BII-6

FRACTURE IN THE PROCESS OF STRESS-RELAXATION UNDER CONSTANT STRAIN

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Abstract

The initiation and development of cracking during stress-relief heat treatment were studied.

It was observed that grain-boundary sliding took place leading into microcracking at a three-grain-boundary junction, which propagated along one of the three grain-boundaries preceded by intra-granular slip.

On account of precipitation of small carbides at slip band in the grain during the stress-relaxation, the grain is strengthened more than grain-boundary whereby the intra-granular slip is suppressed until the inter-granular sliding is preferred. As a result of the grain-boundary sliding, the stress is concentrated at the three-grain-boundary junction to such a level that exceeds the fracture strength thereof.

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1. Introduction

When thick plates of high tensile steels of tensile strength 80 kg/mm^2 and over, for example No. 4 steel in Table 1 are stress-relieved after welding, cracks have often been found in the weld heat affected zone (1).

Photo. 1 illustrates a long crack which formed in an 80 kg/mm^2 high tensile steel plate of 35 mm thickness. Actually the crack was initiated and developed along the boundaries of coarser grains of heat affected zone, as shown in Photo. 1, and finally this large crack was formed. This type of cracking is called the stress-relief cracking, because the cracking took place when the welded plate was reheated for stress-relief.

When the welded plate is tempered, the residual stress is relaxed. In the case of usual steel, the heat treatment for stress-relief has a good effect on the performance of welding. However, in the case of treatment is done carefully.

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The conditions which are necessary for the occurrence of this type of crack are reviewed with special reference to the following points.

i. The base metal must be such that it is liable to crack.
ii. Some kind of heat cycles must take place in the plate.
iii. The plate must contain some stress raisers.

Since this type of cracking that occurs in the process of stress-relaxation in a steel structure is actually constant strain type rather than constant stress type, this characteristic sequence was simulated by a constant strain device in the laboratory.

2. Observation of Initiation and Development of Cracking

Fig. 1 shows the specimens that were used for direct observation of initiation and development of the stress-relief cracking. Various high tensile steels of more than 80 kg/mm^2 were heat-treated to go through a heat cycle that simulated the actual welding process (peak temperature = 1350°C, cooling rate = 18°C/Sec). Then cylinder specimens were prepared from those steels as shown in Fig. 1. The specimens were opened at one end, while a notch was cut at the opposite end, then, they were closed to give certain pre-strain, and welded to complete the cylinder. The specimen was then mounted on a high temperature microscope, and heated to the stress-relief temperature in vacuo (10^{-5} mmHg).

Fig. 3 shows the range where the stress-relief cracking takes place, i.e. in the region that is defined by cross signs. For example, when the tempering temperature is 500°C, cracking does not occur until about half-an-hour; on the other hand, the crack appears almost immediately if tepered at 600°C.

Photo. 2 shows the time sequence of crack formation and development. The crack initiates near the notch root and develops along grain boundaries. As the temperature is raised, grain-boundary sliding takes place (Photo. 3), and microcracking occurs at a three-grain-boundary junction (Photos. 4 and 5). Here, it is seen that the crack is formed at the three-grain-boundary junction, and propagates along one of the grain-boundaries, preceded by intra-granular slip at the crack-tip (Photo. 6).

It was observed that this sequence outlined above is characteristic when a crack develops into an extensive intercrystalline cracking. That is to say, according to the observation, the grain-boundary sliding takes place first. The microcracking is induced at a three-grain-boundary junction, which develops into an extensive intercrystalline cracking.

3. Mechanism for Crack Formation

Fig. 4 shows the basic mechanism of the microcracking. Here, in order for the grain-boundary sliding to take place the following conditions must be satisfied: the flow stress of grain-boundary per se should be smaller than the residual stress, and it should also be smaller than the flow stress of grain proper.

Once the grain-boundary sliding starts, stress concentration occurs at the three-grain-boundary junction, and along one of those three grain-boundaries, the cracking takes place when the concentrated stress becomes higher than the cohesive strength of the boundary. In this case, the stress concentration at the grain-boundary junction must not be relieved before it is raised to the level for the crack to occur on the grain-boundary.

For the wedge type cracks that were observed, the formation of the crack may be prevented by vacancy diffusion as hown in Fig. 4. The creep rate in the grain can be related to the vacancy diffusion in such a way as shown by the Nabarro's equation (2). It is seen that the initiation of the cracking is easier in larger grains.

$$\dot{\varepsilon} = A \frac{\sigma D}{d^2}$$

where $\dot{\varepsilon}$: Diffusion creep rate

σ : Internal stress

D : Self diffusion coefficient

d : Mean grain diameter

From the results obtained, it was concluded that the crack initiation is the easier the lower the intercrystalline strength than the strength of grain proper, or the larger relative difference, and the larger the grains.

