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Weldability of Fe-36%Ni Alloy (Report IV)†

– Dynamic Observation of Reheat Hot Cracking in Weld Metal by Means of Hot Stage Microscope –

Yue-Chang ZHANG*, Hiroji NAKAGAWA** and Fukuhisa MATSUDA***

Abstract

Deformation and cracking behavior of weld metal of Fe-36% Ni alloy Invar reheated in hot stage microscope is observed dynamically to reveal the behavior and mechanism of reheat hot cracking in weld metal of this alloy. It is shown that grain-boundary sliding and its resultant cavity formation and coalescence precede the occurrence of the reheat hot cracking. It is also suggested that grain-boundary migration improves the hot ductlity.

KEY WORDS: (Hot Cracking) (Controlled Expansion Alloys) (Containers) (GTA Welding)

1. Introduction

In the previous paper[1)], the dynamic behavior of reheat hot cracking in the weld metal of Fe-36%Ni alloy (Invar) during actual welding was analyzed by means of direct photographing (MISO)[2)] technique, and proper testing condition of simulated hot ductility test was established. The microstructural behavior of the cracking, however, has not been revealed, because the magnification of the microscope used in the MISO technique was not so high. This study was planned to analyze the microstructural behavior of the cracking during reheating by means of hot stage microscope.

As well known, intergranular fracture in elevated temperature generally occurs by the formation and coalescence of cavities at grain-boundaries. Although it has been said that cavities are formed by cohesion of vacancies or by grain-boundary sliding, it seems[3,4)] that some detailed experimental results support the mechanism of cavity formation by grain-boundary sliding. Nevertheless, there are some reports[5,6)] which showed no significant role of grain-boundary sliding in intermediate temperature embrittlement of copper alloy and commercially pure nickel, and thus suggested the mechanism of cavity formation by accumulation of dislocations to grain-boundary. Hitherto, there has been few studies concerning the detailed mechanism of weld hot cracking in any material. Therefore, the first objective of this study is to confirm whether grain-boundary sliding and/or cavity formation take part in the reheat hot cracking in weld metal of Invar.

2. Materials Used and Experimental Procedures

2.1 Materials used

The Fe-36%Ni alloy used has the chemical composition shown in **Table 1**, and has 3 mm in thickness. GTA welding was done without filler metal under the following conditions with Ar back shielding; welding current of 100 A (DCEN), arc voltage of 11 – 13 V and welding speed of 100 mm/min. Consequently, the bead width obtained was about 5 – 6 mm on top and back surfaces. After the welding, the specimen was machined to the configuration shown in **Fig. 1** for the observation in hot stage microscope.

Table 1 Chemical composition of material used.

C	Si	Mn	P	S	N	O	Al*	Ni
0.033	0.19	0.35	0.003	0.005	0.0035	0.0021	0.001	36.05

* soluble

2.2 Procedures of dynamic observation

The surface of the specimen was polished and etched a little electrolytically. Moreover, several straight scratches perpendicular to each other were made by a razor in order to observe grain-boundary sliding. The specimen was set

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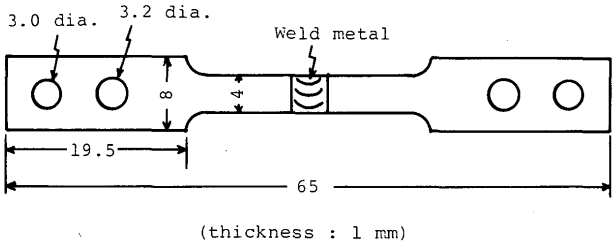


Fig. 1 Specimen configuration for hot stage microscope.

