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# Some Fractographic Features of Various Weld Cracking and Fracture Surfaces with Scanning Electron Microscope†

—Studies on Fractography of Welded Zone (I)—

Fukuhisa MATSUDA\* and Hiroji NAKAGAWA\*\*

## Abstract

Typical examples of various weld cracked and fractured surfaces, that is, solidification crack, liquation crack, hydrogen-induced crack, lamellar tear, quenching crack, fatigue fracture and others are displayed and classified with scanning electron microscope. Moreover some fractographic features are investigated with the aid of microanalyzer.

## 1. Introduction

Since various weld crackings during and after welding and fractures of welded joint which are classified as shown in **Table 1** are one of the serious problems related to welding, many researches have been performed to make clear the causes and to develop the prevention methods of these problems. Hitherto most of the techniques of the investigation for the causes has been mainly limited to; (1) estimation of the position, temperature and environment where the crack and/or the fracture occurred, (2) observation of

the microstructure near the crack and/or fracture with an optical microscope, (3) observation of the degree of brilliance and oxidization of the cracked and/or fractured surface with a naked eye or a microstereoscope, etc.

Recent years the microfractography has been developed with the advance of electron microscopy, and thus the relation between the cause or mode of the fracture and the microfeature of the fractured surface has gradually become clear. The typically basic relations are shown in **Table 2**. Such systematization of these rela-

**Table 1** Classification of weld crackings and fractures

|  |   |                           |
|--|---|---------------------------|
| Weld cracking<br>in welding performance  | } Hot cracking -----                                    | Solidification cracking   |
|  |   | Liquation cracking        |
|  |   | Ductility-dip cracking    |
| } Cold cracking -----                    | Hydrogen cracking<br>(Delayed cracking)                 |                           |
|  | (Lamellar tearing)                                      |                           |
|  | Quenching cracking during<br>Martensitic transformation |                           |
| Weld cracking<br>and fracture in service | Reheat cracking   |                           |
|  | (Overload fracture)                                     |                           |
|  | Brittle fracture  |                           |
|  | Fatigue fracture  |                           |
|  | } Environmental fracture -----                          | Stress corrosion cracking |
|  |   | Corrosion fatigue<br>etc. |
| Creep fracture<br>etc.                   |   |                           |
| Other defect -----                       | Blow hole   |                           |
|  | Lack of fusion  |                           |
|  | Slag inclusion  |                           |

† Received on March 30, 1977

\* Professor

\*\* Research Instructor

Table 2 Relation between basic fracture mode and microfeature of fractured surface

|                        |                                |                               |  |
|------------------------|--------------------------------|-------------------------------|--|
| Transgranular fracture | }                              | Ductile fracture              |  |
|                        |                                | { Microvoid coalescence-----  | Dimple(Equiaxed, Shear, Tear dimple)                     |
|                        |                                | { Glide plane decohesion----- | Serpentine glide, Ripple, Stretching                     |
|                        |                                | Brittle fracture              |  |
|                        |                                | { Cleavage fracture-----      | River pattern, Tongue                                    |
|                        | { Quasi-cleavage fracture----- | River pattern, Tear ridge     |  |
|                        |                                | Fatigue fracture              |  |
|                        |                                | -----                         | Striation, Tire track, Rub mark                          |
| Intergranular fracture | }                              | Ductile fracture              |  |
|                        |                                | -----                         | Separated grain facet, surface of which shows dimples    |
|                        |                                | Brittle fracture              |  |
|                        |                                | -----                         | Separated grain facet, surface of which is flat          |
|                        |                                | Fatigue fracture              |  |
|                        |                                | -----                         | Separated grain facet, surface of which shows striations |

tions must enable the researchers to obtain various and important informations about the cause of the fracture.

Therefore the microfractographic technique has been gradually applied to the fracture analysis of welded joint. As is generally known, however, a welded zone is generally suffered under a metallurgically and mechanically complicated condition. This causes a complicated fracture mode and thus a complicated fracture surface. This means that the individual and the mutual effects of the various factors must be especially taken into account for the establishment of the weld microfractography. Moreover the features of blowhole, lack of fusion, slag inclusions and etc. on the fractured surface must be clear, since they have a possibility to become nucleation sites of a huge fracture.

From these viewpoints the authors have been investigating the various cracked and fractured surfaces in welded joint. For the observation a scanning electron microscope (SEM, HITACHI HSM-2B type), which was set up in 1975, has been used, the general view of which is shown in **Photo. 1**. The magnification is continuously variable from  $\times 12$  up to  $\times 100,000$ . Moreover this SEM contains two kinds of microanalyzer. One is a wave dispersive type analyzer (EPMA) composed of two channels and six analyzing crystals, with which analysis from boron to uranium is possible. The other is an energy dispersive type analyzer (EDX), with which analysis from sodium to uranium is possible. These microanalyses offer very important information for the fracture analyses.

This report describes the outline of various weld cracked and fractured surfaces, using typical examples.

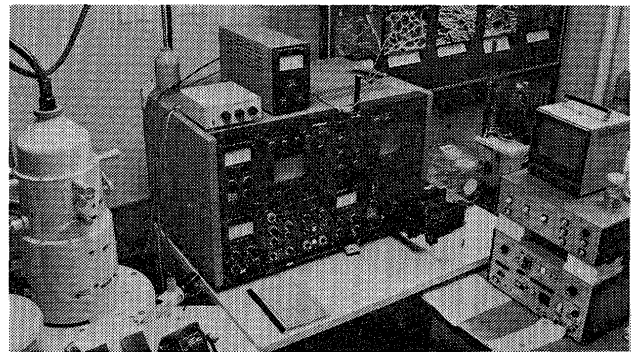


Photo. 1 General appearance of the scanning electron microscope in JWRI

## 2. Examples of Weld Cracking and Fractured Surfaces

### 2.1 Hot Cracking

#### 2.1.1 Solidification Crack

**Photograph 2** shows a solidification cracked surface of fully austenitic stainless steel of SUS310S\* tested with Trans-Varestraint method. One of the merit of this testing method is to be able to determine the relation between the each location in the crack and its temperature during welding, since the crack occurs instantaneously. In **Photo. 2** the temperature is lowered from the left toward the right side. The cracked surface as a whole shows a feature of intergranular cracking which is elongated unidirectionally due to the columnar growth. The detail, however, changes from the higher temperature region to the lower temperature region. That is, in the region at the highest tem-

\* SUS310S corresponds to AISI310S. SUS is the designation for stainless steel in Japan Industrial Standard (JIS).

