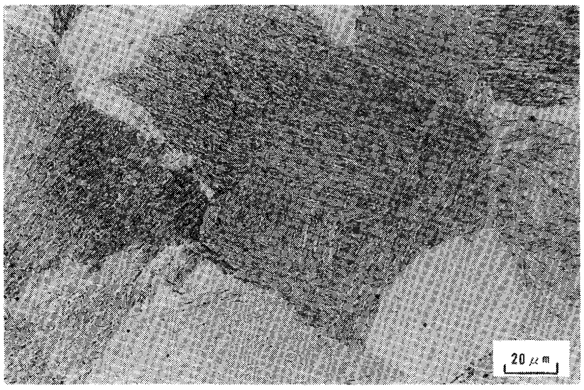
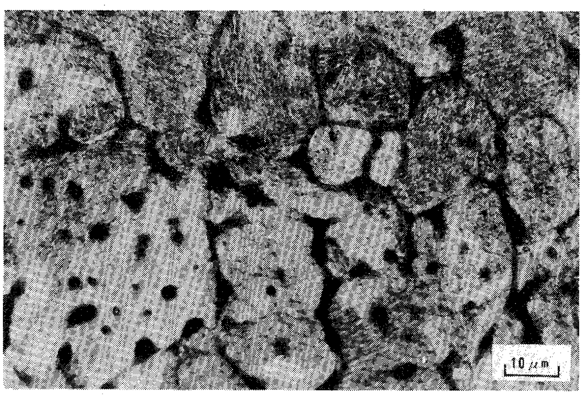


Fig. 4 Effect of peak temperature T_p and grain-boundary liquation on fracture stress vs. temperature in SNCM439.



(a) T_p; 1643K, meaning no definite grain-boundary liquation



(b) T_p; 1653K, meaning definite grain-boundary liquation

Fig. 5 Microstructure after the test in SNCM439 etched with aqueous solution of saturated picric acid including wetting agent.

with asterisk were liquated definitely, but without asterisk were not liquated definitely. By the way, the direct observation by means of hot stage microscope utilizing direct current method to get high heating rate of about 50 K/sec revealed that the liquation temperature of grain-boundaries was about 1658K.

Considering these microstructural features and comparing these data with those in the RRC test, it is concluded that the fracture stress is decreased with the peak temperature, especially by grain-boundary liquation, and that the fracture stress obtained under grain-boundary liquation nearly agrees with that in the RRC test, where the crack initiation site was associated with the liquated grain-boundary in HAZ near fusion boundary.

Besides, the temperature dependency of the fracture stress which is clearly seen in the specimens without liquation is interesting, especially in the point that the fracture stress is improved a little near room temperature. The reason of this behavior, however, is not understandable yet.

Figure 6 compares the fracture stress and the area fraction of intergranular fracture mode in relation to peak temperature in SNCM439, where the specimens fractured about 323K. Intergranularly fractured area tends to increase with the decrease in the fracture stress. Particularly, in the specimens with liquated grain-boundaries, intergranular fracture mode reached to about 80% with abrupt decrease in fracture stress. This suggests that intergranular fracture is promoted by impurity segregation to grain-boundary caused of the grain-boundary liquation.

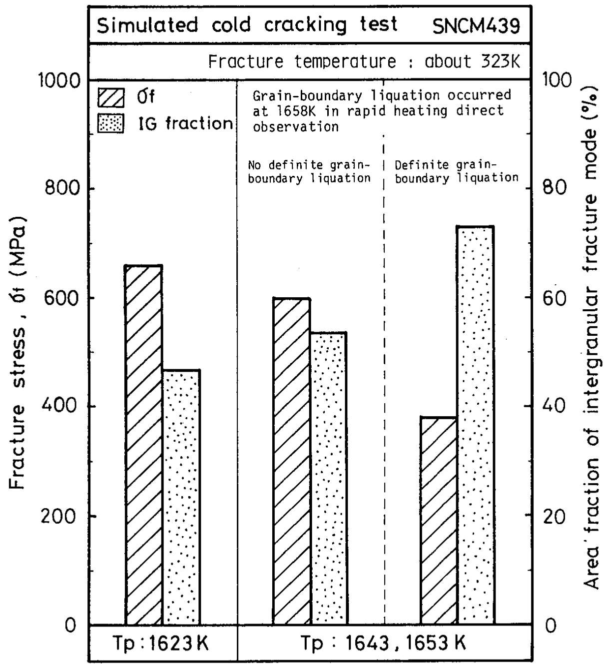
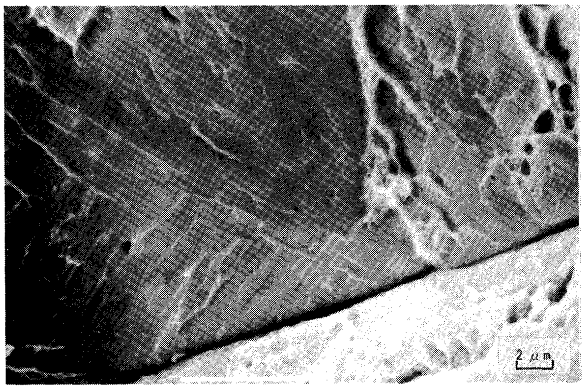


Fig. 6 Comparison of fracture stress and area fraction of intergranular fracture mode in relation to peak temperature among specimens fractured at about 323K in SNCM439.

