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Weld Cracking Behavior of 100kg/mm² High Strength Steel By Large Size Restraint Testing Machine*

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Abstract

Various kinds of weld cracking testing methods such as Tekken type and Lehigh type have been developed to study weld cracking phonomena and mechanism and many useful investigations are conducted. The testing methods, however, have a weak point in the difficulty to obtain the restraint condition in quantitatively. To eliminate such weakness, the restraint cracking testing methods such as RRC and TRC tests have been developed. Even these testing methods have the following limitations: (a) it is difficult to reproduce the restraint force for a wide range as encountered in actual structures, (b) small sized cracking tests are liable to have some size effect on the test results.

For the purpose to remove the above mentioned weak points, the authors have developed a testing machine of 2,000 tons capacity for the use of cracking test of a wide and heavy section plate.

Using this machine, the authors conducted one pass and multi pass weld cracking tests of high strength steel of 100 kg/mm² in tensile strength and investigated the effect of the preheat temperature and restraint force on weld crack and the correlation between small size cracking test and large size cracking test.

1. Introduction

Weld cracking tests have been mostly conducted by use of restraint test specimens such as the Tekken type and the Lehigh type and there have been many useful studies on the behavior of weld cracking. But it is comparatively difficult to measure quantitatively the restraint force at the time of occurrence of weld cracks. To solve this weakness, two of the auhtors[1] have developed a Rigid Restraint Cracking Test (RRC test) by which the change of the restraint force during the cooling stage can be measured directly. Dr. Suzuki and his members[2] have developed a Tensile Restraint Cracking Test (TRC test), and they made clear the effect of the restraint force on weld cracking. However, it is rather difficult to reproduce the restraint force of such a wide range as would be induced in actual structures because the capacities of testing machines used hitherto for these tests are not sufficient. Besides, it should be considered that there are differences between weld cracking behaviors in small restraint test and those in actual structures; i.e. size effect.

To reproduce a restraint condition close to that of actual structures, the authors have developed a weld cracking testing machine with a capacity of 2000 tons, by which wide and hevay plates can be tested.

Using this testing machine, the authors performed mostly one pass weld cracking tests of high strength steel of 100 kg/mm² in tensile strength and for comparison sake, multiple pass welds cracking tests and investigated the effects of restraint force and preheating temperature on weld cracking, and the correlation between the weld cracking behavior of large size cracking test and that of small size cracking test.

2. Large Size Restraint Cracking Testing Machine

There are many available data on the mechanism of weld cracking of high strength steel. These are mostly obtained from small size restraint test specimens. However, when the preheating temperature and welding condition determined on the basis of small size restraint test specimens are applied to actual structures, weld cracking behaviors which are not observed in small size test specimens, sometimes occur due to the differences of restraint condition, cooling process, specimen size and so on. Therefore, the authors have developed a large size testing machine to investigate the relation between weld cracking behavior of large size test and that of small size test, and to obtain more practical data on welding conditions suitable for actual structures. This testing machine should be designed to satisfy the following requirements:

1) The capacity of this testing machine is required to be about 2,000 tons in order to examine the weld cracking behavior of a wide plate of heavy section (up to at least 1,000 mm in width and 30 mm in section), and the space between both chuck holders is desirably wide enough to test the structural model of small type.
2) The displacement control for RRC test and the load control for TRC test should be automatically conducted.
3) In consideration of the characteristics of weld cracking test, the specimen should be set in flat position.
4) In addition, it is preferable to use the testing machine also for the brittle fracture test and the fatigue test.

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5) This testing machine is designed for the cracking test using the data-recorder memorizing the distortion of actual welding and the fatigue test programmatic control.

In consideration of above-mentioned requirements, the testing machine was finally specified as follows:

Capacity : tensile load ....2,000 tons
compressive load ....200 tons
Ram stroke : 300 mm (max.)
Loading system: servo valve control by oil pressure
Control system : constant displacement control (RRC test)
constant load control (TRC test)
Dimensions of specimen: width 2,000 mm (max.)
length 3,000 mm (max.)
Ram speed : 30 mm/min (max.)
Cyclic speed : 0.6∼6 cpm

a) The Testing Machine

This machine has two cylinders each of which is capable of up to 1,000 tons and adopts the servo-control system for loading. It is flat type of 8,000 mm in overall length and of 90 tons in weight as shown in **Photo. 1**. The whole machine is placed in the pit of 1,200 mm in depth. This machine has the following components:

One ends of two cylinders are set together with the chuck holder of fixed side, and the other ends are connected with the other movable chuck holder on the rails through two pistons. Test specimen is inserted between both chucks, and a tensile or a compressive load is given on it. The restraint load which is imposed the test specimen is detected by biaxial wire strain gauge on the piston rods. The attached equipment are as follows:

Pump : Pumping volume 50 l/min.
Pressure 210 kg/cm^2
Motor : 22 KW, 220 v, 60 Hz.
Capacity of oil tank : 500 l.

b) Control of Testing Machine

Fig. 1 shows a schematic diagram of control system of this machine. For example, in case of the load-constant control (TRC test), the potentiometer is set up before testing, and a tensile load is electrically given by the signal through the control amplifier.

The output signal detected by means of load cell is given to the measuring amplifier as feed back through the control amplifier, and the tensile load is controlled. If a differential transformer is used instead of load cell, a test of the constant displacement control (RRC test) can be conducted. The detectable capacity of the differential transformer for the displacement is from min. 0.01 mm to max. 4 mm.

3. Experimental Procedures

3–1. *Test Plate and Weld Material*

Test plate is a high strength steel of 100 kg/mm^2 in tensile strength treated by special heat treatment (40 mm thickness). The chemical composition and the mechanical properties of this plate are shown in **Table 1**. Test electrodes corresponding to this test plate are used in this experiment. The chemical composition, the mechanical properties and the hydrogen content of the all-weld-metal are shown in **Table 2**.