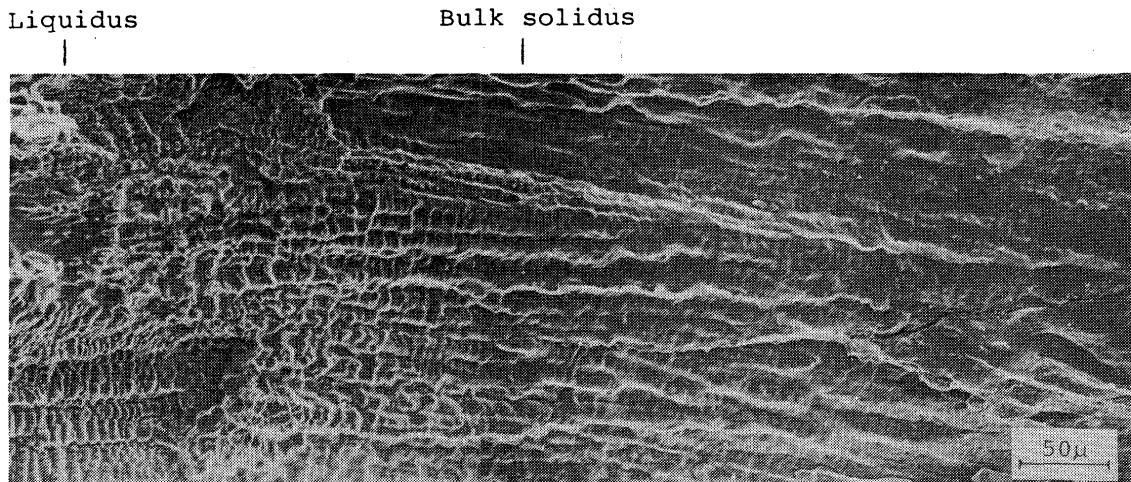


Photo. 2 Solidification cracked surface of SUS310S occurred with Trans-Varestraint test

perature many and fine protuberances are remarkably observed, which correspond to the primary and secondary arms of cellular dendrites. In the region at the medium temperature the protuberances of secondary arms gradually become obscure. Further, in the region at the lowest temperature the protuberances of primary arms also become obscure, and a flat surface becomes dominant. The reason of such a change is mainly because of the decrease in the residual liquid together with the temperature drop, and partly because of the grain boundary migration among residual low melting liquids in the lowest temperature region<sup>1)</sup>.

Similar cracked surface is also observed for a weld solidification crack of aluminum alloy<sup>2)</sup>. It is, however, doubtful in aluminum alloy whether the grain boundary migration affects or not.

Using this feature, it is possible to estimate the cracked temperature during welding of any specimen tested with another cracking test or in actual welding performance. For example Photo. 3 shows a solidifi-

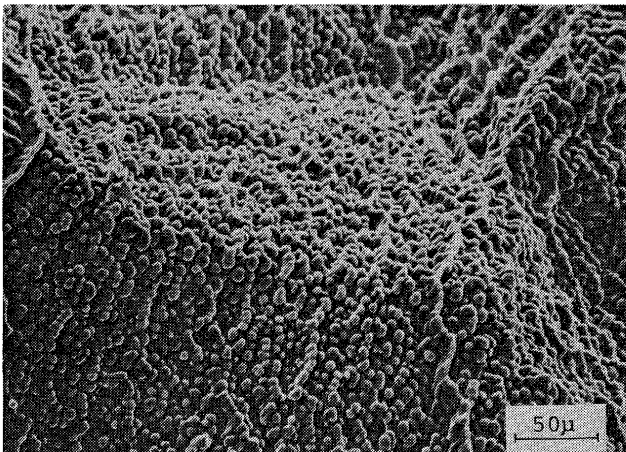


Photo. 3 Solidification cracked surface of 5083 aluminum alloy occurred with Houldcroft type test

cation cracked surface of aluminum alloy 5083 tested with Houldcroft type method. Though the cracked surface shows a non-directional intergranular cracking due to the equiaxed crystals, many protuberances are remarkably observed. Therefore it is considered that the crack occurred near the liquidus temperature. The authors confirmed this by photographing the tip of solidification cracking with 16 mm movie camera. Moreover the cracked surface near the arrested location of the cracking in this specimen was similar to that in the lowest temperature region in Photo. 2.

#### 2.1.2 Liquefaction Crack

For an example, a liquation cracked surface of a heat-affected zone of SUS310S is shown in Photo. 4.

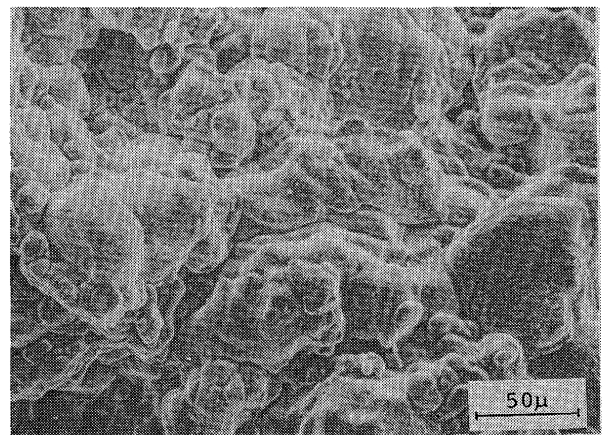


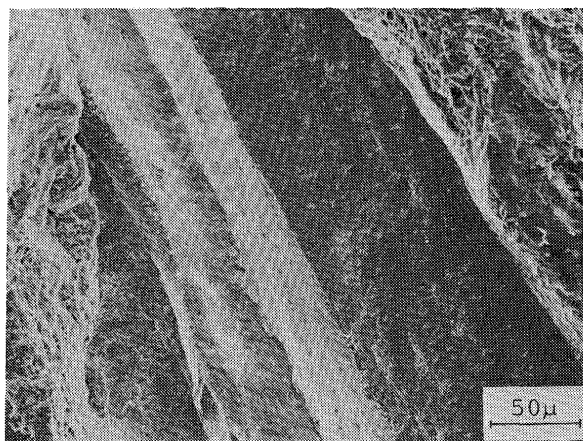
Photo. 4 Liquation cracked surface in HAZ of SUS310S

The cracked surface shows a feature of intergranular cracking, but gives an rounded appearance compared with that in cold cracking mentioned later. Besides, in Photo. 4 some protuberances which are somewhat similar to those of dendrites are observed. Since the location of Photo. 4 is an extreme vicinity of the

fusion boundary, it is considered that these protuberances mean the existence of much liquid among the grain boundaries during welding.

