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# Strength of Candidate Materials for Nuclear Fusion Reactor and Their Electron Beam Welded Joint at Cryogenic Temperature†

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**Abstract**

*Tensile test of base metal and electron beam welded joint of some aluminum alloys (A7NO1, A5083, A6061) and a ferritic special steel (JFMS) was conducted at cryogenic temperature.*

*These materials are candidate materials for nuclear fusion reactor in Japan.*

*Testing temperatures were 293K, 77K and 4.2K. Most aluminum alloys and their welded joint exhibit serration in the tensile test at 4.2K. Base metal and welded joint of A5083-0 alloy exhibit comparatively high strength and high ductility at cryoginic temperature. Welded joint of A6061-T4 alloy and A7NO1-T6 alloy exhibits relatively low ductility at cryoginic temperature compaired with base metal. Base metal of JFMS exhibits brittleness at 77K. Welded joint of this steel exhibits high notch brittleness at the temperature between 293K and 77K.*

**KEY WORDS :** (Nuclear Fusion Reactor) (Cryogenic Temperature) (Aluminum Alloy) (Ferritic Special Steel) (Tensile Test) (Notch Brittleness) (Welded Joint)

## 1. Introduction

Aluminum alloys (A7NO1, A5083 and A6061) and ferritic special steel (JFMS) are selected as testing materials in this study from the candidate materials for nuclear fusion reactor in Japan. Aluminum alloys are expected as structural material at cryogenic temperature, because they do not exhibit low temperature brittleness and are excellent in processing ability, weldability, decrement characteristic of induction radioactivity, although they are not suitable to be used where the stress is high[1]. They are investigated to use as the materials for the first wall and super conductivity stabilization material of nuclear fusion reactor[2]. JFMS (Japanese Ferritic and Martensitic Steel) is selected as candidate material for nuclear fusion reactor in 9Cr - 2Mo ferritic steel[3]. 9Cr - 2Mo steel is a heat proof material but it is superior than austenitic stainless steel in resistance to swelling by neutron irradiation and resistance to helium embrittlement[2].

So, in this investigation, these materials are welded by electron-beam welding and the strength of base metal and welded joint is examined at cryogenic temperature. JFMS is a material for high temperature use but test is conducted at only low temperature, in this investigation.

## 2. Testing Method

### 2.1 Testing materials

Chemical composition and heat treatment condition are shown in **Table 1** and **Table 2**, respectively.

### 2.2 Processing of the materials

After the materials are welded by electron beam welding method in the condition shown in **Table 3**, the smooth specimen and notched specimen are sampled in the direction of rolling shown in **Fig.1.** Size of the specimens is shown in **Fig.2.** Small size of specimens are used under the consideration of evaporation of helium and capacity of testing machine. It has volume ratio of 1/360 compared with that of JIS No.4 specimen. The location of notch

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**Table 1** Chemical compositions and heat-treatments of All alloys

| Alloys | Chemical compositions(wt%) | | | | | | | | | | Heat treatment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Al | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Zr | |
| A7N01 | BAL. | 0.05 | 0.11 | 0.16 | 0.30 | 1.12 | 0.06 | 4.73 | 0.01 | 0.15 | 738K 90min{WQ}+393K 24h{AC} |
| A5083 | BAL. | 0.05 | 0.11 | 0.01 | 0.68 | 4.61 | 0.13 | 0.03 | 0.01 | – | 683K 90min{AC} |
| A6061 | BAL. | 0.72 | 0.12 | 0.18 | 0.01 | 0.50 | 0.00 | 0.04 | 0.005 | – | 803K 90min{WQ}+448K 8h{AC} |

**Table 2** Chemical compositions and heat-treatments of JFMS

| Material | Chemical compositions(wt%) | | | | | | | | | | | Heat treatment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fe | Si | Mn | Cr | Ni | C | P | S | Mo | V | Nb | |
| JFMS | BAL. | 0.67 | 0.58 | 9.58 | 0.94 | 0.05 | 0.009 | 0.006 | 2.31 | 0.12 | 0.06 | 1073K 30min{AC} |