The intercrystalline strength is decreased by the presence of precipitates of the kind that have small surface free energy, such as low melting point compounds. On the other hand, the solution strengthening, strain hardening, precipitation hardening and the development of cell structure are the factors that increase the flow stress of the grain proper at the temperatures of stress-relief.

In the case of a commercial 80 kg/mm^2 steel which was found to be liable to stress-relief cracking, it was necessary for the crack to occur that the grain-growth should take place and alloying elements should be dissolved in super-saturation due to welding heat cycle before the heat-treatment for stress-relief (3). The alloying elements precipitate again in 450 to 700°C range on heating for stress-relaxation, and precipitation hardening takes place (4).

Photo. 7 shows the micro-structures of the 80 kg/mm^2 steel which was heat treated in simulation of the welding heat cycle and tempered in 400 to 700°C for 2 hours, where it is seen that fine particles are precipitated at slip bands in the grain and the stress-relief cracking takes place, at about 600°C. These precipitates were analyzed by electron difraction, and found to be mainly of M_2C type carbide.

It was thought that these precipitates contribute to the strength of the grain. In the case of over aged structure, this type of cracking did not take place.

4. Effect of Alloying Elements

The effects of alloying elements on the tendency for this type of cracking of high tensile steels were examined. It was found that the following relation (5) describes whether the material is susceptible to stress-relief cracking.

$$\Delta G = [Cr] + 3.3\,[Mo] + 8.1\,[V] - 2$$

$$G > 0 \quad \text{Cracked}$$

$$G < 0 \quad \text{Not cracked}$$

here, (Cr), (Mo) and (V) are the concentrations of these elements, in weight %, and ΔG is the stress relief cracking susceptibility such that when ΔG is larger than zero the material is liable to stress relief cracking, and when the ΔG is smaller than zero, it is safe against this type of cracking.

5. Discussion of Results

Now, macroscopically speaking, the main contribution factors to the formation of stress-relief cracking are the fracture strength, the temperature and the time of heat treatment for stress-relief. In order to determine the correlation between these factors, the stress-relaxation tests, the high-temperature tension tests and creep rupture tests, were carried out at various temperatures (6).

Some specimens were as-received namely quench-and-tempered state, and others were so heat-treated as to simulate the actual welding. The results obtained at 600°C are shown in Fig. 5. The fracture stress of the notched and heat-treated specimen drops to a level that is lower than the residual stress in about an hour of time.

In Fig. 6, the stress-temperature-time diagram for the cracking tendency of heat-affected and notched material is shown. The rupture stress which is presented by solid line becomes lower than the internal stress as indicated by the dotted line in the temperature range of about 450 - 700°C when heated for more than about 1 hr.

It can be shown that this diagram, which was deduced from macroscopic observations, is in an excellent agreement with microscopic findings made on small specimens. Therefore, it is believed that the stress-relief cracking behavior of a large plate of high tensile strength steel can be understood by the microscopic crack formation mechanism.

6. Summary and Conclusions

The mechanism and condition for initiation and development of stress-relief cracking were examined for 80 kg/mm^2 class high tensile strength steels. It was found:

(i) the crack occurs at a three-grain-boundary junction, and propagates along one of the grain-boundaries;

(ii) the precipitation of carbide at slip band that takes place during the stress-relief annealing is thought to be directly responsible to the formation of the crack in that the carbide precipitates elevates the strength of the grain proper over that of grain boundary;

(iii) the crack initiation is the easier the lower the intercrystalline strength as compared to the strength of grain proper, or the greater the relative difference, and the larger the grains;

(iv) the proapagating crack is always preceded by intragranular slip as its tip;

(v) the stress-relief susceptibility of a steel can be descrived by

$$\Delta G = [Cr] + 3.3\,[Mo] + 8.1\,[V] - 2$$

such that when ΔG is positive the steel is susceptible; and

(vi) the macroscopic behavior is in a good agreement with and underwritten by the microscopic observations.