### 2.1.3 Ductility-dip Crack

In SUS310S tested with Trans-Varestraint method, ductility-dip cracks occur between about 1200°C–850°C. The cracked surface also shows a feature of intergranular cracking as shown in **Photo. 5\***, but the



**Photo. 5** Ductility-dip cracked surface in weld metal of SUS310S occurred with Trans-Varestraint test

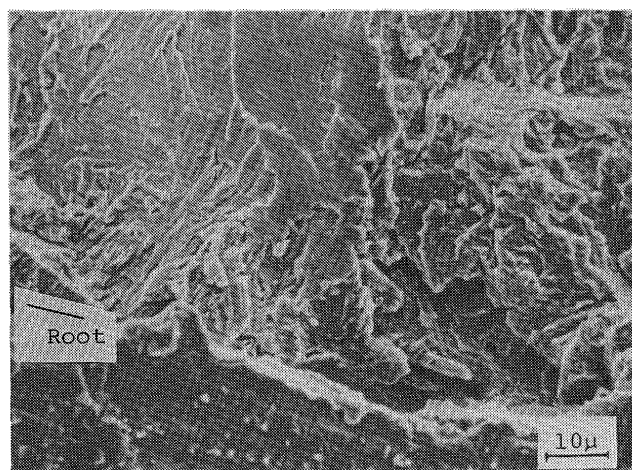
ridge of the grain boundary is seemed to be somewhat sharper than that in the lowest temperature region in **Photo. 2**. Besides the cracked surface looks slightly rough in higher magnification. Moreover the ductility-dip cracked surface differs from the solidification cracked surface in their element distributions. On the solidification cracked surface the elements such as sulphur forming low melting products are often observed. On the ductility-dip cracked surface, however, carbon which may form carbide of  $M_{23}C_6$  type was detected.

## 2.2 Cold Cracking

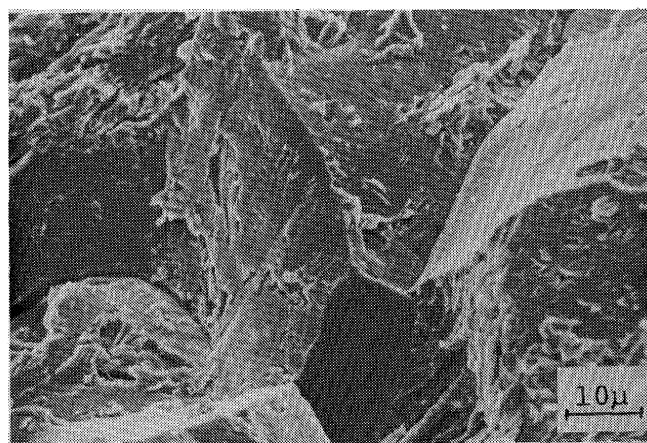
### 2.2.1 Hydrogen-Induced Crack

#### (a) Root Crack

It is shown<sup>9)</sup> that the root crack in the y-groove cracking test generally originates in the heat-affected zone and propagates into the weld metal. The cracked surfaces in both the heat-affected zone and the weld metal are composed of either intergranular, quasi-cleavage, dimple, or their two or three mixed fracture mode. **Photograph 6(a)** shows an example of the quasi-cleavage fracture mode in heat-affected zone. Since in any welded zone the evaluation of the stress intensity factor and the hydrogen concentration at each crack tip is impossible at present, the systematic



(a) vicinity of the root



(b) coarse grained region near fusion boundary

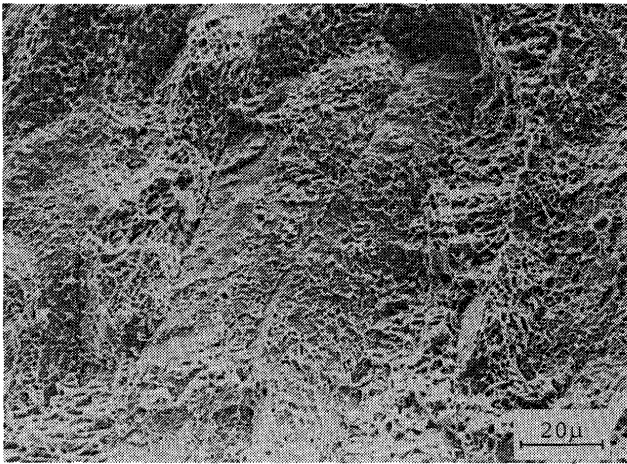
**Photo. 6** Root cracked surface in HAZ occurred with y-groove cracking test. material; HT50 (40 mm thickness), electrode; JIS D5016 (diffusible hydrogen; 4 cc/100 g), heat input; 22,000 J/cm, non-preheating

description of the distribution of fracture mode in the cold cracked surface is difficult. Despite this circumstance, intergranular fracture mode is often observed in the coarse grained region of the heat-affected zone as shown in **Photo. 6(b)**.

Besides, in most weld metal not only the intergranular mode but also the quasi-cleavage and dimple modes have often a directional appearance due to an elongated prior austenite grain. An example of this is shown in **Photo. 7**.

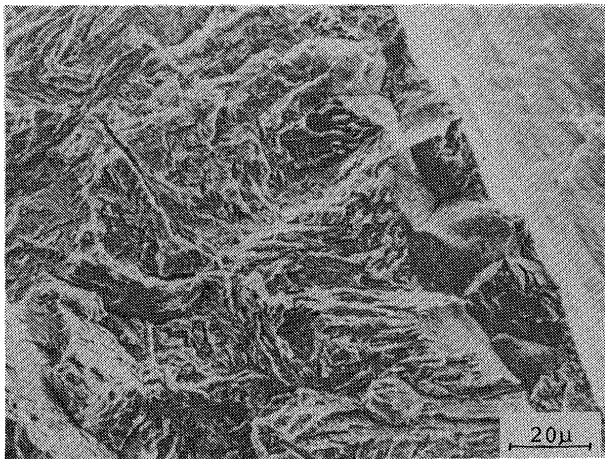
**Photograph 8** shows a fractured surface near the notch of an Implant tested specimen, in which the intergranular and the quasi-cleavage fracture modes are clearly observed.