**Table 3** Welding condition of used materials ($5\times10^{-5}$ Torr)

| Matelial | Welding position | Beam power (kw) | Beam voltage (kV) | Beam current (mA) | Welding speed (m/min) |
|---|---|---|---|---|---|
| A5083-0 A7N01-T6 | Flat | 4.8 | 60 | 82 | 0.6 |
| A6061-T4 | Flat | 4.8 | 60 | 90 | 0.3 |
| JFMS* | Horizontal | 8.0 | 100 | 60 | 0.6 |

* Beam oscillation :fx=30(Hz) , dx=3(mm)

agrees with the center of weld metal in welded specimen of aluminum alloys. The locations of notch agrees with weld metal, heat affected zone, and weld boundary in the specimen of JFMS steel.

### 2.3 Tensile test at cryogenic temperature

Testing apparatus used is shown in **Fig.3.** Cryostat has double structure which use the pre-cooling vessel with liquid nitrogen, made of SUS 304 steel. Tensile test is conducted by Autograph (AG-500A type : Capacity 500Kg). The load-displacement curve is recorded. Testing temperatures are room temperature (293K), liquid nitrogen temperature (77K) and liquid helium temperature (4.2K).

Crosshead speed is controlled in 0.1 mm/min for smooth specimen and 0.05 mm/min for notched specimen.

