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Hirokazu YAMADA and Hiroshi KAWAMURA

Blanket Irradiation and Analysis Group
Fusion Research and Development Directorate

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Division of Fusion Energy Technology
Fusion Research and Development Directorate
Japan Atomic Energy Agency
Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

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As a study about the joint technology of copper alloy and stainless steel for utilization as cooling piping in International Thermonuclear Experimental Reactor (ITER), Al_2O_3-dispersed strengthened copper or CuCrZr was joined to stainless steel by three kinds of joint methods (casting joint, brazing joint and friction welding method) for the evaluation of the neutron irradiation effect on joints. A neutron irradiation test was performed to three types of joints and each copper alloy. The average value of fast neutron fluence in this irradiation test was about $2X10^{24}n/m^2$(E>1MeV), and the irradiation temperature was about 130°C. As post-irradiation examinations, tensile tests, hardness tests and observation of fracture surface after the tensile tests were performed.

All type joints changed to be brittle by the neutron irradiation effect like each copper alloy material, and no particular neutron irradiation effect due to the effect of joint process was observed. On the casting and friction welding, hardness of copper alloy near the joint boundary changed to be lower than that of each copper alloy by the effect of joint procedure. However, tensile strength of joints was almost the same as that of each copper alloy before/after neutron irradiation. On the other hand, tensile strength of joints by brazing changed to be much lower than CuAl-25 base material by the effect of joint process before/after neutron irradiation. Results in this study showed that the friction welding method and the casting would be able to apply to the joint method of piping in ITER.

This report is based on the final report of the ITER Engineering Design Activities (EDA).

Keywords: Copper Alloy, Stainless Steel, Joint Material, Neutron Irradiation, ITER

+: Policy Planning and Administration Department (Serve concurrently in Division of Fusion Eergy Technology)

銅合金/ステンレス鋼接合材の中性子照射試験

日本原子力研究開発機構核融合研究開発部門
核融合エネルギー工学研究開発ユニット
山田　弘一・河村　弘+

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国際熱核融合実験炉(ITER)における冷却配管のための銅合金とステンレス鋼の接合方法に関する研究として、銅合金にアルミナ分散強化銅（Al_2O_3 含有率：0.5wt%(CuAl-25)）及び CuCrZr を選定し、ステンレス鋼（SUS316LN-IG）との各種接合方法による接合材を製作し、中性子照射効果の評価を行った。照射試験として、高速中性子照射量 約 $2\times10^{24}n/m^2$(E>1MeV)及び照射温度約130℃にて中性子照射を行った後、照射後試験として、引張試験、硬さ試験及び破面観察を行った。

その結果、中性子照射により、いずれの接合材も脆化したが、接合による影響に起因する中性子照射効果は認められなかった。接合による影響としては、硬さ試験の結果から、鋳込み接合法及び摩擦圧接法では、接合による影響で接合界面近傍の銅合金の硬さの低下が確認された。しかしながら、中性子照射前後とも、引張強度は接合材、銅合金ともに同等の特性であった。一方、ロウ付け接合材は照射材、未照射材とも、接合により著しい引張強度の低下が見られた。

以上のことから、鋳込み接合材及び摩擦圧接接合材については、本研究で用いた接合要領が、核融合炉における異種接合方法として適用できることを明らかにした。

本報告書は、ITER工学設計書に補筆を行ったものである。

大洗研究開発センター：〒311-1393　茨城県東茨城郡大洗町成田町4002
+：経営企画部（核融合エネルギー工学研究開発ユニット兼務）

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1. Introduction

From the requirement in the design condition of International Thermonuclear Experimental Reactor (ITER), some kinds of material will be applied to the each equipments of ITER. At the plasma facing material or heat sink, copper alloys such as CuCrZr and CuAl-25 are promising due to their high heat conductivity and sufficient high-temperature strength [1]. Stainless steel such as SS316LN-IG is a promising material for structure material and cooling water piping lines [2]. For the application of various materials, studies about joining technique were performed in the research and development of ITER, and the evaluation of neutron irradiation effect on joints material is necessary.