3–2. *Shapes of Test Specimens*

The authors adopted a large size specimen for 2,000 tons RRC test, a small size specimen for 100 tons TRC test and a y-groove restraint weld cracking test specimen. The shapes and the dimensions of these test specimens are shown in **Fig. 2**. Regarding the test specimens of the large size RRC test and the small

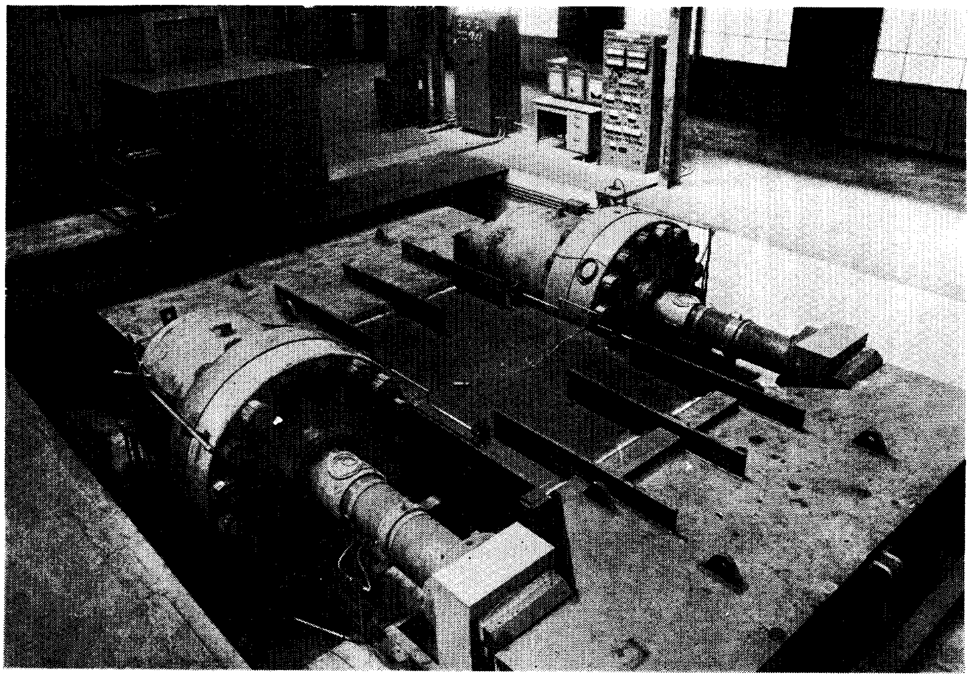


Photo. 1 2,000 ton trestraint cracking testing machine

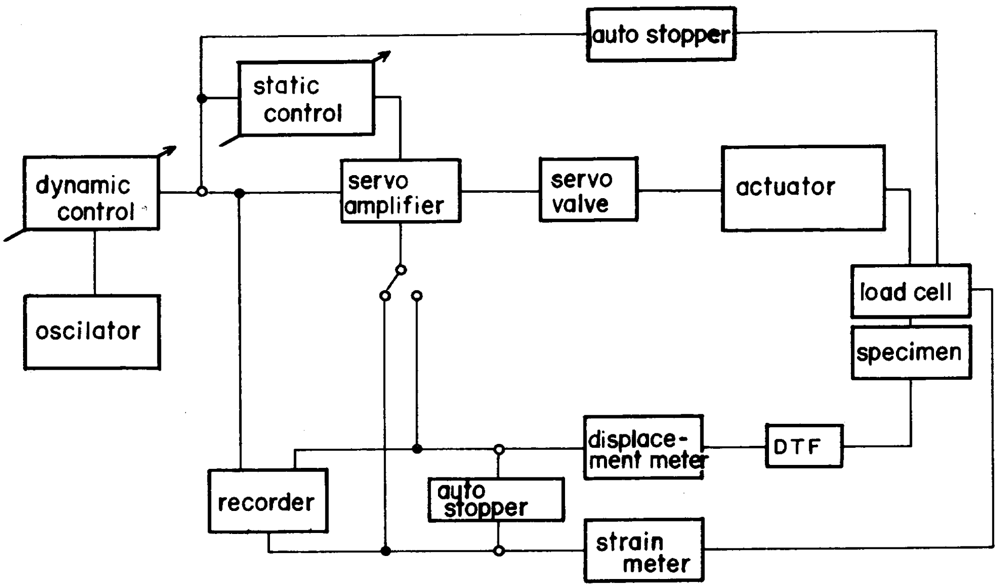


Fig. 1 Control system of 2,000 ton restraint testing machine

Table 1 Chemical composition and mechanical properties of test plate

plate thick (mm)	special heat treatment	chemical composition (%)												mechanical property		
		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Ti	Al	Y.P. (kg/mm²)	T.S. (kg/mm²)	El. (%)
40		0.09	0.25	0.46	0.007	0.007	0.05	4.91	0.65	0.53	0.003	—	0.024	96.7	100.0	23

Y.P.….. Yield Strength, T.S. ….. Tensile Strength, El.….. Elongation (Gage length : 50 mm)

Table 2 Chemical composition and mechanical properties of all-weld-metal of test electrade

dia. of electrode (mm ø)	Chemical composition (%)								mechanical property			hydrogen content (cc/100g)	drying before test
	C	Si	Mn	P	S	Ni	Cr	Mo	Y.P. (kg/mm²)	T.S. (kg/mm²)	El (%)		
4	0.04	0.42	1.85	0.007	0.007	3.10	0.52	0.66	92.5	96.2	19	0.97	400°C×1hr

Y.P. ….. Yield Strength, T.S. ….. Tensile Strength, El. ….. Elongation (Gage length : 50 mm)

size TRC test, a pair of test specimens are usable for a few times for these cracking tests by remaking the grooves by gas cutting. The shapes of the grooves are of y-type with the angle 60 degrees. The purpose of choosing three kinds of the test specimens is to investigate the applicability of weld conditions derived from the small size y-groove restraint weld cracking test to large weld structures.

3–3. *Experiment*

The authors used a weld restraint cracking testing machine of 2,000 tons capacity for the large size test specimen and carried out an RRC test to keep the restraint length constant during welding and cooling processes. For the small size TRC test specimen, the authors adopted a flat type tensile testing machine of 100 tons capacity and conducted the TRC test giving some constant tensile load after finishing of welding.

As for the y-groove restraint weld cracking tests, the authors made the welding of specimens in an atmosphere-controlled room.

The test electrodes were re-dried at 400°C for one hour. The test welding was performed under the standard welding conditions of weld current 170A and arc voltage 28V with welding speed 150 mm/min. The test specimen was preheated at 50°C, 100°C and 150°C in order to change these cooling processes. Preheating method of the large size test specimen is shown in **Photo. 2**.

Room temperature was between 7°C and 18°C and humidity was from 50% to 65% all through experiments. The testing condition for the y-groove restraint weld cracking test specimen as described above was constant temperature of 20°C and constant humidity of 50%.