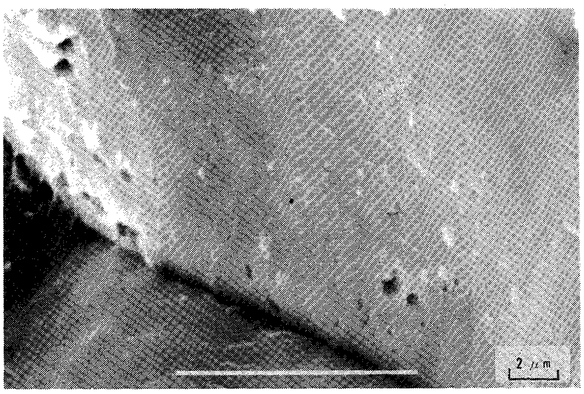
Figures 7 (a) and **(b)** show microfractographs of the intergranular facets with and without definite grain-boundary liquation, respectively. The traces of the plastic deformation, namely tear lines and dimples are less on intergranular facet with definite grain-boundary liquation than that without definite grain-boundary liquation. These behaviors are linked with those in Fig. 6. Moreover, it should be emphasized that the intergranular facets with definite grain-boundary liquation resemble that in the RRC test.

Figure 8 shows the relationship between fracture temperature and fracture stress in SK5. The peak temperature *Tp* used were 1523, 1538 and 1553K. Also in this case, fracture stress has a tendency to decrease with the increase in *Tp*. Moreover, the fracture stress with definite grain-boundary liquation designated by asterisk corresponds approximately to the crack initiation stress in the RRC test.

In general, simulated thermal cycle test by which CCT or impact test specimen are made, the peak temperature is set to 1623K readily which is far below the liquidus temperature in low carbon - low alloy steel. This study, however, has shown that only the peak temperature where grain-boundary liquation occurs gives the consistent re-



(a) T_p; 1643K, giving no definite grain-boundary liquation



(b) T_p; 1653K, giving definite grain-boundary liquation

Fig. 7 SEM microfractograph of intergranular fracture facet in SNCM439.

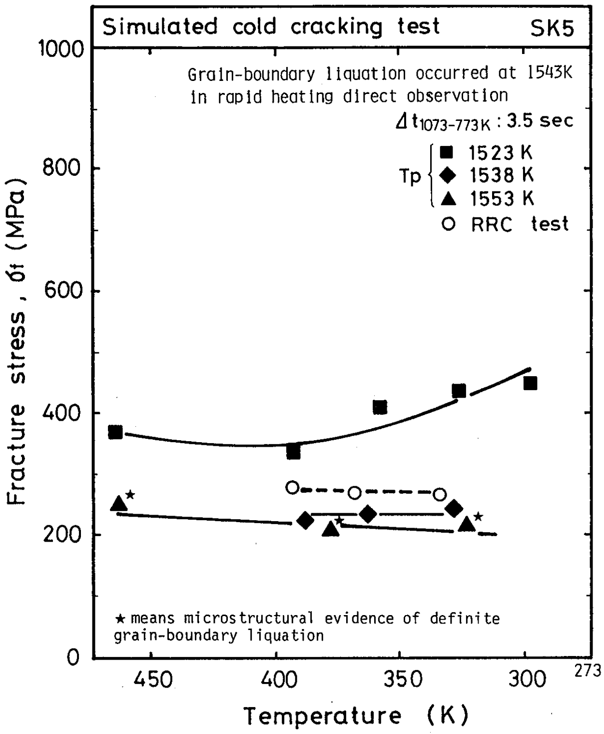


Fig. 8 Effect of peak temperature T_p and grain-boundary liquation on fracture stress vs. temperature in SK5.

sults with those in the RRC test. Although this reason is a future subject, the conditions of simulated cracking test has been well established to compare the crack susceptibilities among materials and to reveal the cracking mechanism in detail instead of the complex RRC test.

4. Conclusions

Main conclusions obtained are as follows:

(1) The thermal and mechanical conditions in simulated cold cracking test by which fracture stress vs. fracture temperature can be evaluated was established by means of notch tensile test using a weld thermal simulator.

(2) Fracture stress has a tendency to decrease with an increase in the peak temperature, and is especially low under the condition of grain-boundary liquation.

(3) The decrease in the fracture stress is accompanied with an increase in the area fraction of intergranular fracture surface. Moreover, intergranular facets in the specimen with definite grain-boundary liquation are more brittle, and are more similar to that in the RRC test than that without definite grain-boundary liquation.

(4) Fracture stress in the specimen with definite grain-boundary liquation agrees nearly well with the crack initiation stress in the RRC test. Therefore, crack susceptibility of these materials can be evaluated with the simulation test developed here by setting the peak temperature to the grain-boundary liquation temperature. This simulation test is called "Simulated Cold Cracking Test".

References

1) F. Matsuda et al.: Trans. JWRI, 15-2 (1986), 135–141.

2) K. Satoh et al.: J. Japan Weld. Soc., 34-3 (1966), 246–256 (in Japanese).