A solid hot isostatic pressing (HIP) method as a joining procedure for copper alloy/stainless steel has been studied for the primary wall fabrication in ITER engineering Task [3]. On the other hand, casting, brazing and friction welding method have been proposed in ITER engineering Task for joint method of copper alloy/stainless steel joint as coolant water piping line connection. However, final joint method for the coolant water piping line connection has not been fixed yet. This issue was investigated within recent R&D of ITER, and the evaluation of the effect of joint procedure and the neutron irradiation effect on joint material is required.

In this study, the neutron irradiation effects on mechanical properties of joint materials were evaluated in an ITER engineering Task (T427 subtask-1).

2. Fabrication of Joint Material

2.1 Materials

Joint methods and materials used in this study are shown in Table 1.

Three kinds of joint methods (casting joint, brazing joint and friction welding joint) were studied as the joint method for cooling water piping line connection. The joints of CuCrZr and SS36LN-IG fabricated by casting were prepared by the Russian Federation Home Team of ITER (RFHT).

CuAl-25/SS316LN-IG joints fabricated by brazing joints and friction welding methods were prepared by the Japan Home Team of ITER (JAHT). Al_2O_3-despersed copper alloys (CuAl-25) and SS316LN-IG were used in the brazing and friction welding method. Chemical compositions of each copper alloy and SS316LN-IG are shown in Table 2 and Table 3, respectively.

2.2 Joint Procedures

Details of three kinds of joint methods in this study are shown as follows.

2.2.1 Casting Joint

The fabrication procedure and temperature history of casting procedure are shown in Fig.1 and Fig.2, respectively. Tensile specimens for post-irradiation examinations (PIEs) were prepared from the casting joints and the CuCrZr base materials. Casting of CuCrZr onto stainless steel was performed at 1100°C in a vacuum vessel. In the heat treatment, the solution annealing condition was 980°C x 1h, and water quenching was performed. After that, the aging(500°C x 3.5h) was performed. As an inspection for the CuCrZr/SS316LN-IG casting joint material, an ultrasonic test was performed, and it was confirmed that there were no defect like crack or pore at the joint area.

2.2.2 Brazing Joint

Details of the fabrication procedure and temperature history of brazing procedure are shown in Fig.3 and Fig.4, respectively. The temperature ramp rate up to the brazing temperature was 500°C/h. The brazing temperature was 980°C, and the soaking period was 5min. The brazing was carried out under a vacuum. Then, joints were cooled in the furnace from 980°C to 300°C. The brazing filler metal was selected by the wettability of base filler metal, melting point and application environment, and the composition of the brazing filler metal is shown in Table 4. CuAl-25 material was the cross rolled plate. In this study, tensile specimens of joint material and CuAl-25 base material were fabricated, and these specimens were arranged that the tension direction of the tensile test was short transverse.

2.2.3 Friction Welding Method

The fabrication flow and the condition of the friction welding method are shown in Fig.5 and Fig.6, respectively. A brake-type friction welding machine was employed. In this joint type, parameters of welding conditions are the friction pressure, the friction time, the upset pressure and the upset time. These conditions were decided by preliminary fabrication tests [4,5]. The CuAl-25 material for friction welding was rod material made by a drawing process. From the results of preliminary fabrication tests, the optimum conditions of the friction welding were selected as the following; the friction pressure was 84.3MPa, the friction time was 0.5sec, the upset pressure was 164.8MPa and the upset time was 7.0s. Tensile specimens for PIE were prepared from the CuAl-25/SS316LN-IG joints and CuAl-25 base material.

For PIEs, tensile specimens were fabricated from each joint material and each copper alloy materials. The dimension of the tensile specimens is shown in Fig.7.

3. Neutron Irradiation Test

Three types of joints and each copper alloy material were irradiated during two operating cycles of Japan Materials Testing Reactor (JMTR). The operating period of JMTR was about 25 days per one operating cycle. Two capsules (capsule name: 99M-52J and 99M-53J) for the neutron irradiation test were fabricated. The structure of the capsules is shown in Fig.8. Two capsules were arranged to be in an equal irradiation condition. Locations of these capsules in JMTR reactor are shown in Fig.9.

The irradiation condition in this study was decided in the ITER engineering Task (T427 subtask-1), and it was based on the condition of cooling water piping in divitor at an early design of ITER. As for the target values of the irradiation condition in this study, the irradiation damage is 0.3dpa and the irradiation temperature is 150°C.