The test specimen which did not rupture completely

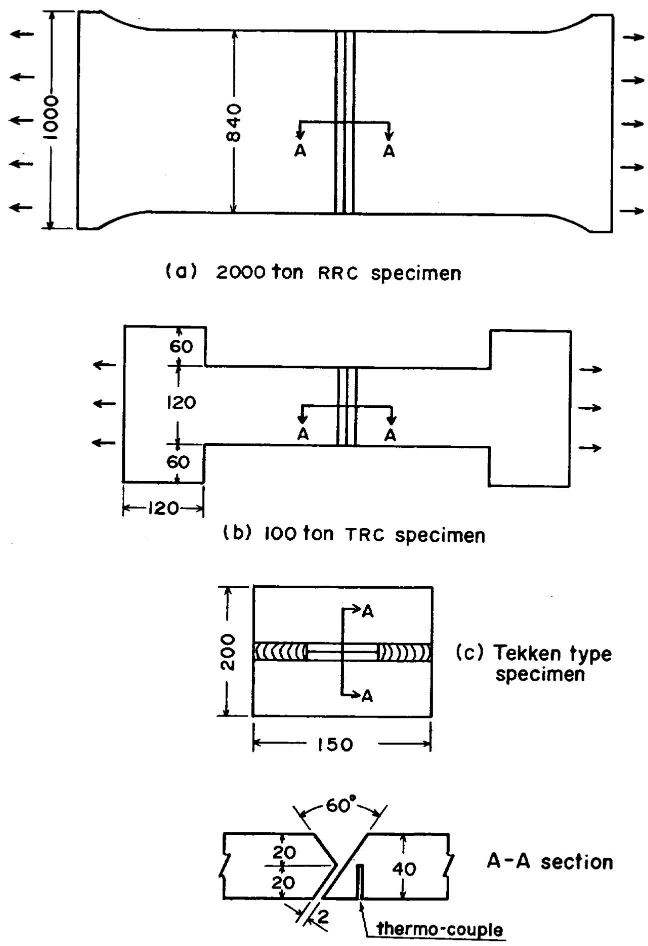


Fig. 2 Size and shape of each test specimen

was kept under loading, just as cooled down to room temperature for 48 hours in order to survey the delayed cracking of the weldment. Occurrences of weld cracks were detected by marco inspection of bead surface and also by microscopic examination of bead section.

4. Experimental Results and Discussions

4–1. *State of Weld Cracking*

Almost all weld crackings were detected in this experiment initiated from the HAZ of the root of groove and propagated along the bond or the weld metal.

The typical weld crackings for one pass weld and multiple pass weld are shown in **Photo. 3**. Weld cracking occurred from both sides of the acute angle and the obtuse angle of the test specimen, and definite tendency could not be recognized in cracking. As for multiple pass welds, weld cracking propagated scarcely along the HAZ and all propagated into weld metal on the way.

4–2. *Restraint Stress and Time of Weld Cracking*

In the large size RRC test, the behaviors of the restraint stress in weld joint were observed in relation to the time after start of welding. Typical example of the result (in the case of preheating temperature at 50°C) is shown in **Fig. 3**. In RRC test, the longer the restraint length L, the slower is the increase of the restraint stress, and also the smaller becomes the final restraint stress.

There are many studies on root cracking of high strength steel, all of which show that weld crackings occur after the weld joints are cooled down[3]. In this research, the restraint stress increases rather rapidly in the course of cooling and the weld joint is ruptured completely in short period. In Fig. 3, the cracking zone for one pass weld and two experimental results of multiple pass welds with the restraint lengths of 150 mm and 300 mm are also described.

On the other hand, the summarized weld cracking zones at various preheating temperatures for the large size RRC test and the small size TRC test are shown in **Fig. 4** and **Fig. 5** respectively. In both cases of the

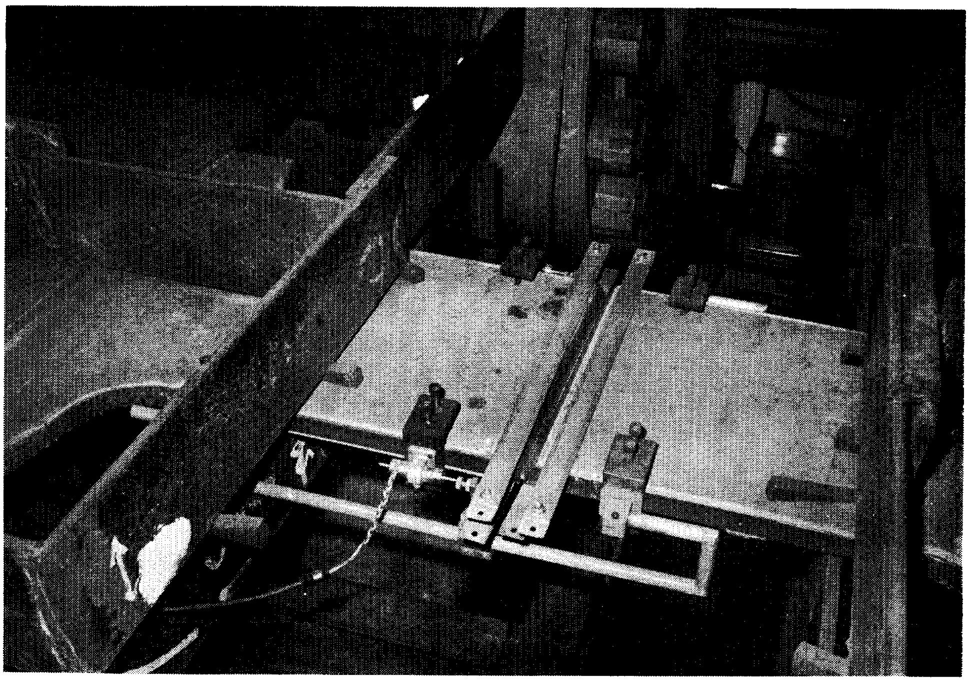
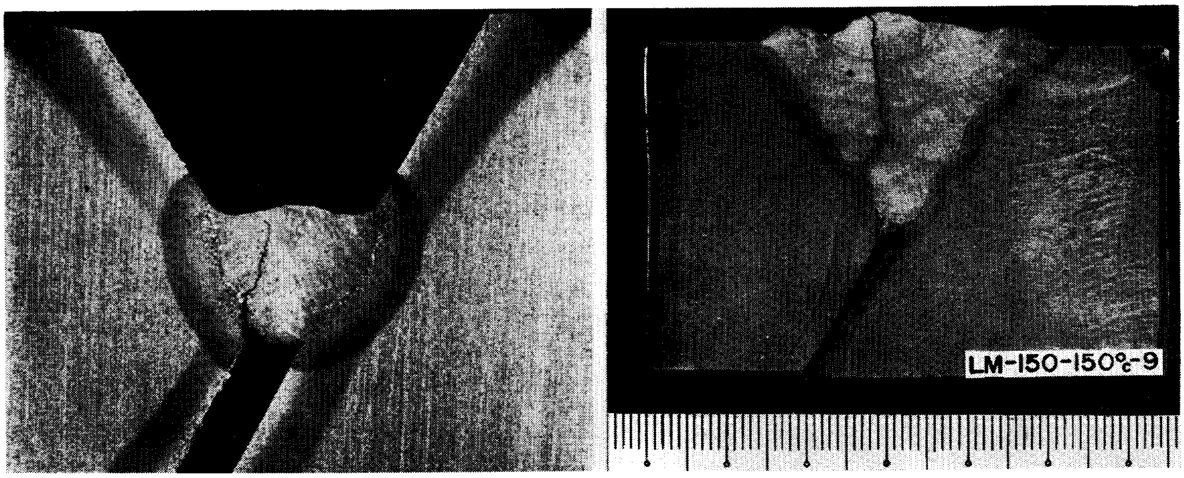