\* In **Photo. 5** the left part and the upper right part are the artificially fractured region showing dimples.



**Photo. 7** Root cracked surface in weld metal occurred with Controlled restraint fillet weld cracking test<sup>4)</sup>. material; HT80 (25 mm thickness), electrode; E11016 (hydrogen; 20 cc/100 g), heat input; 17,000 J/cm, non-preheating

Notch



**Photo. 8** Root cracked surface near the notch occurred with Implant cracking test. material; HT80, electrode; E11016 (hydrogen; 2 cc/100 g), applied stress; 70 kg/mm<sup>2</sup> heat-input; 17,000 J/cm, non-preheating

#### (b) Heel Crack

A heel cracked surface at an extreme vicinity of the root in HT50 (high tensile steel more than 50 kg/mm<sup>2</sup> in ultimate strength) with Non-restraint T type cracking test<sup>5)</sup> shows a quasi-cleavage or fine dimple fracture mode, both of which are affected by hydrogen. An example of the fine dimple fracture mode is shown in **Photo. 9(a)**. **Photograph 9(b)**, whose abscissa is X-ray energy and the ordinate is the intensity, is the EDX result of an inclusion A in a dimple in **Photo. 9(a)**, and this shows the existence of Si, Ca, Mn and Fe. Since the large quantity of Fe is considered to be due to an effect of the matrix judging from the resolving

power of EDX, the inclusion must be an oxide composed of Si, Ca and Mn. Moreover the existence of Si and Ca which are the slag constituents may suggest that the heel crack at the extreme vicinity of the root is passing through the weld metal.

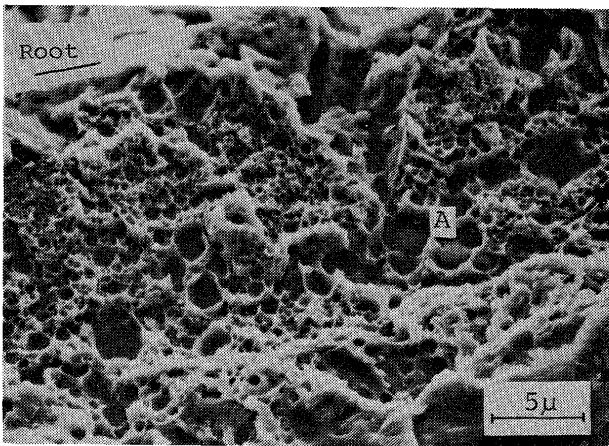
Except the extreme vicinity of the root, the cracked surface is composed of a mixture of intergranular and quasi-cleavage fracture mode, as shown in **Photo. 9(c)**. By the way, the sulphur content of this HT50 is 0.009% and thus the inclusions which were mainly composed of manganese sulphides elongated along the rolling direction were sometimes observed as shown in **Photo. 9(d)**.

On the other hand, in a heel crack of another HT50 containing 0.018% sulphur, a cracked surface as shown in **Photo. 10(a)** was sometimes observed, which is similar to the terrace and wall type in a lamellar tear. Moreover, a cracked surface where many and flat manganese sulphides were clustered together as shown in **Photo. 10(b)** was often observed, although the major cracked surface was the same as in **Photo. 9(c)**.  
2.2.2 Lamellar tearing

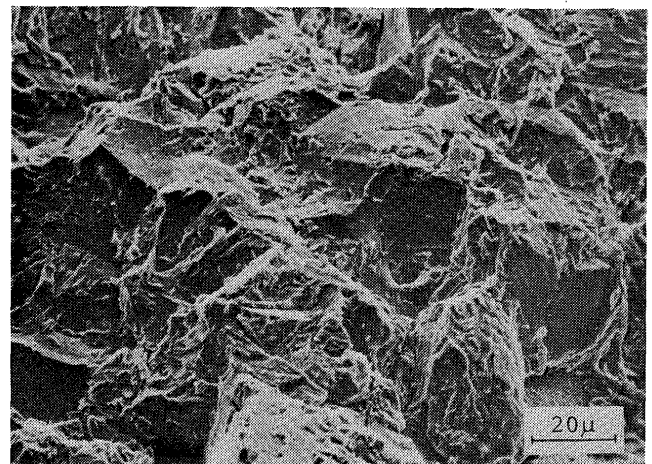
**Photograph 11(a)** shows a lamellar tearing occurred from a root in a corner joint of HT50 (40 mm thickness, 0.018% sulphur), and this is the typical example of the terrace and wall type reported by Elliot et al<sup>6)</sup>. That is, the terrace part shows an equiaxed dimple fracture mode in which manganese sulphides along the rolling plane are mainly observed, and the wall part shows a shear dimple mode. Near the root, however, the wall part and the intermediate zone between the adjacent manganese sulphides on the terrace part occasionally show a quasi-cleavage fracture affected by hydrogen, which is similar to **Photo. 10(a)**.

**Photograph 11(b)** shows another example of the lamellar tearing which occurred at a distance of about 15 mm from the fusion boundary in the same joint as in **Photo. 11(a)**. This is somewhat similar to the terrace and wall type, but the terrace part shows a feature of flat separation between the matrix and the manganese sulphide. The reason may be that there are lots of large manganese sulphides in the nearer position to the thickness center. Though obscure in **Photo. 11(b)**, the large and flat manganese sulphides are often observed on the terrace parts.