into the specimen chamber in the hot stage microscope used, and the chamber was evacuated up to less than 2×10^{-4} torr. Then, the specimen was heated by molybdenum heaters, which were set above and under the specimen, up to the testing temperature of 600, 700, 800, 850 and 880°C in the heating rate of about 0.2°C/sec. At the moment of heating to the testing temperature, constant load was applied by dead weight while the temperature was maintained constant. Now, the selection of the constant load was very important because of the following problems: (i) Too high level of the load or stress would cause very fast fracture, which would occur even during the increase in the load. (ii) Too low level of the load or stress would never cause cracking. (iii) Reheated hot ductility of the weld metal of Invar is affected by crosshead speed as shown in the previous paper[1]. Namely, higher the crosshead speed is, higher the hot ductility is. (iv) As well known, the ratio of grain-boundary sliding to total strain generally depends on stress level. Considering these four problems, the load was selected so that the average applied stress might be about 0.4 times of the maximum stress obtained at the same testing temperature under the crossheadspeed of 0.093 mm/sec in the previous paper[1]. Namely, the applied stress of 7.5, 6, 4, 3 and 2 kgf/mm^2 was loaded under the condition of testing temperature of 600, 700, 800, 850 and 880°C, respectively. Consequently, fracture occurred within about 300 sec in the specimen of peak temperature 800, 850 and 880°C. Only cracks but no fracture occurred within about 300 sec in the specimen of testing temperature 700°C. Even cracks did not occur within about 300 sec in the specimen of testing temperature 600°C.

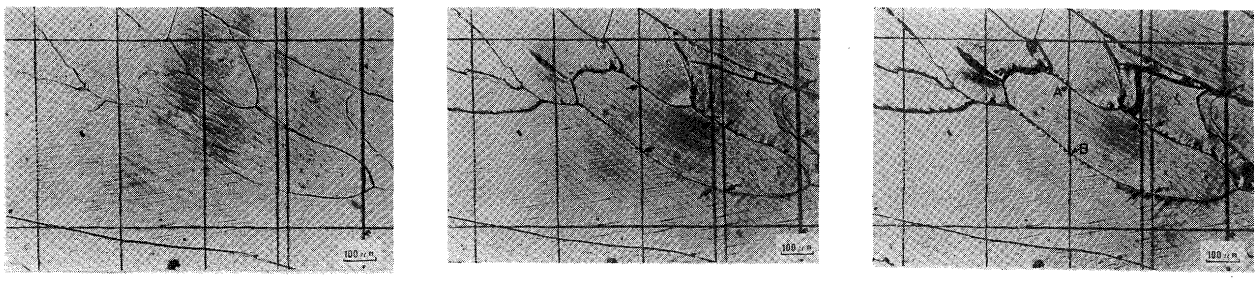
Dynamic microstructural change and cracking were observed and photographed in the magnification of × 100 and × 400. Because the specimen was etched only a little as already mentioned, grain-boundaries were not clear before heating. Above about 450°C, however, grain-boundaries became clear gradually due to thermal etching effect in spite of no injection of a little amount of oxygen. Subsequently, there was no problem to observe the behaviors of all grain-boundaries above 600°C.

Some specimens were fractured during the observation, but others were unloaded before the fracture. After cooling to the room temperature, detailed manner of grain-boundary sliding, grain-boundary migration, slip bands, cavity formation and so on was studied by Nomarski differential interference microscope and SEM.

3. Experimental Results and Discussions

3.1 Dynamic observation

As an example of the dynamic observation, **Fig. 2** shows the deformation behavior in the weld metal of the specimen tested at 850°C, where the rectangular straight lines are the scratches made to observe the grain-boundary sliding. The load was applied to the upper and the lower directions. Figure 2(a) gives the appearance just before the loading, and grain-boundaries are observed clearly together with solidification substructure. During the cooling after welding, almost all the grain-boundaries migrated a little from the original positions formed at the weld solidification. During heating before the loading, further progress of the grain-boundary migration was hardly observed. Just after the loading, grain-boundaries became clear and grain-boundary sliding started to occur at two or three grain-boundaries. Figure 2(b) gives the appearance at 6 sec after the loading, and grain-boundary sliding is shown by arrows. All the grain-boundaries in Fig. 2(b) is clear than those in Fig. 2(a), which means that strain was concentrated to the grain-boundaries. Also grain-boundary migration and folding due to the strain concentration within grain by grain-boundary sliding are



(a) just before loading (b) 6 sec after loading (c) 14 sec after loading

Fig. 2 Dynamic observation of deformation behavior prior to cracking at 850°C (arrows show grain-boundary sliding).

observed. At 14 sec after the loading, in Fig. 2(c), the grain-boundary sliding, the strain concentration to the grain-boundaries, the folding and the grain-boundary migration became noticeable. Also slip bands are observed partly. The detailed appearance arround marks A and B in Fig. 2(c) is magnified in **Fig. 3**. After such gradual progress of the grain-boundary sliding, cracks occurred.