Photo. 2 Prenheating method in 2,000 ton testing machine



(a) one pass weld (b) multiple pass welds

Photo. 3 Typical root crack in HAZ of 2,000 ton RRC specimen

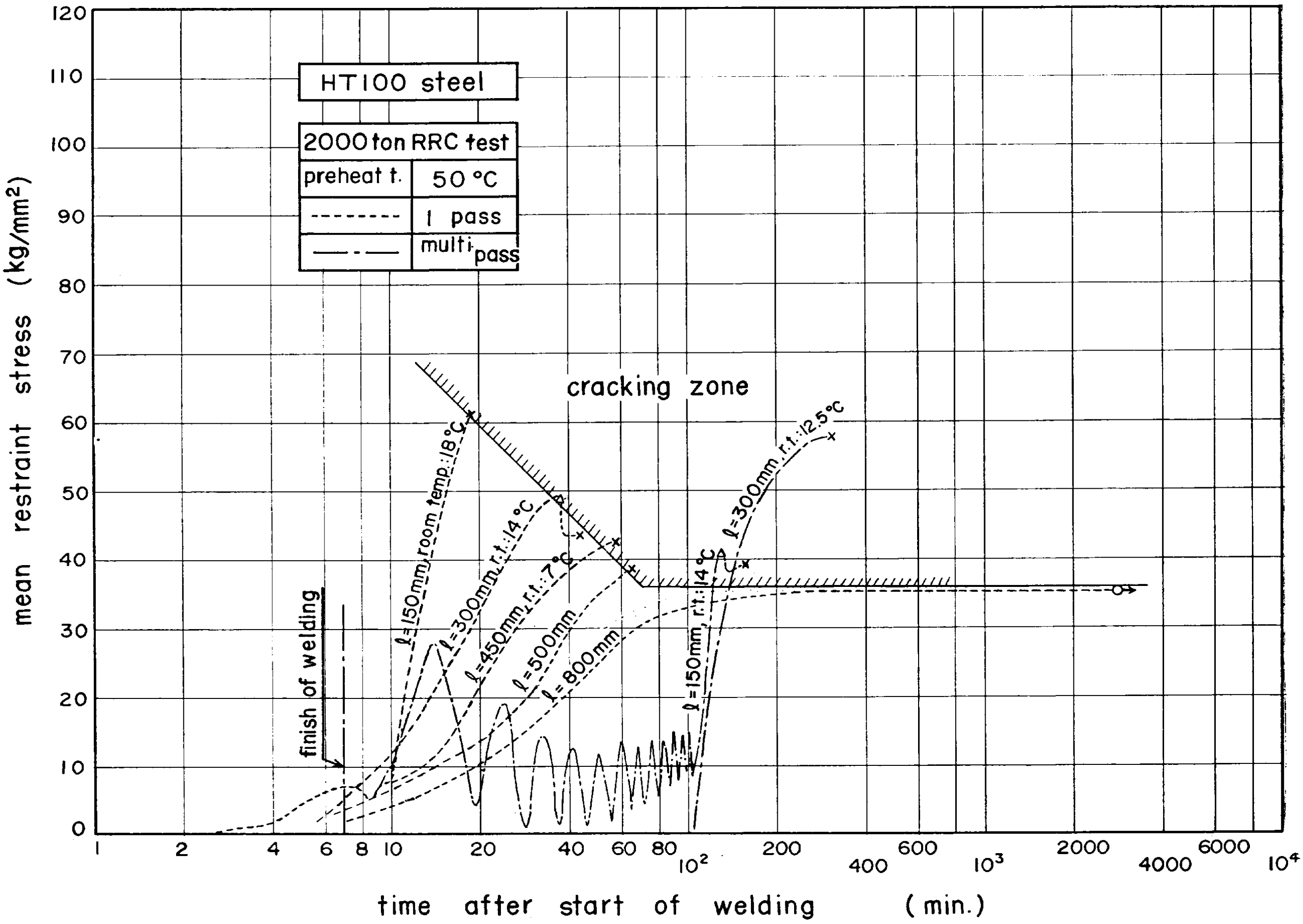


Fig. 3 Mean restraint stress in weld jcints during cooling on large size specimen, in 2,000 ton RRC test

large size RRC tests and the small size TRC tests, the period until weld cracking occurrence becomes longer as the preheating tempera ture increases. The critical restraint stresses of weld cracking become also higher with increase of preheating temperature. The critical restraint stress of cracking, for example, in case of preheating temperature at 150°C is about 75 kg/mm² in the small size TRC test and about 50 kg/mm² in the large size RRC test, which is a half of yield strength of test plate. The difference of the critical restraint stress between the large size RRC test and the small size TRC test is generally 20 kg/mm² at each preheating temperature. The weld cracking zone of the large size RRC test is wider than that of the small size TRC test. It seems that the large size RRC test is in more severe condition as for weld cracking than the small size TRC test. This means that application of welding conditions induced from no weld cracking zone of the small size test specimen to actual structures would be afraid to lead to the unfavorable results.