Acknowledgement

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Table 1-1 Chemical compositions and mechanical properties of steels used

Steel	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Ti	B	Al	T.S. kg/mm^2	Y.P. kg/mm^2	E. %	Thickness mm
No. 1	0.16	0.23	0.82	0.009	0.009	0.24	1.45	0.75	0.53	0.07		0.004	0.081	102	98	19	25
No. 2	0.15	0.19	0.87	0.017	0.011	0.25	0.89	0.53	0.50	0.05		0.004	0.03	97	92	31	18
No. 3	0.16	0.23	0.88	0.016	0.013	0.24	0.89	0.52	0.50	0.06		0.003	0.03	92	86	22	42
No. 4	0.15	0.23	0.80	0.008	0.008	0.31	0.88	0.53	0.61	0.082	0.006	0.005	0.034	83	77	24	35
No. 5	0.13	0.35	0.83	0.014	0.007	0.25	0.80	0.62	0.48	0.03	0.007	0.005	0.072	82	77	15	25
No. 6	0.14	0.30	0.89	0.011	0.007	0.26	tr	0.95	0.37	tr		0.002		88	83	21	25
No. 7	0.18	0.23	0.31	0.01	0.008	0.13	2.99	1.47	0.46	tr	tr	tr	0.025	75	63	28	38
No. 8	0.11	0.42	1.00	0.016	0.018	(0.15)	0.84	0.47	0.31	tr	tr	tr		72	63	44	35
No. 9	0.15	0.26	1.02	0.013	0.012	0.13	0.60	0.10	0.37	0.08	tr	tr	0.032	63	48	30	100
No.10	0.09	0.30	0.72	0.010	0.009		3.47							53	38	34	12
No.11	0.13	0.16	0.53	0.017	0.010			0.96	0.56					52	32	38	20

Table 1-2 Chemical compositions of weld metal

Electrode	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Al
A	0.058	0.32	1.66	0.013	0.006	0.084	2.53	0.15	0.43	0.038
B	0.058	0.32	1.66	0.013	0.006	0.029	1.90	0.25	0.46	0.030
C	0.06	0.43	0.88	0.015	0.011	-	-	-	-	-

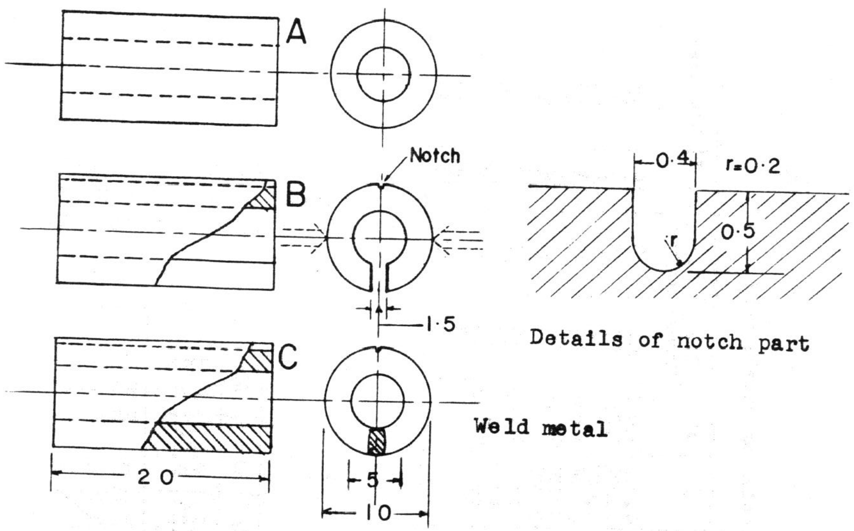
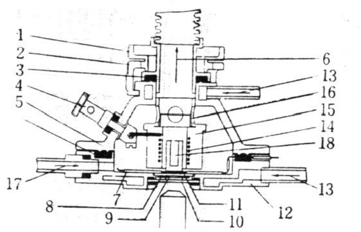


Fig. 1 Preparation and details of cylinder type restraint SR cracking test specimen, closed gap by pressing sides and fixed by welding.



1) Pressure screw
2) Cap
3) Gasket
4) Furnace terminal
5) Base of upper portion
6) Vacuum connection (Seamless lead pipe)
7) Thermocouple
8) Metal diaphragm
9) Quartz shutter
10) Quartz window
11) Quartz specimen table
12) Base of lower portion
13) Water input
14) Tungsten coil
15) Furnace unit
16) Heat stop plate
17) Argon input
 a) Prevention of vaporization use input nozzle.
 b) Gas etching use input nozzle
18) Specimen
19) Screws for fastening heating stage to microscope stage
20) Nuts for separating upper and lower portion
21) Shutter handle
22) Pyrometer terminal