In this study, the irradiation temperature was estimated by the result of calculation using ABAQUS code [6], and the irradiation damage was estimated by the result of a calculation using MCNP code [7]. On the calculation parameters of ABAQUS, the temperature of the coolant water was 50°C and the heat transfer coefficient of the outer pipe was 1.16 W/m^2K

For arrangement of irradiation conditions, the irradiation position and the irradiation period in JMTR were determined by results of these calculations.

Actual irradiation damage in this irradiation test was determined by fluence monitors that were set in the irradiation capsules.

Details of the irradiation damage and irradiation temperature are shown in Fig.10 and Fig.11.

4. Post-irradiation Examinations (PIEs)

4.1 Test Procedure

Tensile tests, fracture surface observation and hardness tests were carried out to evaluate the properties of the joints.

Tensile tests were performed in air at two temperatures (25˚C and 150˚C), and 0.2% yield strength (0.2%YS), ultimate tensile strength (UTS) and total elongation (TEL) were measured. A crosshead speed of 0.1 mm/min was used before the yield strength, and after that the crosshead speed was changed into 1 mm/min. The fracture surfaces after tensile tests were observed by scanning electron microscopy (SEM).

Hardness tests were performed using a Vicakers micro-hardness tester with a knoop indenter. The weight and the loading period of the hardness tests were 1000g and 30s, respectively.

4.2 Tensile Test

Results of the tensile tests of the joints by each joint method are shown in Fig.12, Fig.13 and Fig.14.

Tensile properties of joint materials were compared with those of the copper alloy base material, because these results of the tensile tests show that casting joints and friction welding joints broke at the part of copper alloy and that brazing joints broke at the joint boundary (see Fig.15 and Fig.16).

The neutron irradiation effect on each joint material can be summarized as follows.

1) Casting joints

Results of tensile tests for the CuCrZr/SS316LN-IG joints by casting and the CuCrZr base material are shown in Fig.12. The comparison of irradiated joints and un-irradiated joints shows that joints specimens changed to be brittle by the neutron irradiation effect like the CuCrZr base material, and that tensile properties of irradiated joints was almost the same as those of the CuCrZr base material based on the influence by the casting process. As a result of the comparison between joints and CuCrZr base material, 0.2%YS and TEL of un-irradiated joints were smaller than those of CuCrZr base material. However, UTS of un-irradiated joint were almost the same as those of the CuCrZr base material. It is concluded that CuCrZr/SS316LN-IG joints by casting is almost the same as the CuCrZr base material on tensile properties before/after neutron irradiation. Therefore, the casting joint procedure was able to join CuCrZr and SS316LN-IG successfully.

2) Brazing joints

Results of tensile tests of the CuAl-25/SS316LN-IG joints by brazing and the CuAl-25 base material are shown in Fig.13. Both of irradiated joints and un-irradiated joint were broken at the joint boundary, and then 0.2%YS and TEL of the joints were not able to measure. It is considered that the tensile strength of the filler metal was lower than that of CuAl-25 and SS316LN-IG.

3) Friction welding joints

Results of tensile tests of the CuAl-25/SS316LN-IG joints by the friction welding method and CuAl-25 are shown in Fig.14. The comparison of irradiated joints and un-irradiated joints shows that these joints changed to be brittle by the neutron irradiation and it was same on CuAl-25 base material.

All joint specimens were broken at CuAl-25 part near the joint boundary. Therefore, it is considered that the friction welding procedure was able to join CuAl-25 and SS316LN-IG successfully. However, the tensile properties of the CuAl-25/SS316LN-IG joints were different from those of CuAl-25 although the fracture position of the joints was the part of CuAl-25. Generally, plastic deformation in the friction welding process makes scroll structure near the joint boundary. Especially, elongation may decrease in the case of the friction welding joints due to materials including many nonmetallic inclusions like alumina. The effect of the plastic deformation at friction welding process changed the mechanical property of CuAl-25 near the joint boundary [8].