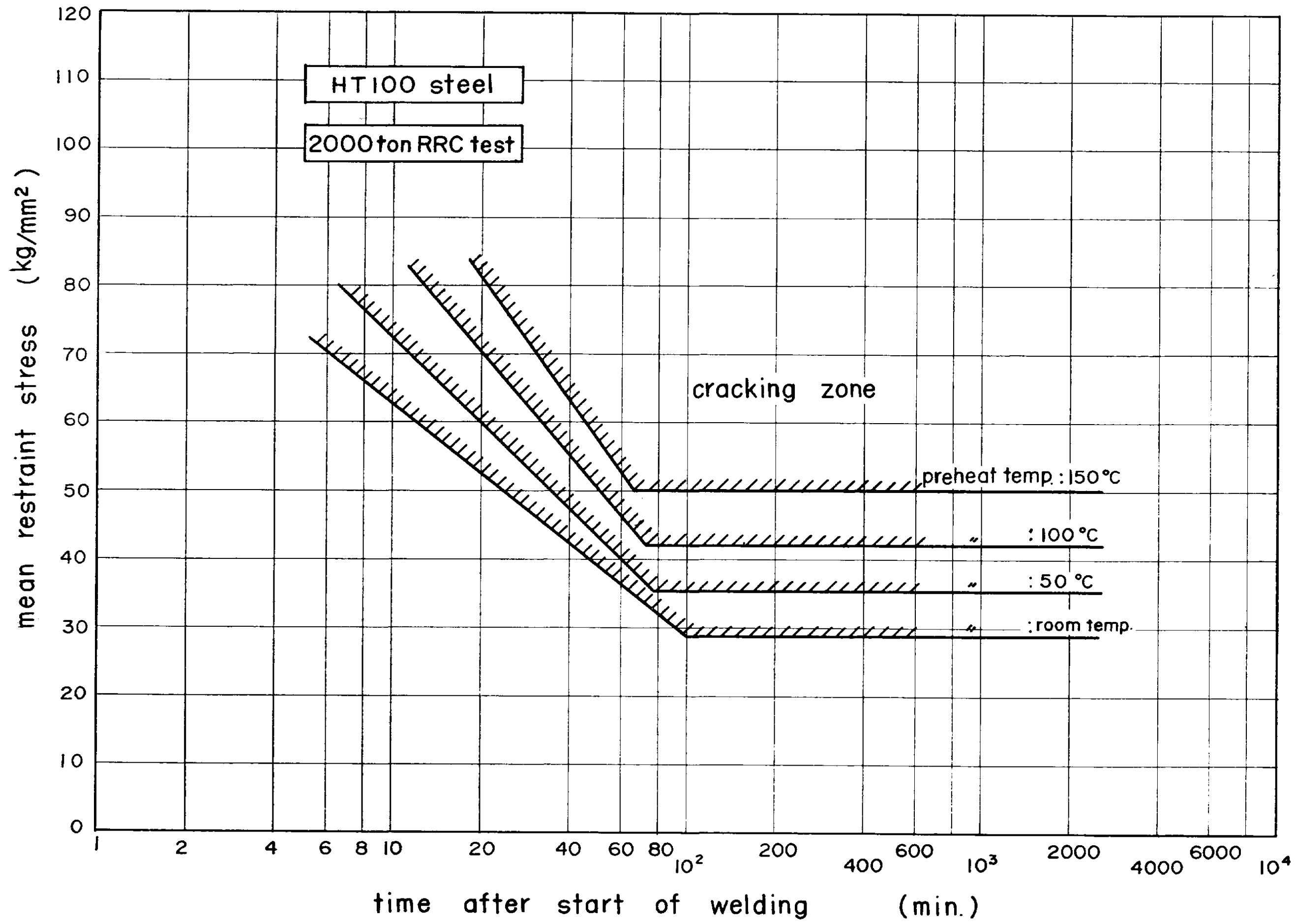


Fig. 4 Cracking zone of large size specimen at different preheating temperatures, in 2,000 ton RRC test

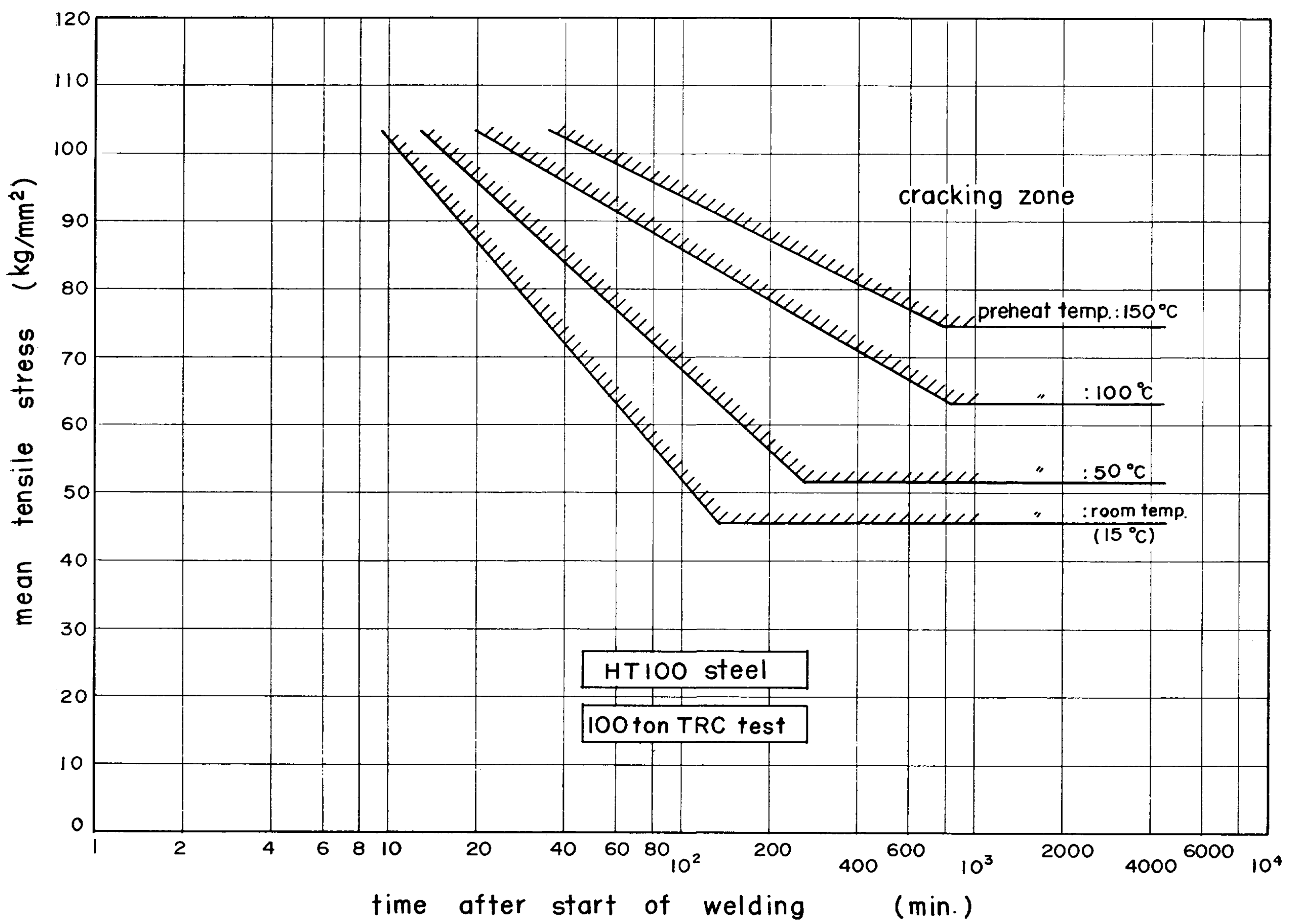


Fig. 5 Cracking zone of small size specimen at different preheating temperatures, in 100 ton TRC test