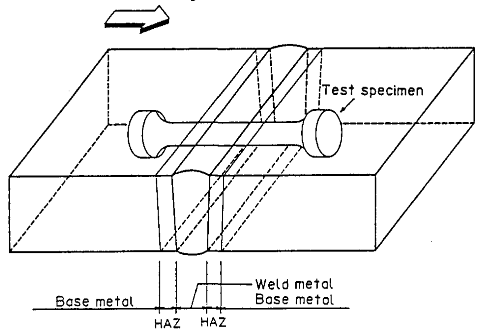



**Fig. 1** Sampling of test specimen from welded joint

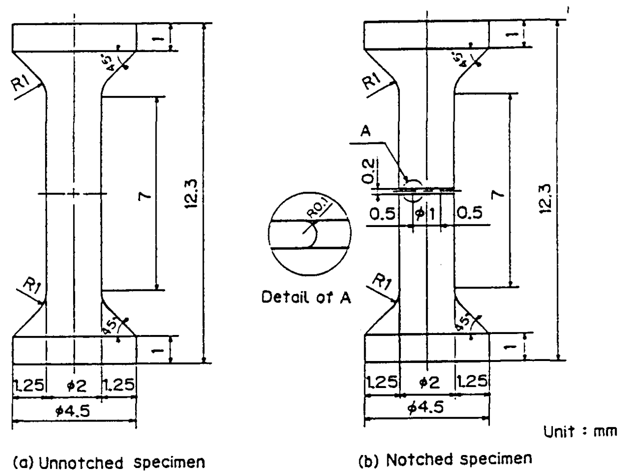



**Fig. 2** Test specimen

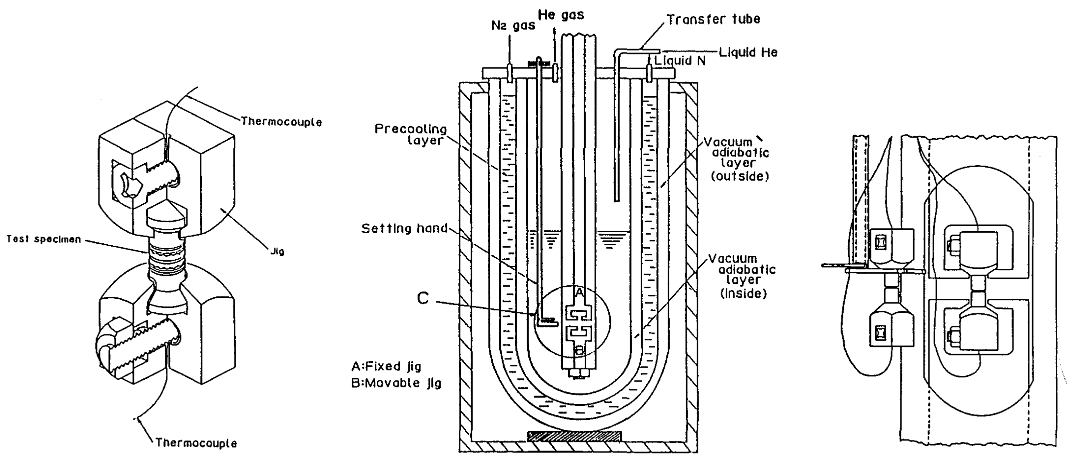
## 3. Results and Consideration

### 3.1 Tensile characteristics

*3.1.1 Nominal stress-nominal strain curve*

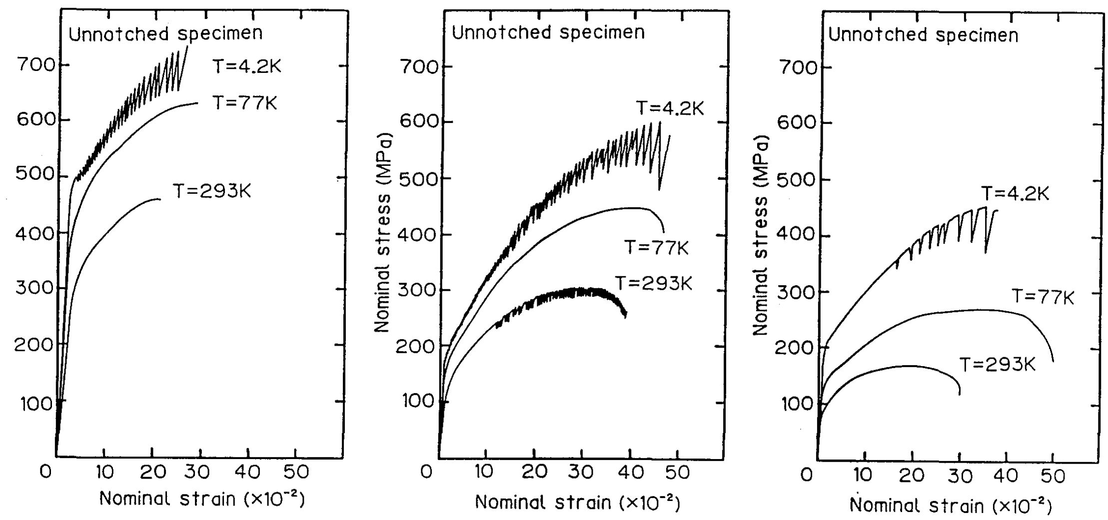
Testing results for base metal and welded joint of aluminum alloys are shown in **Fig.4** and **Fig.5**, respectively. The serration is observed in the result at 4.2K of every materials. The serration is also observed at room temperature for A5083. This phenomenon is due to strain aging which observed in the temperature range in which the speed of dislocation is larger than that of solute atom[4)5)], and it is a different phenomenon from the serration at 4.2K.

Nominal stress-nominal strain curve of JWMS is shown in **Fig.6**. The serration is not observed in this case. Strength of welded part is higher than that of base metal at 293K. Smooth specimen of welded joint fractured in the base metal at room temperature. However, smooth specimen fractured in welded joint at 77K and 4.2K. It is seemed that strength of welded joint of JFMS steel is lower than that of base metal at cryogenic temperatures.