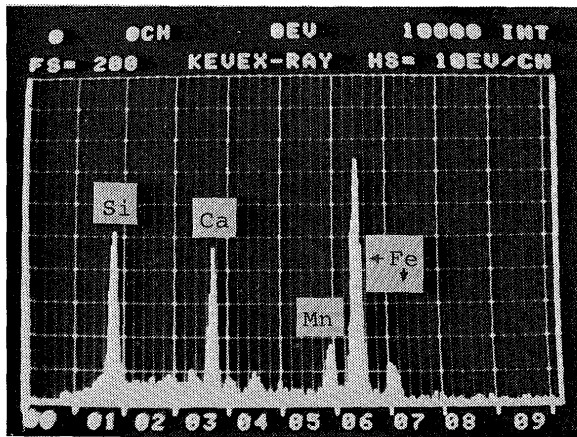
By an application of the Implant cracking test of the thickness direction without notch to the above mentioned HT50, a lamellar tearing easily occurred at a distance of about 12 mm from the fusion boundary. The fractured surface is shown in **Photo. 12(a)**, which is similar to **Photo. 11(b)**. The lower portion of **Photo. 12(a)** is the wall part composed of shear



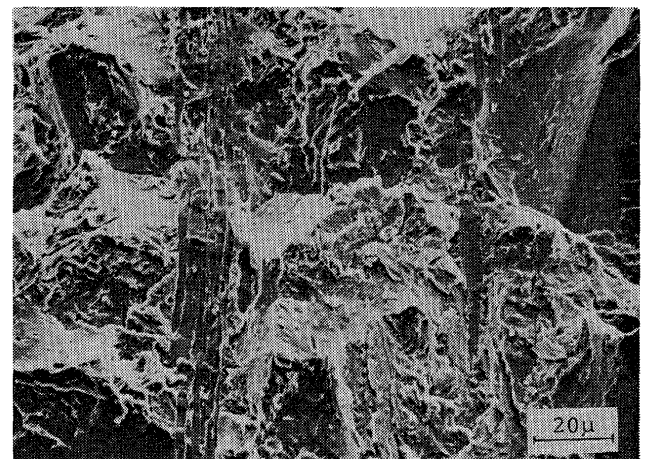
(a) vicinity of the root



(c) general feature

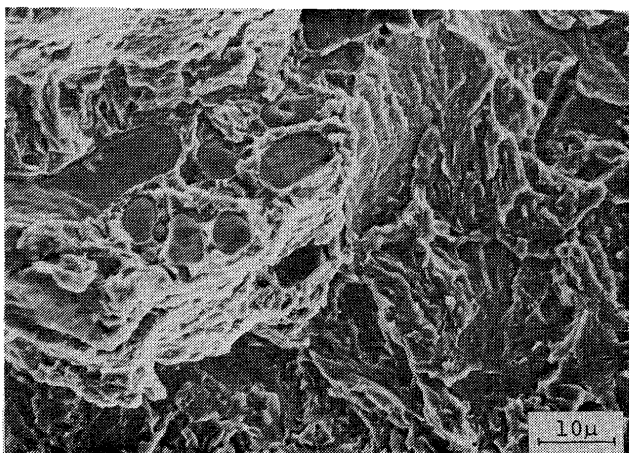


(b) EDX result of inclusion A in (a)

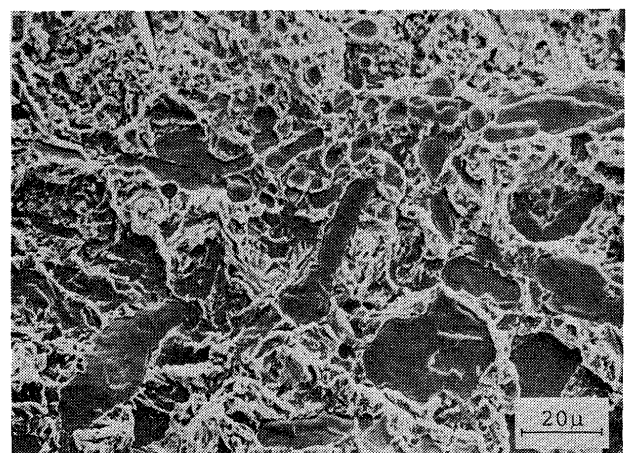


(d) elongated manganese sulphides on the cracked surface

**Photo. 9** Heel cracked surface occurred with Non-restraint *T* type cracking test<sup>5)</sup>. material; HT50 (16 mm thickness), electrode; D5016 (hydrogen; 4 cc/100 g), heat input; 17,000 J/cm, non-preheating

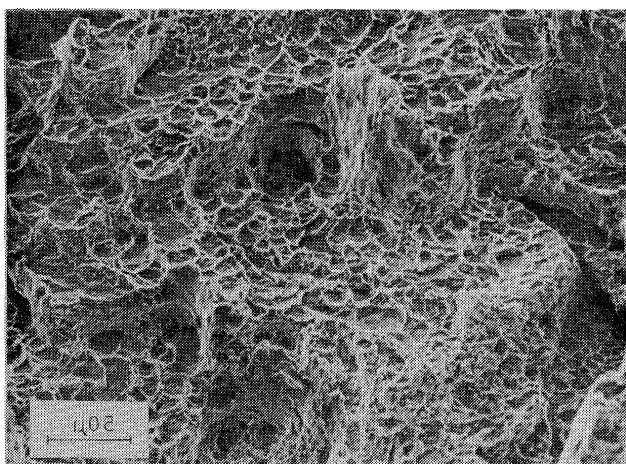


(a) cracked surface as a lamellar tearing

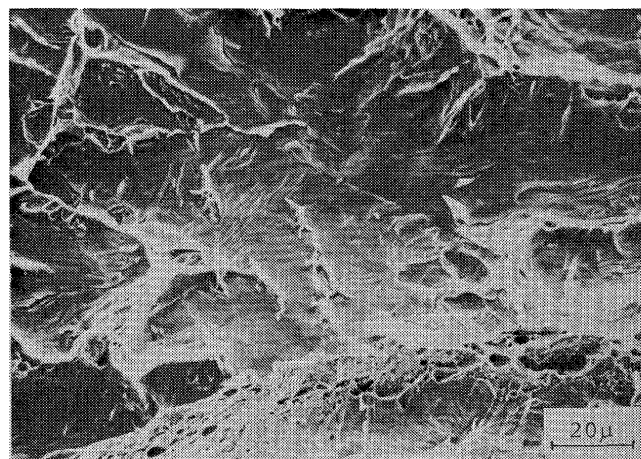


(b) cracked surface where manganese sulphides are clustered

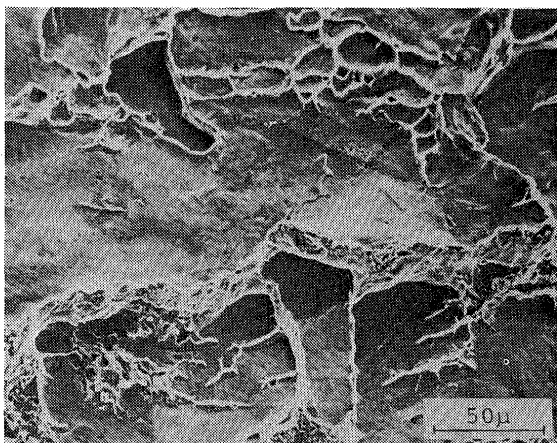
**Photo. 10** Another example of heel cracked surface. material; HT50 (40 mm thickness), other conditions are the same as in Photo 9.