4) Comparison between three types of joint materials

The comparison between three types of joints shows that UTS and 0.2%YS of the CuAl-25/SS316LN-IG joints by the friction welding method were larger than those for other joints. On the other hand, TEL of the CuCrZr/SS316LN-IG joint by casting was larger than that of other joints. On the comparison of CuCrZr and CuAl-25, tensile strength of CuAl-25 was bigger than that of CuCrZr both in irradiated and un-irradiated conditions. It is considered that mechanical properties of joints were based on those of the copper alloy.

Results of fracture surface observations of un-irradiated tensile specimens after the tensile tests at 150°C are shown in Fig.17 and Fig.18 for different magnifications. Those of irradiated specimens are shown in Fig.19 and Fig.20. The results of fracture surface observation shows that the status of fracture did not changed by the neutron irradiation effect because fracture surfaces of irradiated material were almost the same as those of the un-irradiated materials.

About casting joint specimens, a dimple pattern was observed at the fracture surface, and this pattern shows that the casting joint fractured by ductile fracture like the case of CuCrZr base material.

On the other hand, a groove pattern was observed at the fracture surface of the friction welding joints by the effect of plastic deformation in the friction welding process, and the fracture surface of the joint specimen was different from that of CuAl-25 base material.

About the brazing, deformation of the filler metal was observed as a bumpy pattern at the fracture surface of brazing joints.

4.3 Hardness Test

1) CuCrZr/SS316LN-IG joints by casting

Result of hardness tests for the CuCrZr/SS316LN-IG joint by casting is shown in Fig.21. The hardness of SS316LN-IG was almost the same at all the test positions. On the other hand, on the part of CuCrZr, the hardness near the joint boundary was lower than the hardness of the bulk part of CuCrZr or the hardness of CuCrZr material. It is considered that the joint process affected the hardness of CuCrZr near the joint boundary.

2) CuAl-25/SS316LN-IG joints by brazing joint method

Result of hardness tests for the CuAl-25/SS316LN-IG joint by brazing is shown in Fig.22. The hardness of SS316LN-IG and CuAl-25 was almost uniformly distributed at all the test positions. It is clear that the joint process did not affect the hardness of the base material.

3) CuAl-25/SS316LN-IG joints by friction welding method

Result of hardness test for the CuAl-25/SS316LN-IG joint by friction welding method is shown in Fig.23. The hardness of SS316LN-IG near joint boundary was a little bigger than that of bulk part of SS316LN-IG or SS316LN-IG base material because of the work hardening by the plastic deformation in the friction welding process. On the other hand, the hardness of CuAl-25 near the joint boundary was lower than the hardness of bulk part of CuAl-25 or CuAl-25 base material. It is considered that the friction welding process affected the hardness of CuAl-25 near the joint boundary.

5. Conclusions

A neutron irradiation test and PIEs have been carried out to clarify the neutron irradiation effect on the mechanical properties of three types of joints. Three types of joint and base materials were irradiated to about 0.3dpa (average value of fast neutron fluence: $2x10^{24}$ n/m^2 (>1MeV)). The irradiation temperature was about 130°C. Mechanical properties of joints were evaluated by tensile test, fracture surface observation and hardness tests.

Results of PIEs show that no particular neutron irradiation effect was observed in any types of joints due to the effect of joint process, and the joints were emblitteled by the neutron irradiation like each copper alloy material.

CuCrZr/SS316LN-IG joints by casting and CuAl-25/SS316LN-IG joints by the friction welding method changed the mechanical properties of copper alloy near joint boundary, because the hardness of copper alloy near each joint boundary changed to be low. However, the tensile properties of these two types joints were almost the same as that of each copper alloy after neutron irradiation. Therefore, the casting and friction welding methods will be able to be applied as joint methods for the cooling water piping of copper alloy and SS316LN-IG in ITER.

On the other hand, it is necessary to improve the joining condition for the fabrication of CuAl-25/SS316LN-IG joint by brazing.

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Table 1 Joint methods and material in this study

Joint method	Copper alloy	Stainless steel	Note
Casting	CuCrZr	SS316LN-IG	Prepared by RFHT[*1]
Brazing	CuAl-25		Prepared by JAHT[*2]
Friction welding			

*1: Russian Federation Home Team of ITER

*2: Japan Home Team of ITER

Table 2 Chemical compositions of copper alloys.