Fig. 2 Method to observe by high- temperature microscope

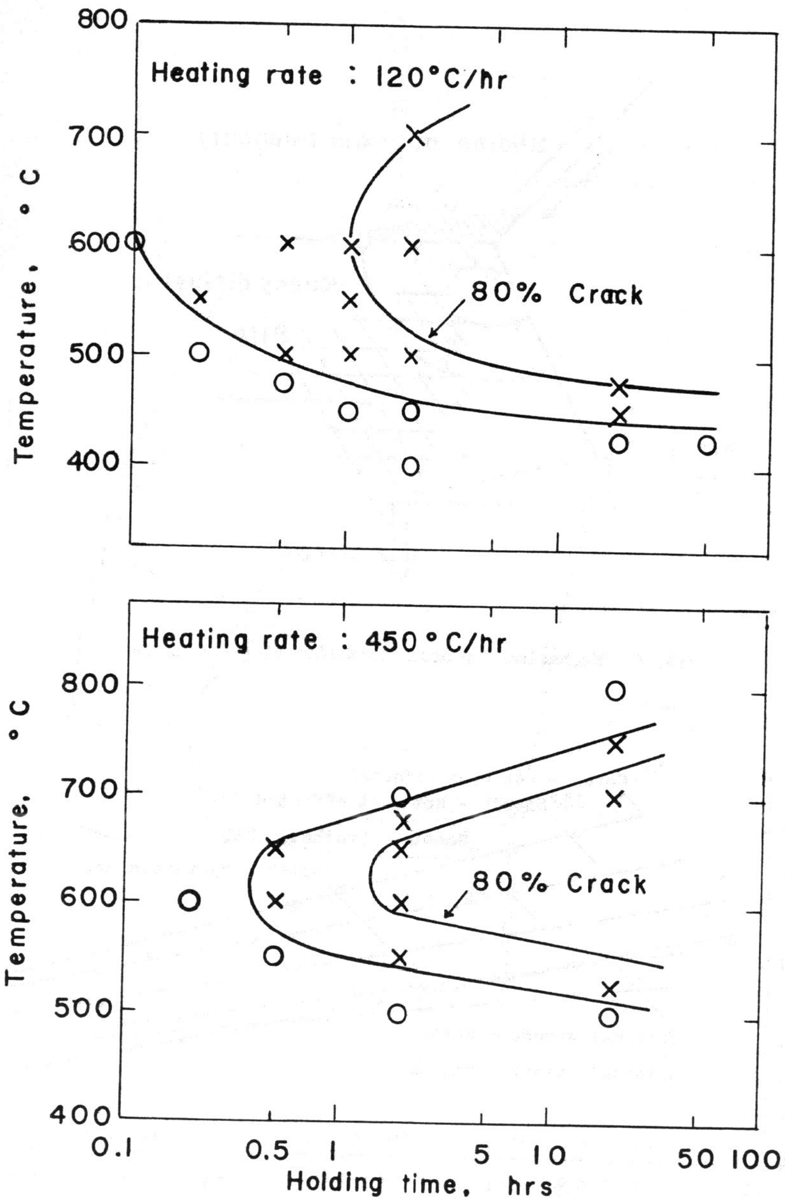


Fig. 3 Relation between cracking and stress-relief heat treatment

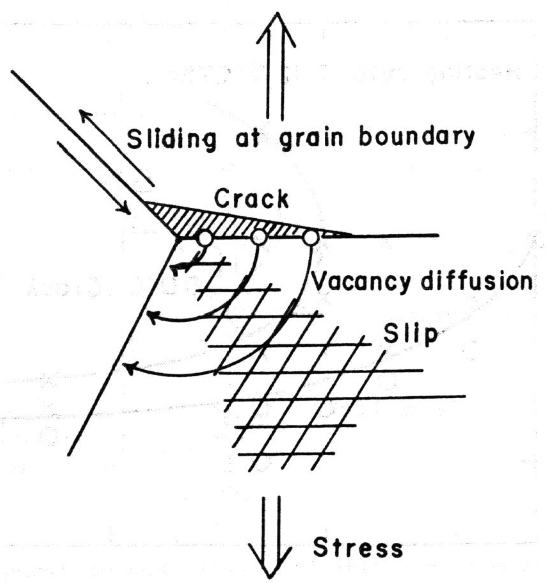


Fig. 4 Mechanism for crack formation at grain corner