Similar phenomena were observed in the specimen of testing temperature 880, 800 and 700°C, though the maximum distance of grain-boundary sliding had a tendency to decrease together with the drop of the testing temperature.

Dynamic observation for the specimen tested at 600°C is shown in **Fig. 4**. Many slip bands and strain concentration to grain-boundaries were observed well, and they developed a little together with the time lapse, but grain-boundary sliding was hardly observed. Consequently, no cracking was observed. Also grain-boundary migration was hardly observed.

Therefore, it is understood that the ductility trough relating the reheat hot cracking is connected closely with grain-boundary sliding.

3.2 Detailed study on deformation mode by differential interference microscope

After the dynamic observation, the deformation mode on the specimen surface was studied in detail by Nomarski differential interference microscope which is suitable for the observation of the surface relief caused by plastic deformation[7].

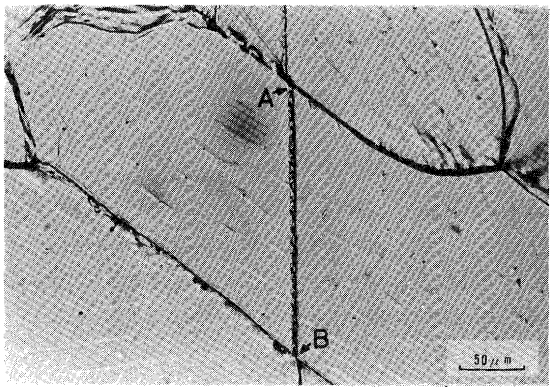


Fig. 3 Magnified view of A and B parts in Fig. 2 (c).

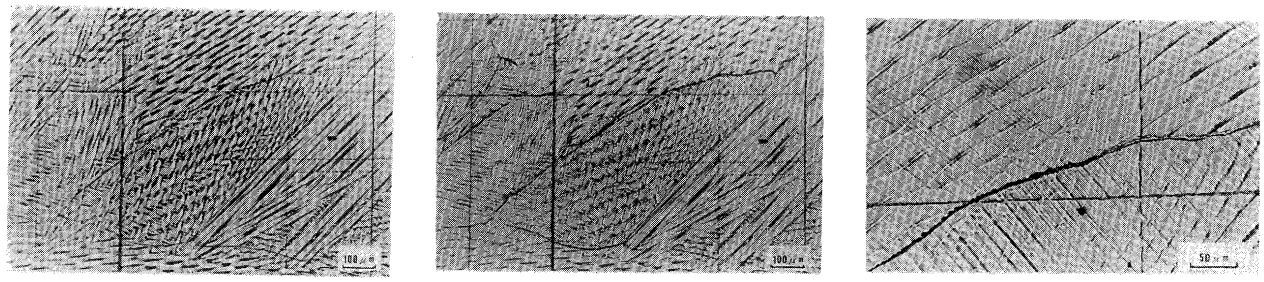
As well known, if grain-boundary sliding is related to hot ductility, the ratio of the displacement of grain-boundary sliding to total strain or strain within grains is very important. As already mentioned in 3.1, the grain-boundary sliding had a tendency to decrease together with the drop of the testing temperature. Conventional optical microscope, however, is not sensitive enough to distinguish the small difference in slip bands within grains. **Figures 5(a), (b)** and **(c)**, photographed by Nomarski differential interference microscope, show the clear difference of slip bands among the specimens tested 880, 700 and 600°C respectively. Thus it is well understood that the degree of slip bands, namely the strain within grains increased together with the drop of the testing temperature.

It seemed noticeable in this study that not only grain-boundary sliding but also grain-boundary migration were significant factors relating the ductility trough, although of course they have opposite effects. Namely, any crack was not observed at the grain-boundaries which were active in the grain-boundary migration. This can be explained by the fact that there was little grain-boundary sliding at such grain-boundary as shown in **Fig. 6**. The number of grain-boundaries which migrated during the loading increased together with the rise of the testing temperature, the tendency of which is nearly the same as that in the hot ductility test shown in the next paper[8]. Furthermore, the migrating distance was compartatively large in the specimens tested at 850 and 880°C.