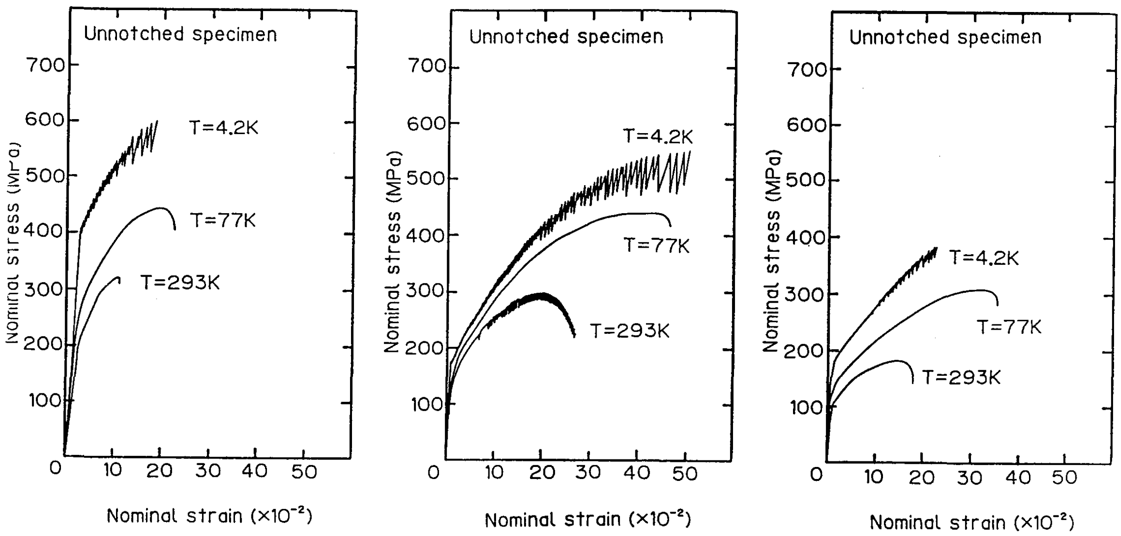

(a) Tensile device (b) Cryostat (c) Detail of C

**Fig. 3** Apparatus for cryogenic test




(a) A7N01 (b) A5083 (c) A6061

**Fig. 4** Nominal stress-nominal strain curves at test temperature of base metal (Al alloys)




(a) A7N01 (b) A5083 (c) A6061

**Fig. 5** Nominal stress-nominal strain curves at test temperature of welded joint (Al alloys)

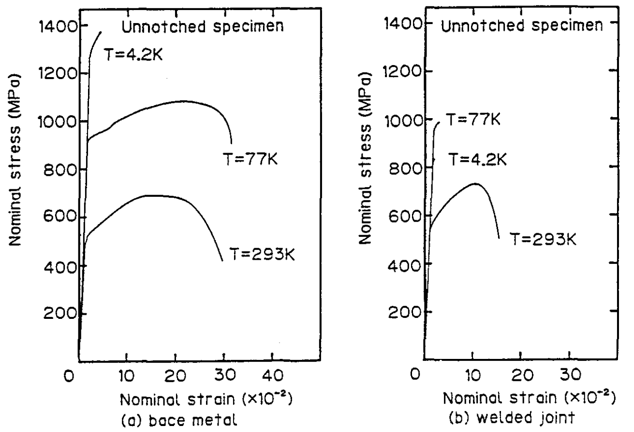



**Fig. 6** Nominal stress-nominal strain curves at test temperature of JFMS

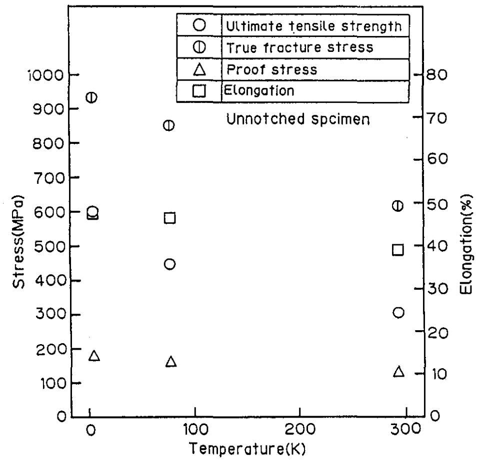



**Fig. 7** Change of the ultimate tensile strength, the true fracture stress, 0.2% proof stress and elongation to fracture against test temperature of base metal (A5083)