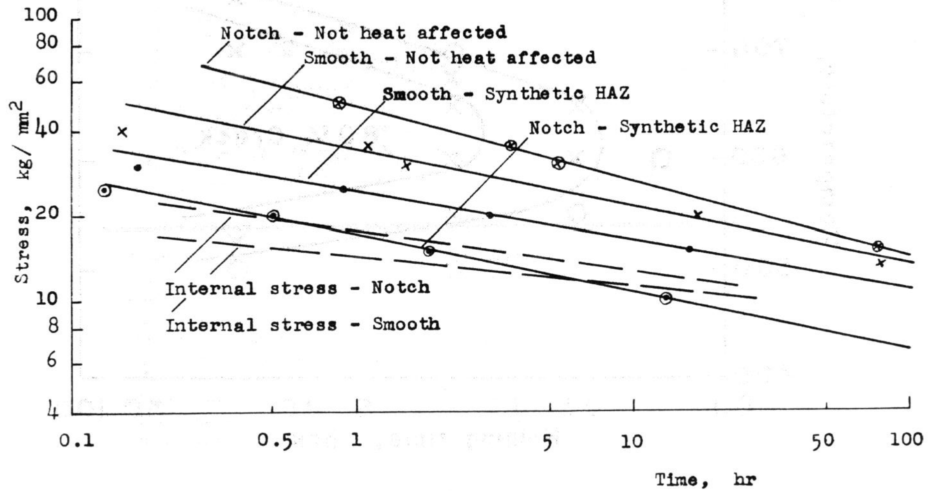


Fig. 5 Rupture - and relaxation - test results at 600°C

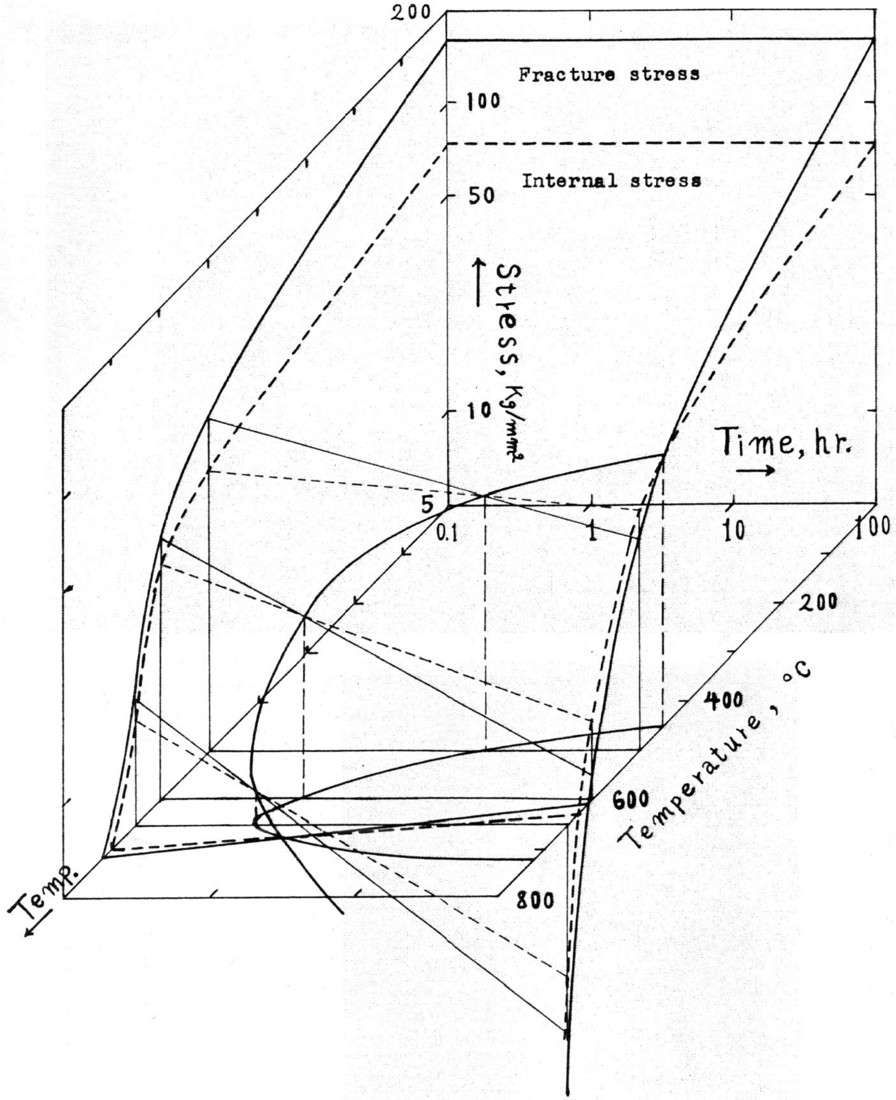
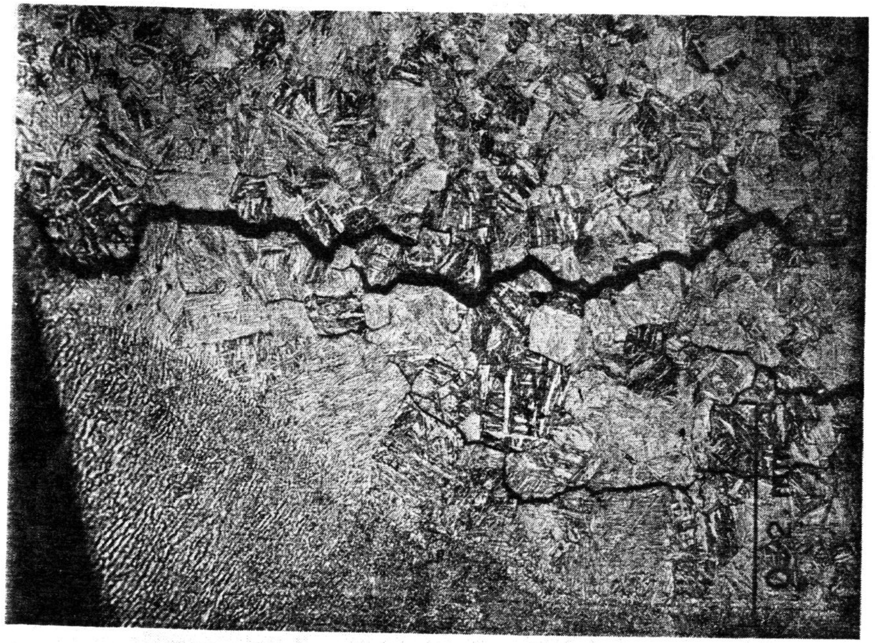
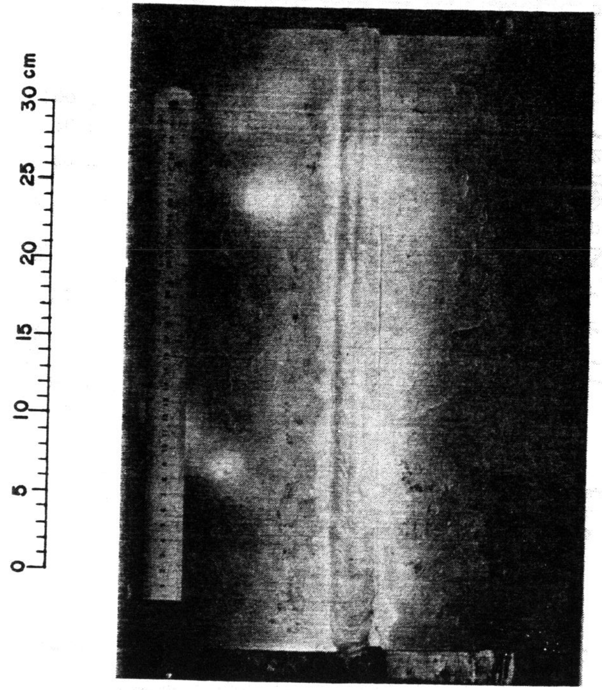