3.3 Cavity formation accompanied by grain-boundary sliding

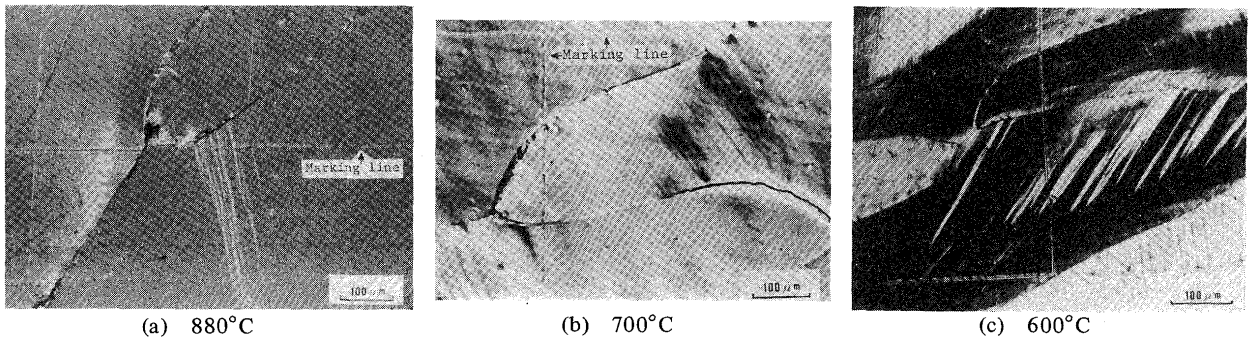
Although it is interesting whether the formation and the coalescence of cavities accompanied by the grain-boundary sliding are connected with this ductility trough, the magnification of hot stage microscope was not enough for this purpose. Therefore, the specimen surface and the fracture surface after the testing were studied by SEM.

Figure 7 shows examples of grain boundaries observed on the surface of specimen. In Fig. 7(a) cavities are formed at the grain-boundary where grain-boundary sliding occurred. In Fig. 7(b), however, neither grain-boundary sliding nor cavity is seen. In the specimen tested at 600°C, only small cavities were observed accompanied by very



(a) just before loading. (b) 20 sec after loading. (c) magnified view of upper parts in (b).

Fig. 4 Dynamic observation of deformation behavior at 600°C.



(a) 880°C (b) 700°C (c) 600°C

Fig. 5 Comparison of slip bands among different temperature, photographed by Nomarski differential interference microscope.

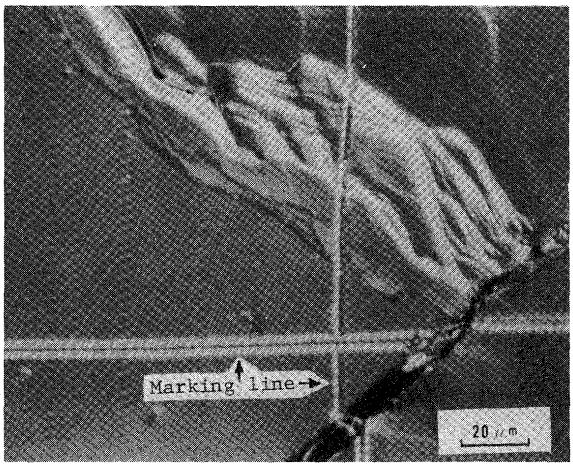
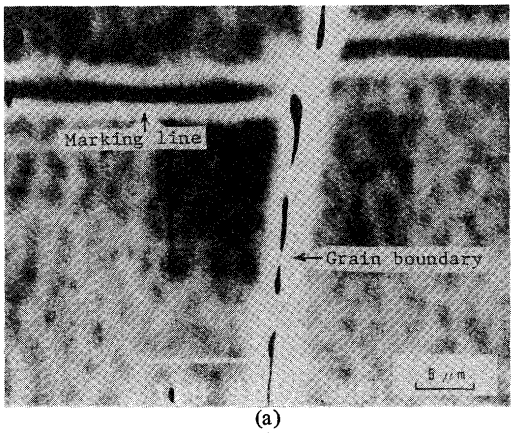
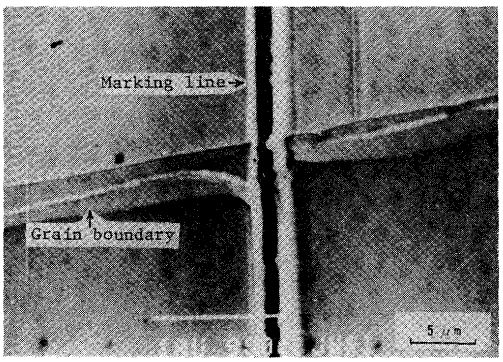