4–3. *Size Effect of Test Specimen on Weld Cracking*

It is obvious that the intensity of restraint in weld joint is an important factor for weld cracking in high strength steel. Regarding the large size RRC test, the small size TRC test and the y-groove restraint weld cracking test, the effect of the intensity of restraint on weld cracking was examined and size effect of test specimen on weld cracking was investigated. Two of the authors[1] define a parameter which represents the degree of restraint in weld joint. That is, the intensity of restraint K (kg/mm.mm) is defined as "force per unit weld length which is necessary to produce an elastic unit change of the groove interval of weld joint". Therefore, the intensity of restraint in RRC test with the restraint length of L mm using a test material of t mm thickness and E kg/mm² Young modulus is

$$K=\frac{E}{L}\cdot t \qquad (\text{kg/mm.mm}).$$

The relation between the final mean restraint stress and the intensity of restraint is obtained in RRC test as various restraint lengths at room temperature by menas of 100 tons tensile testing machine. In this RRC test, the final mean restraint stress is acquired by conducting postheat treatment at comparatively low temperature after test welding to prevent weld cracking occurrence. The results are shown in **Fig. 6**. In this figure, the results[4)5)] of mild steel and high strength

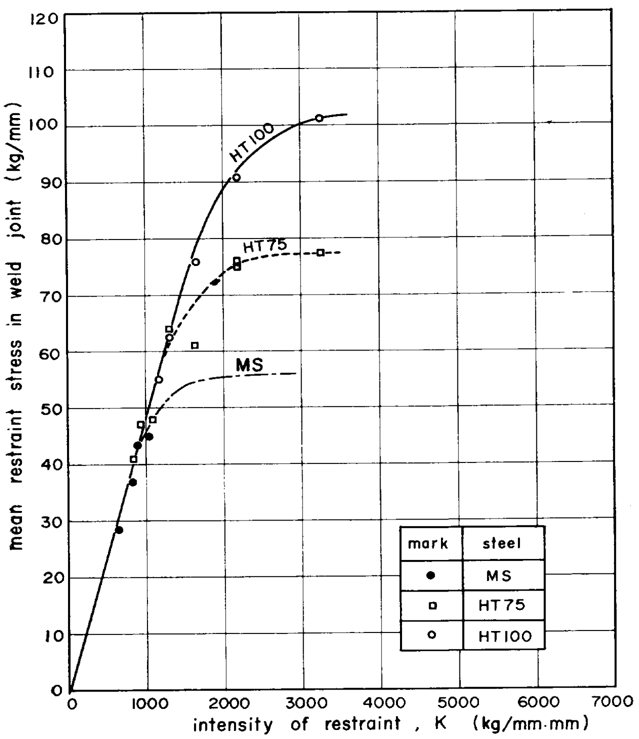


Fig. 6 Relation between mean restraint stress and intensity of restraint K in 100 ton test

steel of 75 kg/mm² in tensile strength which are obtained previously by the authors are also shown together. The intensities of restraints in the large size RRC test and the small size TRC test are seen from Fig. 6 using restraint stress of cracking occurrence in respective tests. This treatment in the large size RRC test was done to eliminate the influence of preheating temperature, because the restraint stress in the large size RRC test increased by preheating of the test specimen and the intensity of restraint came to increase virtually; and to obtain the intensity of restraint in the small size TRC test because the intensity of restraint could not be measured directly.

Regarding the intensity of restraint for the y-groove restraint weld cracking test, one of the authors[6)] carried out an experiment in detai and indicated that the intensity of restraint for the y-groove weld cracking test was shown in the following equation; $K=69t$ kg/mm·mm. Therefore, the intensities of restraint for the y-groove restraint weld cracking test specimen of 40 mm, 30 mm and 20 mm thickness adopted in this research are respectively 2760 kg/mm.mm, 2070 kg/mm.mm and 1380 kg/mm.mm.

The critical intensities of restraints below which no crackings occur in the large size RRC test, the small size TRC test and the y-groove restraint weld cracking test are shown in Fig. 7 in cases of 50°C and 100°C preheating temperatures. In the y-groove restraint weld cracking test of 40 mm and 30 mm thickness, no crackings occur either at 100°C or at 50°C preheating temperature as shown in Fig. 9 described later, and so the authors adopt these cases as the critical intensity of restraint. The critical intensities of restriants for the large size RRC test and the small size TRC test at various preheating temperatures are also shown in **Fig. 7**. The differences of the critical intensity of restraint for each test specimen are from 400 kg/mm.mm to 500 kg/mm.mm and the smaller becomes the test specimen, the higher the critical intensity of restraint.

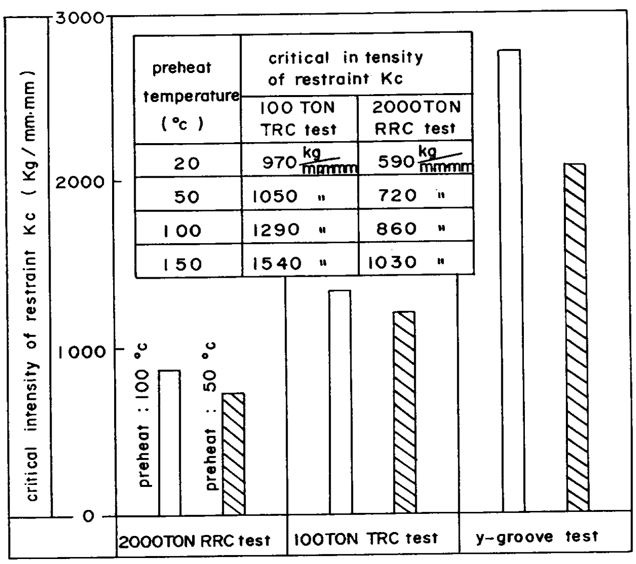


Fig. 7 Comparison of critical intensity of restraint Kc in each weld cracking test

On the other hand, the weld cracking percentage has been hitherto adopted as means of evaluation of root cracking sensitivity for steel plate. The change of