Fig. 6 Stress-temperature-time diagram for heat affected-notched bar, showing effect of temperature and time on internal and rupture stress.



(b)



(a)

Photo. 1 Restraint butt joint in HT80 steel, stress-relieved at 600°C for 2 hr., showing cracks along heat affected zone.

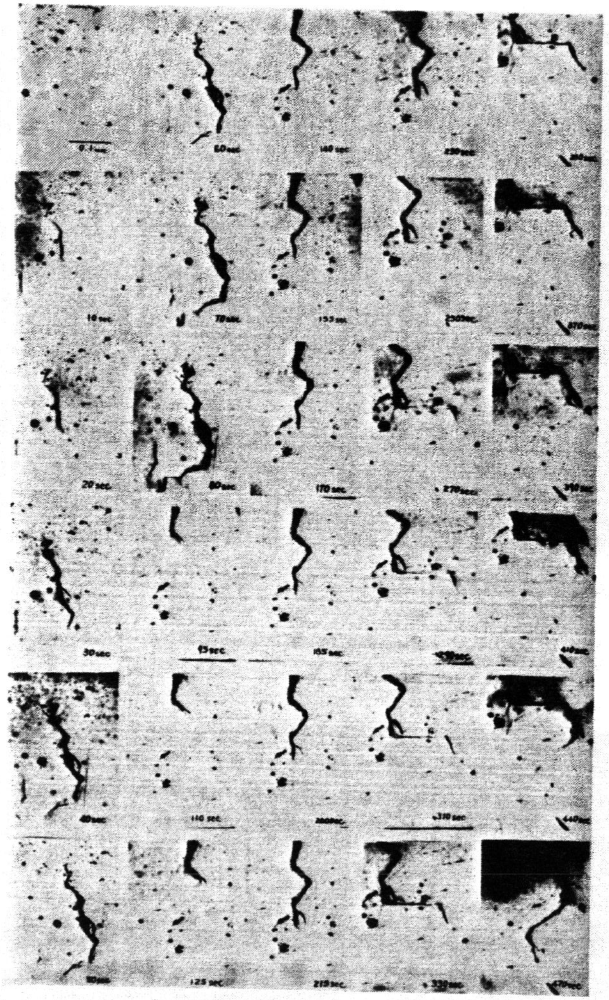


Photo. 2 Propagation of cracks in cylinder type restraint SR cracking test specimen.