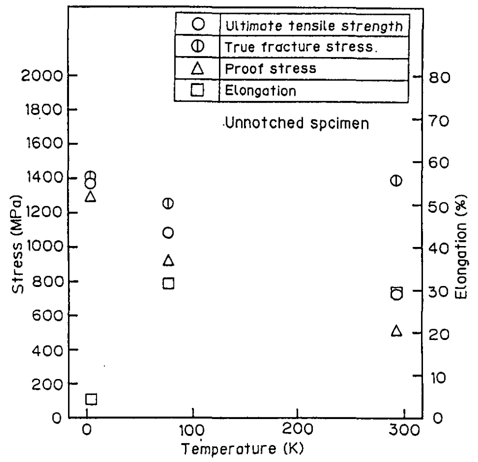



**Fig. 8** Change of the ultimate tensile strength, the true fracture stress, 0.2% proof stress and elongation to fracture against test temperature of base metal (JFMS)

Serration occurs because of stress relief or stress dropping due to instantaneous rearrangement of atoms or instantaneous slipping of atoms at unusual wide range. It was reported that a evident temperature rising recognized when the stress dropping occurred, in the serration of aluminum alloys.[6)7)]

From above observation mechanism of serration of aluminum alloys is considered as follows. The heat conductivity and specific heat of aluminum alloys decrease with the dropping of temperature, and the heat generated by local deformation during plastic deformation became hard to conduct, and the material softens, and decreasing of stress is occurred by large scale slipping. Then, hardening occurs by cooling of material due to heat conduction, and the stress rises again.

*3.1.2 Tempertature dependence of the strength*

Ultimate strength, 0.2% proof stress, true fracture stress, and elongation to fracture against temperature of base metal of A5083-0 alloy and JFMS steel are shown in Fig.7 and Fig.8, respectively. Ultimate tensile strength, 0.2% proof stress and true fracture stress increase with the decreasing of temperature besides in the case of welded joint of A7NO1-T6 alloy, and the strength of base metal is higher than that of welded joint for every alloys at 4.2K.

Welded joint of A5083 alloy also exhibits relatively high strength at 4.2K. Elongation increases with decreasing of temperature in the case of A5083-0 alloy, but it exhibits maximum value at 77K and decreases at 4.2K in the case of A6061-T4, A7NO1-T6 alloys.

Ultimate tensile strength and 0.2% proof stress of base metal of JFMS steel increases with decreasing of temperature but true fracture stress decreases to 77K and increases at 4.2K and equals to the value at 293K.

*3.1.3 Temperature dependence of ductility and toughness*

Change of the true strain $\varepsilon_U$, $\varepsilon_F - \varepsilon_U$ corresponding to the uniform and localized elongation against test temperature of A5083 is shown in **Fig.9**. Uniforms strain is large compared with the strain after necking in aluminum alloys. Temperature dependence of uniform elongation well corresponds to the temperature dependence of fracture strain mentioned before. Elongation after necking of base metal and welded joint of A5083-0 alloy decreases with the decreasing of temperature. Elongation after necking of base metal of A6061-T4 alloy exhibits maximum at 77K but that of welded joint decreases with decreasing of temperature.