(a) typical terrace and wall type

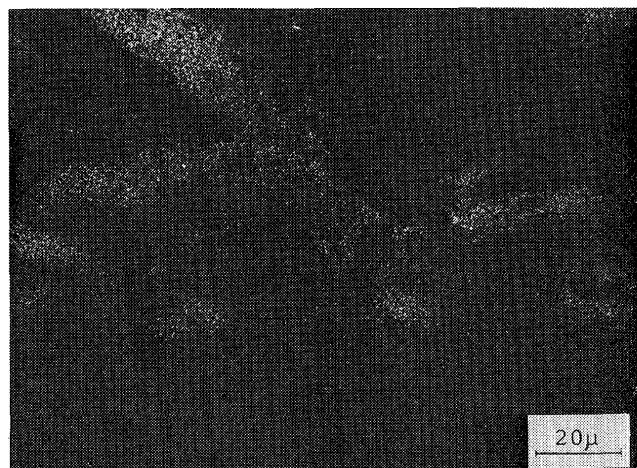


(a) secondary electron image



(b) another feature of terrace and wall type

**Photo. 11** Lamellar teared surface occurred in a corner joint. material; HT50 (40 mm thickness), electrode; D5016



(b) sulphur characteristic X-ray image of (a)

**Photo. 12** Lamellar teared surface occurred with Implant cracking test of thickness direction without notch. material; HT50 (same as in Photo 11), electrode; D5016 (hydrogen; 4 cc/100 g), applied stress; 40 kg/mm<sup>2</sup>, heat input; 17,000 J/cm, non-preheating

dimples, and the other portion is the terrace part. The bright lines in the terrace part are the tear ridges between matrices, and the other part shows a flat separation between the matrix and the inclusion. **Photo. 12(b)** is the sulphur characteristic X-ray image of Photo. 12(a), from which the distribution of manganese sulphides is distinctly observed.

### 2.2.3 Quenching Crack during Martensitic Transformation

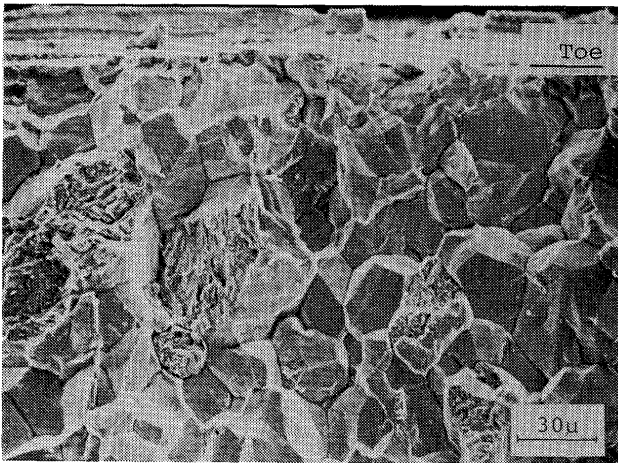
It was reported by Kobayashi et al.<sup>7)</sup> that another type of cold cracking, that is, a kind of quenching crack during martensitic transformation occurs in hardenable steels. **Photograph 13** shows a toe crack in a SAE4340 steel occurred by the same method as Kobayashi et al.<sup>7)</sup>. **Photograph 14** shows a similar crack occurred in an electron beam weld metal of a high

carbon bearing steel (JIS SUJ2). In both cracked surface, intergranular fractures are mainly observed, though transgranular fractures are partly observed.

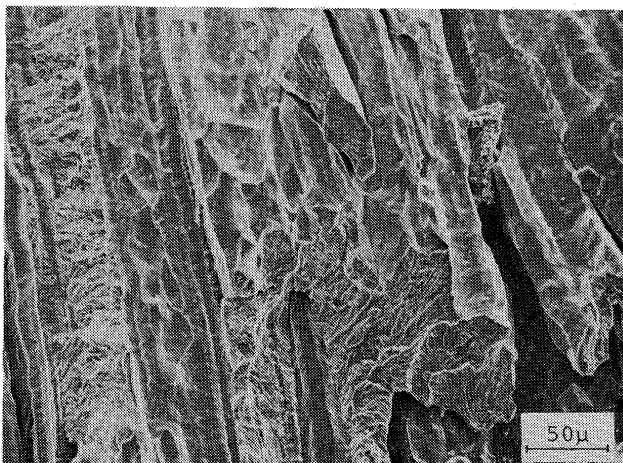
### 2.3 Reheat Cracking

When HT80 specimen of y-groove cracking test which was conducted in the environmental and welding conditions free from hydrogen-induced crack was annealed at 600°C as the stress-relief, a stress-relief crack readily occurred. **Photograph 15** shows the surface which is a typical intergranular fracture. The cracked surface of the specimen annealed for long duration was severely oxidized, and the feature of the intergranular fracture became obscure.