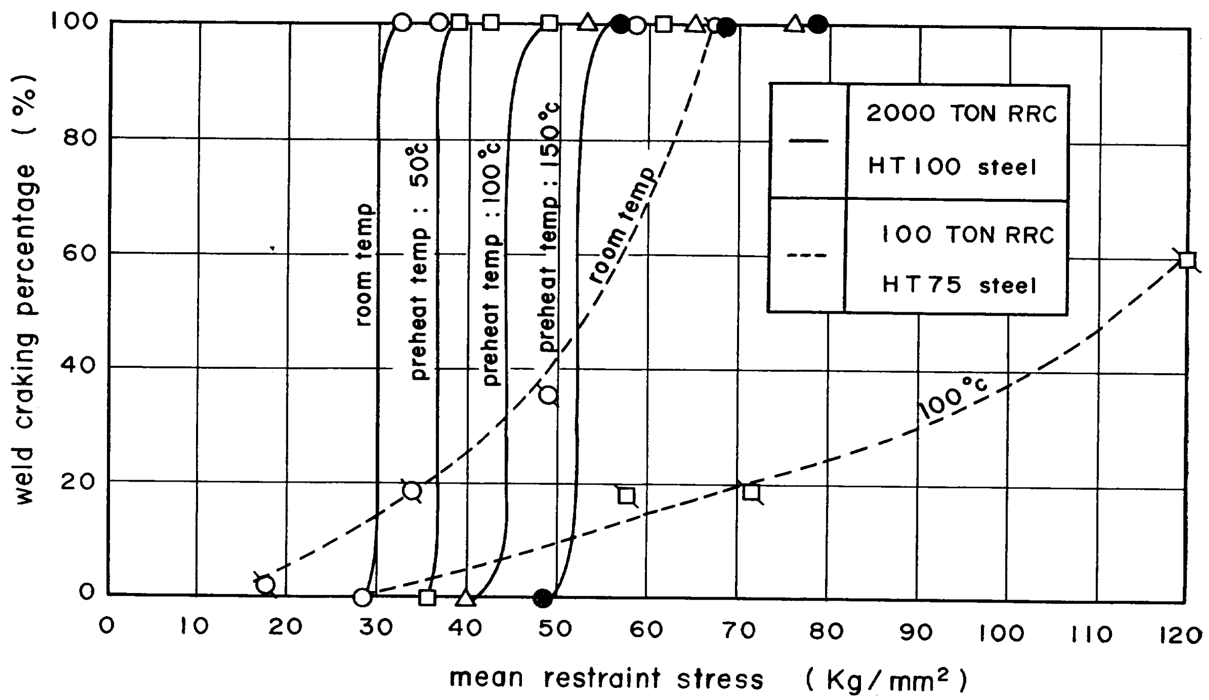


Fig. 8 Relation between weld cracking percentage and mean restraint stress in RRC test

the weld cracking percentage is investigated at various preheating temperatures for the large size RRC test. This result is shown in **Fig. 8**. The weld cracking percentage is a ratio of cracking length to all welding length in test specimen. Occurrences of weld cracks were detected by taking 10 macro-structure sections in the large size RRC test and 5 macro-structure se ctions in the small size TRC test.

The results[4] of the small size RRC test for high strength steel in 75 kg/mm² tensile strength by means of 100 tons tensile testing machine, which the authors conducted formerly are also shown together in Fig. 8. In the large size RRC test for 100 kg/mm² high strength steel, it is found that weld cracking percentage curve is very steep and when the cracking once occur, it surely lead to complete rupture. On the other hand, weld cracking sometimes is arrested on the way and stays inside the weld joint in the small size RRC test of 75 kg/mm² high strength steel.

In both experiments, the higher the preheating temperature, the weld cracking percentage curve shifts toward the higher restraint stress. However, weld cracking in the large size RRC test of 100 kg/mm² high strength steel occurs at lower restraint stress than in the small size RRC test of 75 kg/mm² high strength steel. It seems that the difference between two test results comes from the effect of the rigidity of testing machine and the dimension of the test specimen, and also from the influence of propagation characteristics of weld crackings in weld joint of high strength steel. These propagation characteristics of weld crackings are the problem which must be investigated in future. In Fig. 8, the restraint stress resulting from 75 kg/mm² high strength steel is great. The reason for this seems to be that stresses around the weld joint are in triaxial conditions.

On the other hand, weld cracking sensitivity of the y-groove restraint weld cracking test is shown in **Fig. 9**

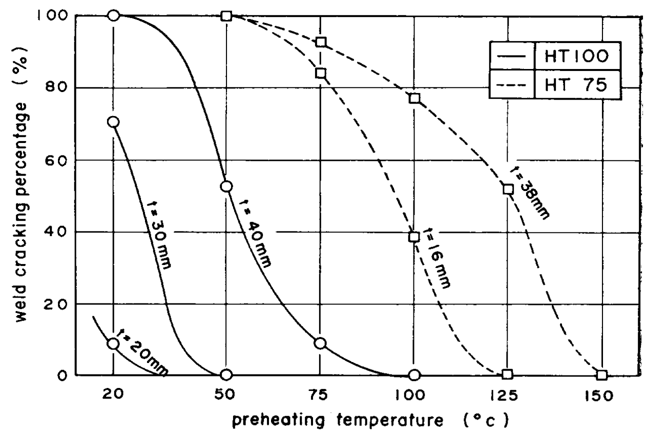


Fig. 9 Relation between weld cracking percentage and preheating temperature in the y groove restraint weld cracking test

with preheating temperature on abscissa. The preheating temperature preventing cracking occurrence in the y-groove restraint weld cracking test is higher in 75 kg/mm² high strength steel than in 100 kg/mm² high strength steel. Judging only from this test result, it is found that 75 kg/mm² high strength steel has less resistance to weld cracking than 100 kg/mm² high strength steel. In Fig. 8, however, 100 kg/mm² high strength steel ruptures completely at lower restraint stress than 75 kg/mm² high strength steel and it is obvious that the testing method and dimension of test specimen have effect on weld cracking behavior as mentioned above.

4–4. *Preheating Temperature Preventing Weld Cracking*

In general, the weld joints of high strength steel in the actual structures are preheated before welding to prevent cold cracking. Therefore, the authors investigated the preheating temperature which is necessary to prevent weld cracking of 100 kg/mm² high strength steel. Weld cracking conditions in the large size RRC test, the small size TRC test and the y-groove restraint weld cracking test are shown in **Fig. 10** with the intensity of restraint on abscissa. The preheating temperature preventing weld cracking is higher in all tests as the intensity of restraint increases. Tendency of weld cracking in the large size RRC test is similar to that in the small size TRC test but not to that in the y-groove restraint weld cracking test. The preheating temperature which is necessary to prevent weld cracking at the same intensity of restraint is the highest in the large size RRC test, followed by the temperature in the small size TRC test and that in the y-groove restraint weld cracking test. In other words, weld cracking in the large