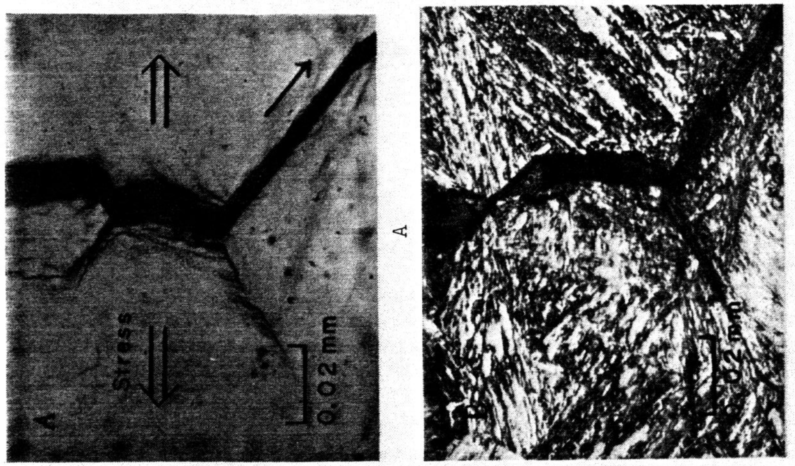


Photo. 4 Intergranular crack formation due to sliding
A : no etching, B : after etching