Uniform elongation of JFMS steel increases at the range from 293K to 77K, but it decreases at 4.2K. This decrease influences greatly on the decrease of fracture elongation. Elongation after the necking decreases with decreasing of temperature and nearly equals to zero at

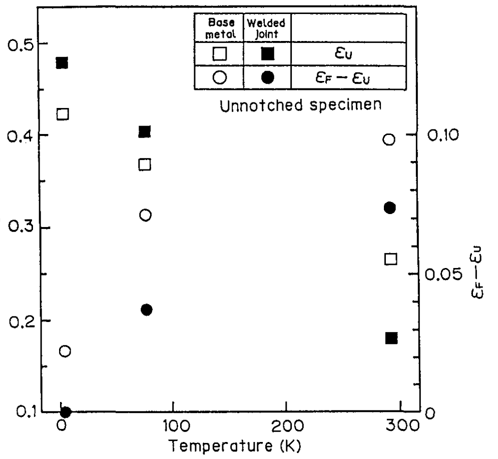



**Fig. 9** Change of the true strain u, F - u corresponding to the uniform and localized elongation against test temperature of A5083

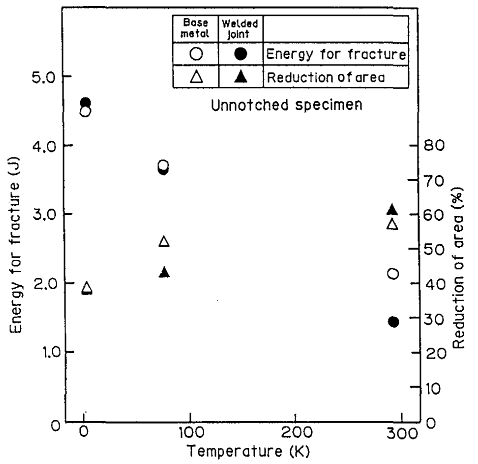



**Fig. 10** Change of energy for fracture and reduction of area against test temperature of A5083

4.2K. Uniform elongation and elongation after the necking both decrease with decreasing of temperature. Especially, elongation after the necking become to nearly zero below 77K.

Temperature dependence of reduction of area of A5083-0 alloy and JFMS steel are shown respectively in **Fig.10** and **Fig.11**. Temperature dependence of reduction of area exhibits good correspondence with that of real strain after necking occurs, and it is considered that considerable part of contraction occurs after the necking initiates. Energy for fracture, shown in Fig.10 is obtained by measuring the area under the load-displacement curve.

### 3.2 Notched bar tensile test

*3.2.1 Notch proof strength ratio*

Notch proof strength ratio (Notch tensile strength / smooth 0.2% proof stress) has good correlation with tear-

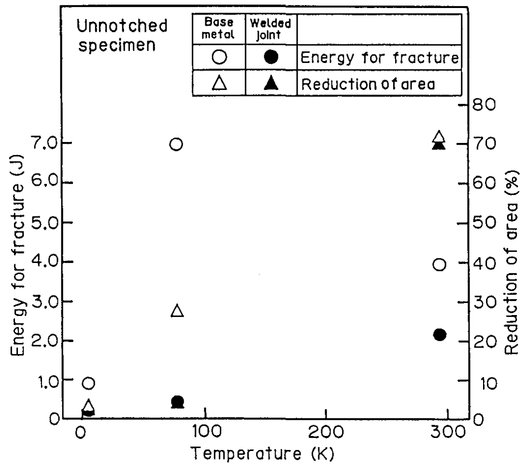



**Fig. 11** Change of energy for fracture and reduction of area against test temperature of JWMS

ing resistance and it is fracture toughness and accepted as a method to evaluate the toughness. Temperature dependence of notch proof strength ratio of A5083-0 alloy and JFMS steel are shown respectively in **Fig.12** and **Fig.13**. Notch proof strength ratio of base metal of 5083-0 alloy increases with decreasing of temperature, and that of base metal of the material decreases at 4.2K but it is larger than the value at room temperature. This indicates that A5083 alloy has considerable fracture energy even at the cryogenic temperature. Because notch yield strength

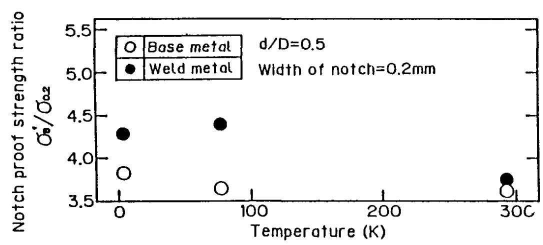



**Fig. 12** Change of notch proof strength ratio between notched and unnotched specimen against test temperature of A5083