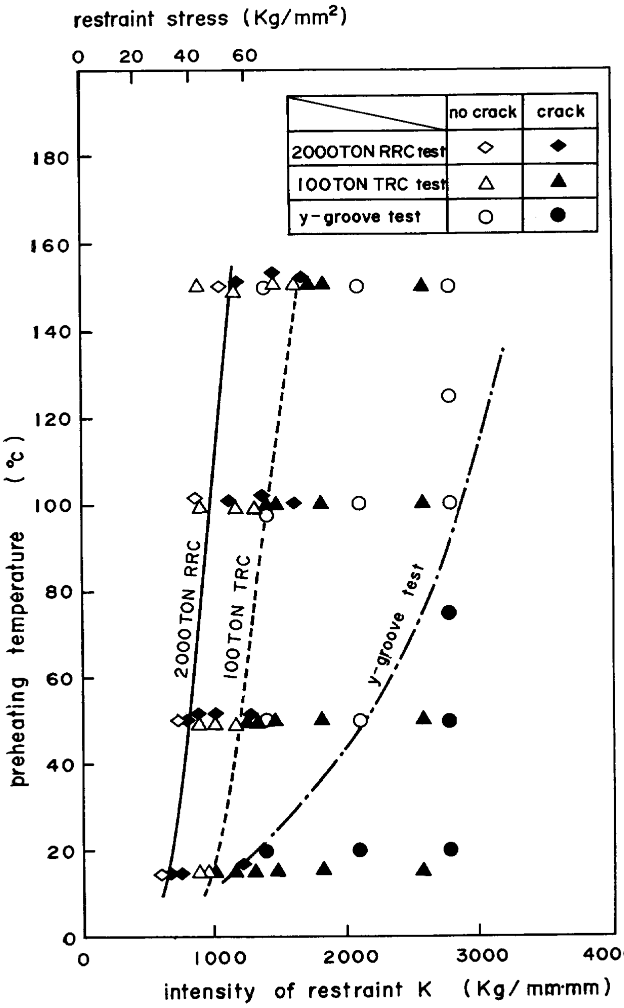


Fig. 10 Effect of preheating temperature and intensity of restraint K on weld cracking of test plate

size RRC test occurs at the lowest intensity of restraint of the three. One of the reasons for this seems to be that the cooling speed which is affected by dimension of test specimen and thermal energy such as preheating and heat input differs in these three test specimens.

Generally speaking, at the same preheating temperature, the cooling speed in actual structures seems to be higher than that of the small size restraint weld cracking test specimen, and it is considered dangerous to apply directly to actual structures the preheating temperature derived from the small size test specimen of the same intensity of restraint. Therefore, it is necessary to make clear the cooling process which is closely related with weld cracking in order to decide suitable weld conditions for actual structures. The authors adopt the cooling time from the peak temperature to 100°C as a criterion which represents cooling process. **Fig. 11** shows weld cracking conditions in the relation between the cooling time and the intensity of restraint. The critical line in the figure is calculated using the Pw value gained by Dr. Ito and Mr. Bessyo,[6] where Pw is represented by

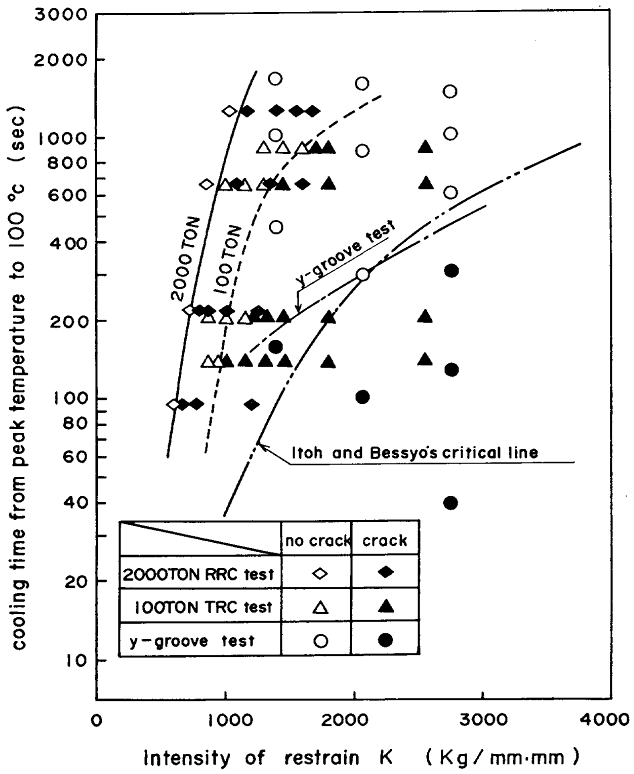


Fig. 11 Effect of cooling time from peak temperature to 100°C and intensity of restraint Kon weld cracking of test plate

$$Pw=C+\frac{Si}{30}+\frac{Cr}{20}+\frac{Cu}{20}+\frac{Ni}{60}+\frac{Mo}{15}+\frac{V}{10}$$

$$+5B+\frac{H}{60}+\frac{K}{40000}\ (\%)$$

The experimental result from the y-groove restraint weld cracking test conforms generally to the Ito and Bessyo's critical line though Ni content of this test plate is beyond the range of Ito and Bessyo's Ni content. But the results from the large size RRC test and the small size TRC test differ from the Ito and Bessyo's critical line, and though the cooling time is considered, there are also considerable differences between the experimental results from the large size RRC test and the small size TRC test. This reasons can be attribute to the facts that there are differences in the rigidity of the testing machine and testing method, and also there are local concentrated residual stresses in the right-angled to welding line because of long welding length. In consideration of the nature of the RRC test, which is loaded immediately after test welding, there may be micro-cracking because of much Ni content of this test plate. The authors will conduct the further investigation on this matter.

5. Conclusions

Experiments using a small size restraint test specimen have been widely made to select optimum welding conditions for estimating the cracking sensitivity by weld cracking percentage. However, there has been no sufficient study on the applicability of the welding conditions selected by the small size restraint test specimen to those of actual structures. Therefore, the authors developed the new weld restraint testing machine of 2,000 tons capacity, which is capable of reproducing approximately such restraint conditions as those of actual structures. Using this machine, the authors carried out weld cracking tests to compare with the results of the small size TRC test of 100 tons capacity and the y-groove restraint weld cracking test. The results obtained in the paper are summarized as follows:

1) The results of the small size TRC test shows a longer incubation period until weld cracking occurrence and a higher one in the critical restraint stress than that of the large size RRC test.
2) The critical intensity of restraint of the large size RRC test is the lowest and that of the y-groove restraint weld cracking test is the highest of the three experiments.
3) In the large size RRC test of 100 kg/mm^2 high strength steel, it is found that weld cracking is never arrested in weld joint on the way, and the only phenomenon is either complete rupture or non-rupture. This seems to be due to the influence of the rigidity of the testing machine and the propagation characteristics of weld cracking in ultra high strength steel such as 100 kg/mm^2 steel.
4) The preheating temperature preventing weld cracking is the lowest for the y-groove restraint weld cracking test, and is the highest for large size RRC test at the same intensity of restraint.
5) Even if the authors consider the effect of the cooling time on weld cracking, it is found that weld cracking behaviors of three experiments; the large size RRC test, the small size TRC test and the y-groove restraint weld cracking test, differ from eath other.
6) The large size weld cracking testing machine is very effective for investigating weld cracking conditions for the large size test specimen of high strength steel. The authors velieve that it will be a useful means for the research on weld cracking in future.

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