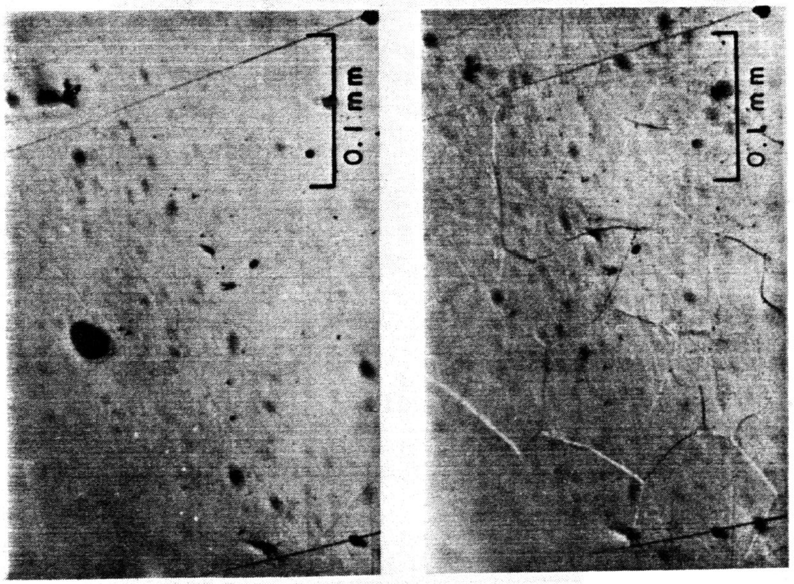


Photo. 3 Grain-boundary sliding prior to cracking

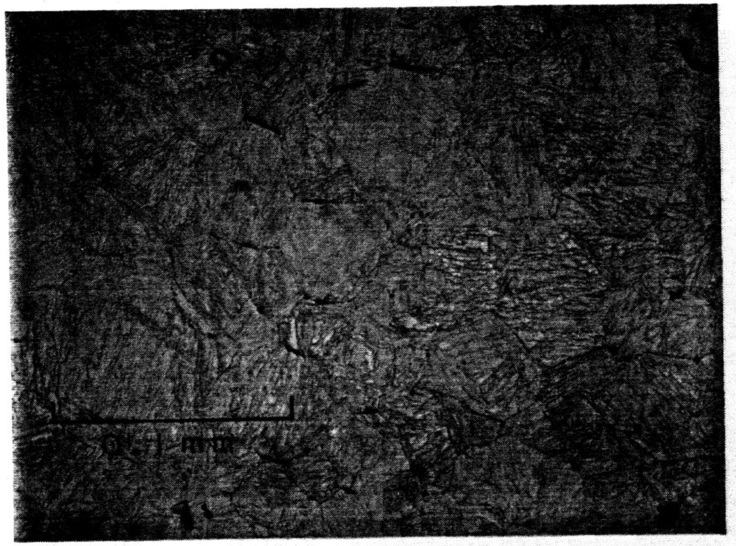


Photo. 5 Intergranular microcracks

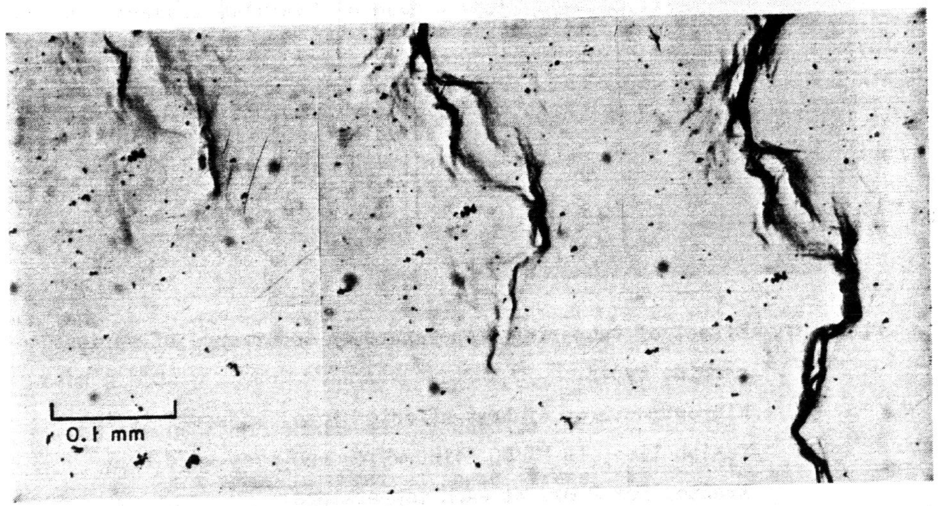


Photo. 6 Propagation of cracks with slip

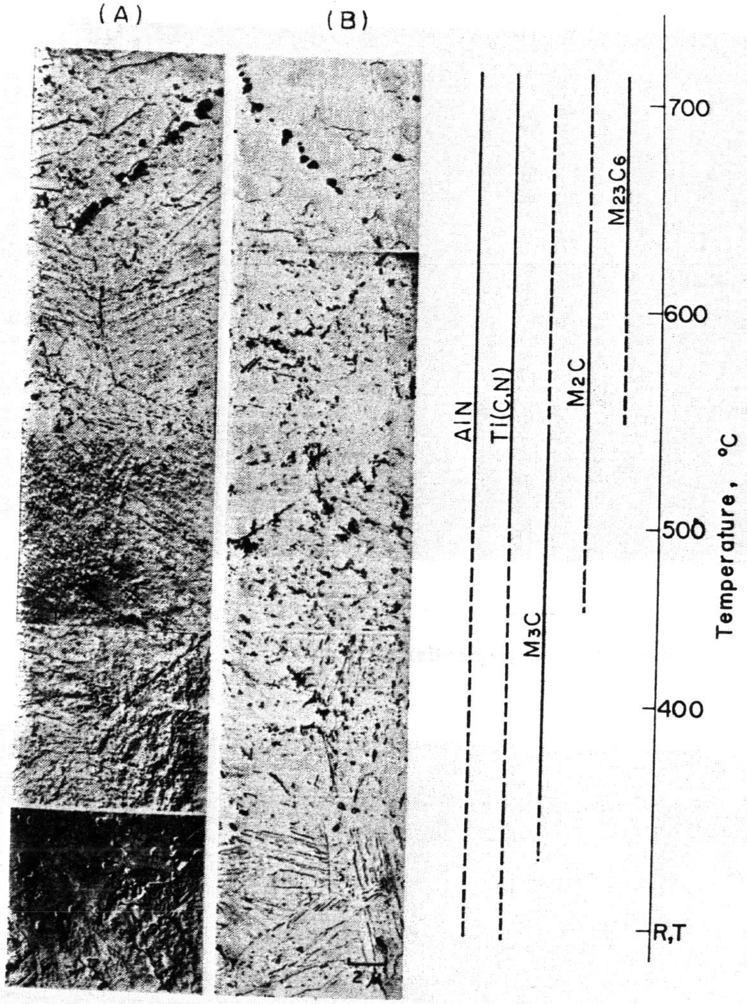


Photo. 7 Effect of tempering temperature on occurrence of various carbide types.

(A) : Microstructures of heat-affected zone, adjacent to the fusion line, in HT 80 joint which was post-weld heat treated for 2 hr. at each temperature.

(B) : Microstructures of HT 80 steel synthetic thermally cycled and tempered for 2 Hr. at each temperature.