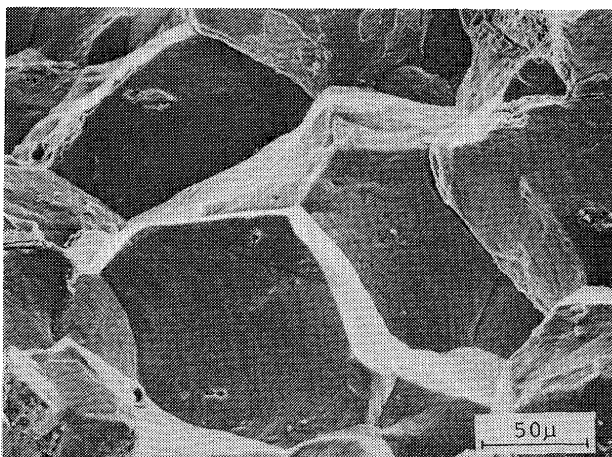




**Photo. 13** Toe cracked surface occurred in SAE4340 steel welds. thickness; 25 mm, electrode; D5016 (hydrogen; 4 cc/100 g), heat input; 25,000 J/cm, non-preheating, water quenched just after welding

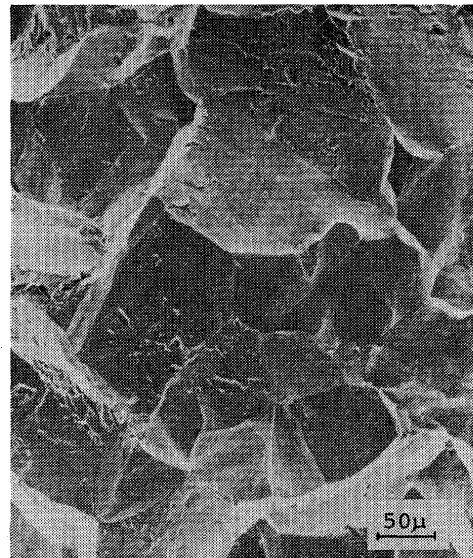


**Photo. 14** Cracked surface occurred in electron beam weld metal of SUJ2 bearing steel. thickness; 30 mm, welding condition; 150 kV, 40 mA, 1,000 mm/min

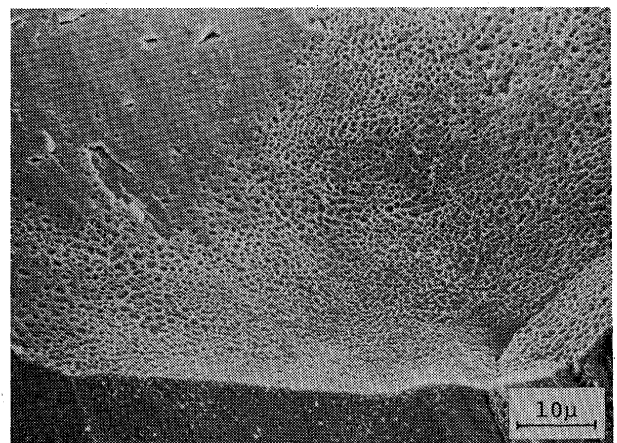


**Photo. 15** Stress-relief cracked surface occurred in HT80. electrode; E11016, heat input; 17,000 J/cm, annealing temperature; 600°C

**Photograph 16** shows an example of the cracked surface of a Ni-Cr-Mo low alloy steel which was overlaid with a stainless steel electrode and then annealed at 620°C as the stress-relief. This crack is called as under-clad crack in Japan. The cracked surface also shows the intergranular fracture, and the observation of a higher magnification often revealed many and small voids as seen in Photo. 16(b).



(a) lower magnification

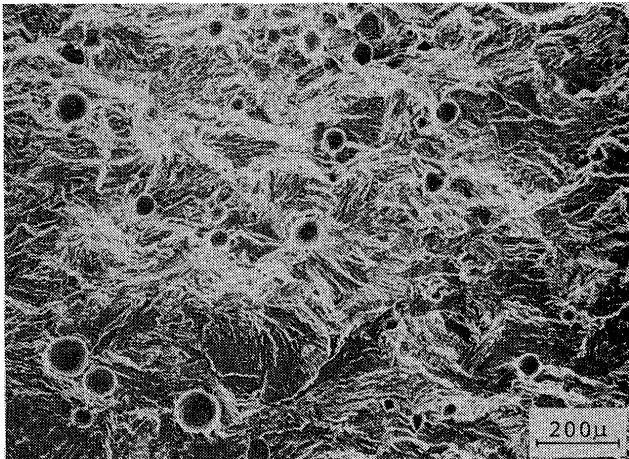


(b) higher magnification

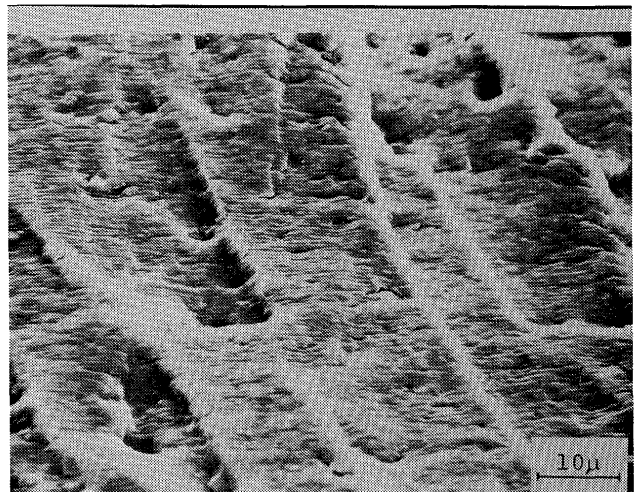
**Photo. 16** Under-clad cracked surface occurred in Ni-Cr-Mo low alloy steel overlaid with stainless steel electrode, annealing temperature; 620°C

#### 2.4 Blowhole

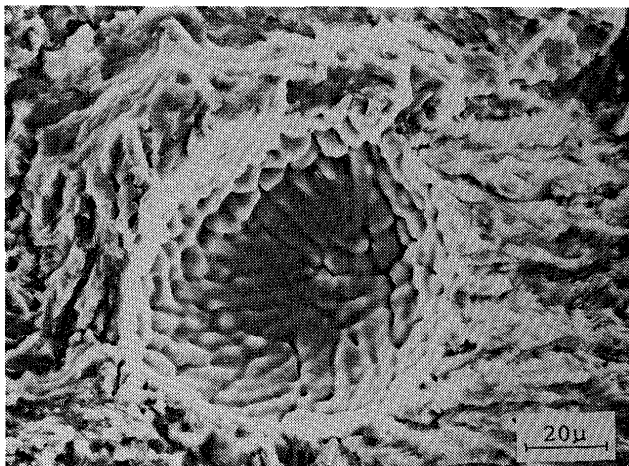
Many and small blowholes were sometimes observed on a fatigue fracture surface of MIG weld metal of aluminum alloy, as shown in **Photo. 17(a)**. The observation of a higher magnification revealed a feature of dendritic protuberances inside the blowhole, as shown in **Photo. 17(b)**. The feature of blowholes of another materials was the same.