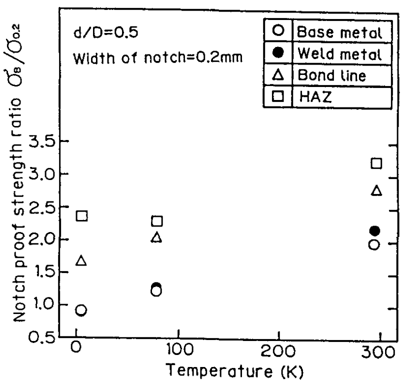



**Fig. 13** Change of notch proof strength ratio between notched and unnotched specimen against test temperature of JFMS

ratio of base metal and welded joint of JFMS steel decreases with decreasing of temperature, it is considered that JFMS steel is sensetive to the existence of notch and it is likely to occur brittle fracture at cryogenic temperature.

*3.2.2 Notch tensile strength ratio*

Notch tensile strength ratio (notch tensile strength / smooth tensile strength) indicates the notch sensitivity of material. Temperature dependence of notch tensile strength of A5083-0 alloy and JFMS steel are shown in **Fig.14** and **Fig.15**, respectively. Notch tensile strength ratios of all materials decrease with decreasing of temperature. It is indicated that the notch sensitivity of base metal and welded joint of these materials is high at cryogenic temperature.

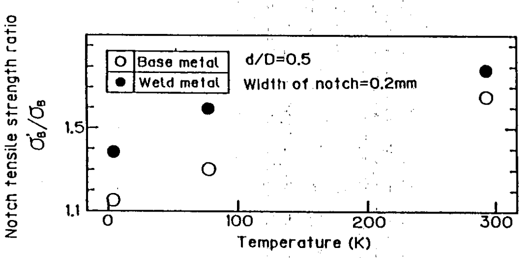



**Fig 14** Change of notch tensile strength ratio between notched and unnotched specimen against test temperature of A5083

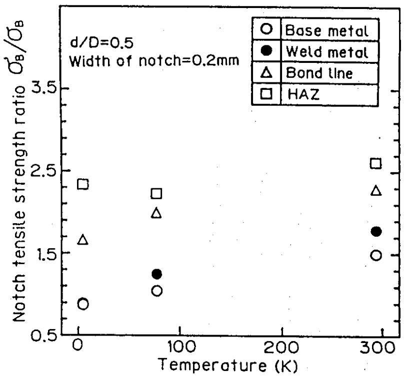



**Fig. 15** Change of notch tensile strength ratio between notched and unnotched specimen against test temperature of JFMS

## 4. Conclusion

Conclusions obtained by above experiments are shown as follows.

(1) Serration occurs in the tensile test of aluminum alloys at 4.2K. Dropping of stress in serration increases with increasing of strain. Frequency of generation of the serration decreases with increasing of strain. Serration of A5083-0 alloy initiates at the stress bellow the yield point.

(2) Base metal and welded joint of A5083-0 alloy exhibits the relatively high strength and high ductility. However notch sensitivity is high, sufficient plastic deformation occurs after initiation of yielding. Probability of use as the material for welded construction in nuclear fusion reactor at cryogenic temperature is relatively high.

(3) Strength of A6061-T4 alloy increases with decreasing of temperature but the strengh, the ductility and the notch toughness is low and use as the material for welded construction is not desirable.

(4) Base metal and welded joint of A7NO1-T6 exhibit high strength, but notch toughness is low.

(5) Base metal of JFMS steel exhibits brittleness below the temperature 77K and welded joint exhibits brittleness at the temperature range from 293K to 77K. Evident serration is not recognized, and notch brittleness recognized evidently.

**Acknowlegement**

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