Fig. 6 Effect of grain-boundary migration on grain-boundary sliding.



(a)



(b)

Fig. 7 Correlation between grain-boundary sliding and cavity formation at grain-boundary.

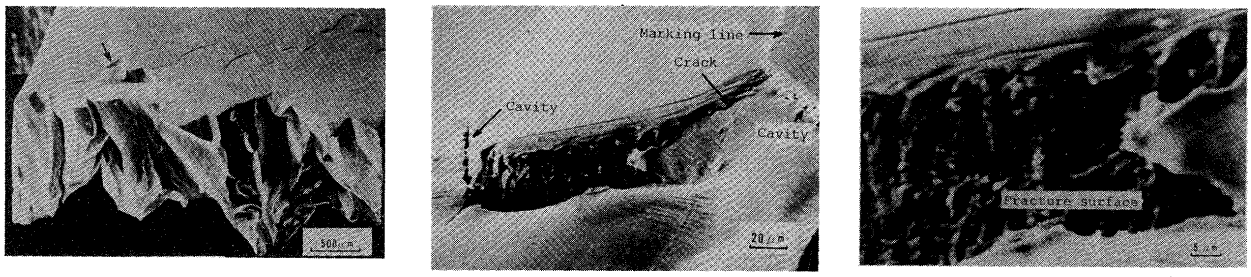
small displacement of grain-boundary sliding on very rare occasions. Then, the specimen tilted by about 45 degree was observed by SEM to study both the specimen surface and cracked or fractured surface simultaneously, and the examples are shown in **Fig. 8**. General view in (a) shows that many small steps corresponding to grain-boundary sliding were formed. Its arrow part is magnified in (b), and means that cavities were formed at low steps, and crack was formed at high step. The cracked surface in (b) is magnified in (c), and it is noticed that the unit size of uneveness on the wavy cracked surface was similar to the size of cavities shown in Fig. 7(a). This problem will be discussed in detail in the next paper[9].

The results in Figs. 7 and 8 confirm that the grain-boundary sliding and its resultant cavity formation and coalescence take part in the ductility trough. Therefore, it is supposed that the sliding displacement at the grain-boundary making cavities, S_{gbc}, reflects the characteristic of temperature dependency of the hot ductility. **Table 2** shows the results measured, and means that S_{gbc} had the minimum value at 800°C. The minimum ductility of the same material evaluated by the hot ductility test in the previous paper[1] occurred at about 800–900°C. Both agree nearly with each other, but the difference is considered to be due to very slow strain rate in this study, judging the dependency of Zener-Hollomon parameter[10] on strain rate.

4. Conclusions

Main conclusions obtained are as follows:

1) Dynamic observation by means of hot stage microscope revealed that the grain-boundary sliding precedes the occurrence of the reheat hot cracking.
2) By the aid of SEM observation after the dynamic observation, it was shown that the cracking is connected with not only the grain-boundary sliding but also its resultant cavity formation and coalescence.
3) It was suggested that grain-boundary migration has a possibility to improve the hot ductility.



(a) low magnification. (b) magnified view of arrow part in (a). (c) magnified view of cracked surface in (b).

Fig. 8 Correlation between grain-boundary sliding or step, cavities and microcrack.

Table 2 Critical displacement of grain-boundary sliding S_{gbc} necessary for cavity formation.

Testing temperature (°C)	S_{gbc}
700	1.5-3.6
800	0.4-1.7
850	1.1-1.9
880	1.2-3.0

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