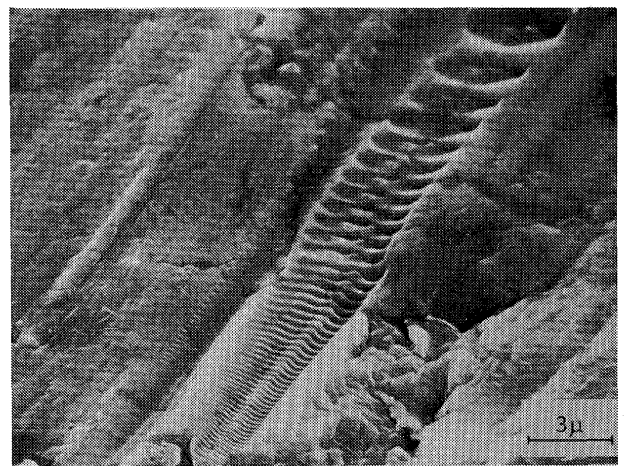
(a) lower magnification



(a) plateau and striation



(b) higher magnification



(b) tire track and rub mark

**Photo. 17** Blowhole observed on a fatigue fractured surface of 5083 aluminum alloy welds.

**Photo. 18** Fatigue fractured surface of 5083 aluminum alloy weld metal. testing method; Schenck bending type, electrode; 5183, stress; 10 kg/mm<sup>2</sup>,  $N$ ;  $2.6 \times 10^5$

## 2.5 Fatigue Fracture

An example of a fatigue fracture of MIG weld metal of aluminum alloy 5083 is shown in **Photo. 18**. Photograph 18(a) shows typical striations on plateaus, and Photo. 18(b) shows a tire track and rub mark which are another evidence of a fatigue fracture.

**Photograph 19** shows a fatigue fracture near a toe of electron beam welds of HT50 which occurred from the toe of welds. Major fracture surface was perhaps a kind of cleavage fracture as seen in Photo. 19(a), and an intergranular fracture was sometimes observed as seen in Photo. 19(b).

## 2.6 Stress Corrosion Cracking

**Photograph 20(a)** and **(b)** respectively show the examples of stress corrosion cracking in heat-affected

zone and weld metal of aluminum alloy (JIS 7N01), and both show intergranular features.

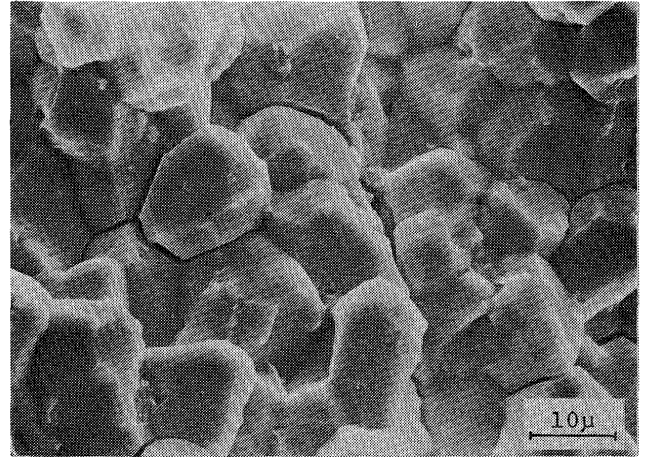
## 3. Summary

Some typical examples of various cracked and fractured surfaces were shown in this introductory report, but as indicated above there remain many unknown problems. Each detail shall be published hereafter by the authors as the investigation proceeds.

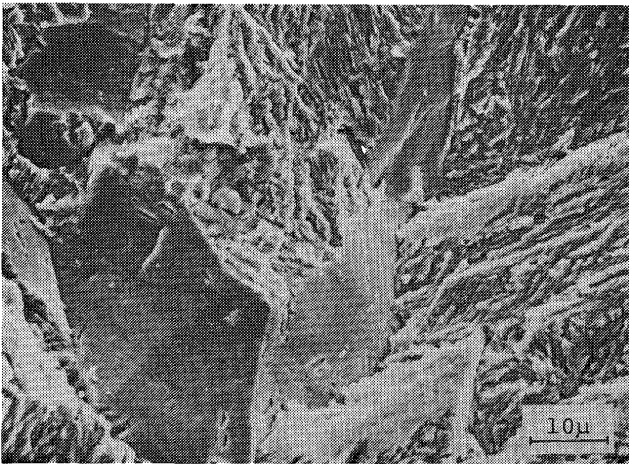
The authors would like to thank many industries for their offering samples and Mr. K. Tohmoto for his assistance.



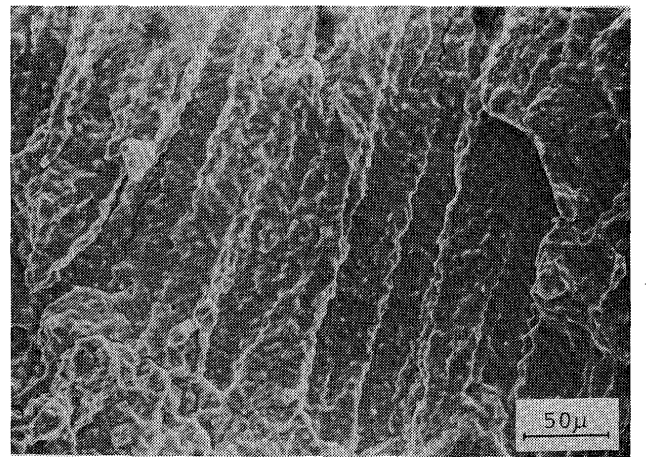
(a) cleavage-like fractured surface



(a) HAZ



(b) intergranular fractured surface



(b) weld metal

**Photo. 19** Fatigue fractured surface near toe part of HT50 electron beam welds. testing method; Schenck bending type, stress;  $18 \text{ kg/mm}^2$ ,  $N$ ;  $7.5 \times 10^5$

**Photo. 20** Stress corrosion cracked surface of 7N01 aluminum alloy welds. electrode; 5556, corrosive agent; chromate saline solution, stress; 75% of the proof stress

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