Material		Cu	Pb	Fe	Bi	As	Zn	Sn	Ni	Al	B	Cr
For Casting	CuCrZr	Base	0	0	0	0.01	0.01	0.01	0.03	-	-	0.6
For brazing	DSCu (CuAl-25)	99.5	6	13	3	1	15	6	-	0.25	0.02	-
For Friction welding	DSCu (CuAl-25)	99.5	6	18	-	-	-	-	~25	0.26	0.02	

Material		Zn	Cd	He	Te	P	S	Sb	Mn	Co	Other
For Casting	CuCrZr	0.07	-	-	-	-	-	-	-	-	-
For brazing	DSCu (CuAl-25)	-	1	1	1	1	3	2	1	-	-
For Friction welding	DSCu (CuAl-25)	-	-	-	-	-	-	-	~25	-	-

(Unit [unshaded]:wt% [shaded]:ppm)

Table 3 Chemical compositions of SS316LN-IG. (wt%)

	C	Mn	Si	P	S	Cr	Ni	Mo	Nb	Cu	Co	N	B (ppm)
SS316LN-IG Standard	0.015 – 0.03	1.60 – 2.00	– 0.5	– 0.025	0.005 – 0.01	17.0 – 18.0	12.0 – 12.5	2.3 – 2.7	– 0.15	– 0.3	– 0.25	0.06 – 0.08	– 20
For Casting	0.03	1.7	0.012	0.012	0.008	18.17	12.32	2.52	-	0.01	0.012	0.08	-
For Brazing	0.029	1.64	0.44	0.012	0.009	17.48	12.11	2.56	<0.01	0.09	0.02	0.067	<3
For Friction Welding	0.029	1.6	0.44	0.014	0.007	17.33	12.14	2.62	<0.01	0.04	0.05	0.076	<3

Table 4 Chemical composition of brazing filler metal. (wt%)

	Major			Minor							
	Cu	Mn	Ni	Al	Ag	In	Ca	Mg	Si	Mo	Bi
Cu-Mn-Ni	52.13	37.99	9.88	0.003	0.003	<0.001	0.001	<0.0001	0.006	<0.01	0.004

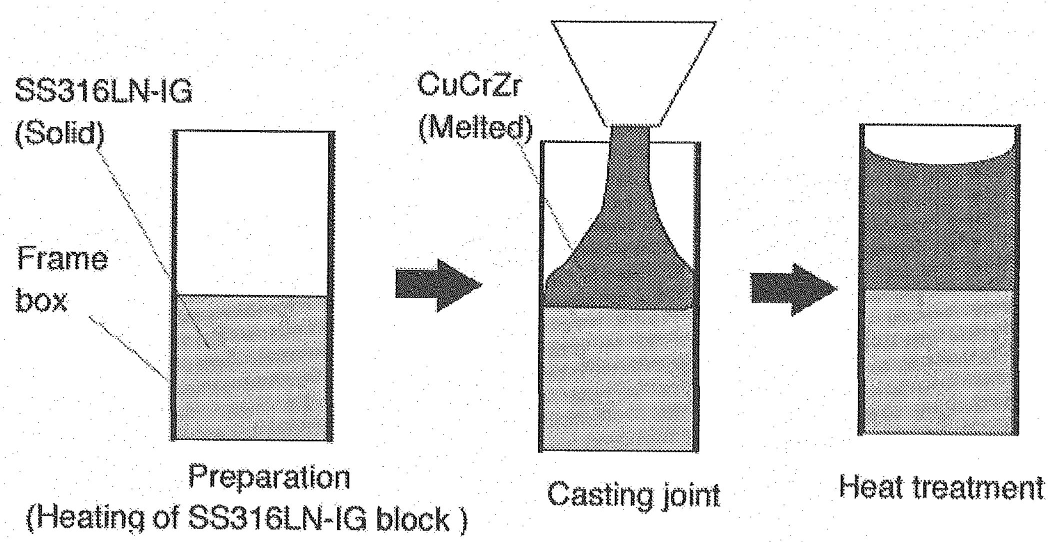


Fig.1 Fabrication procedure of casting Joint.

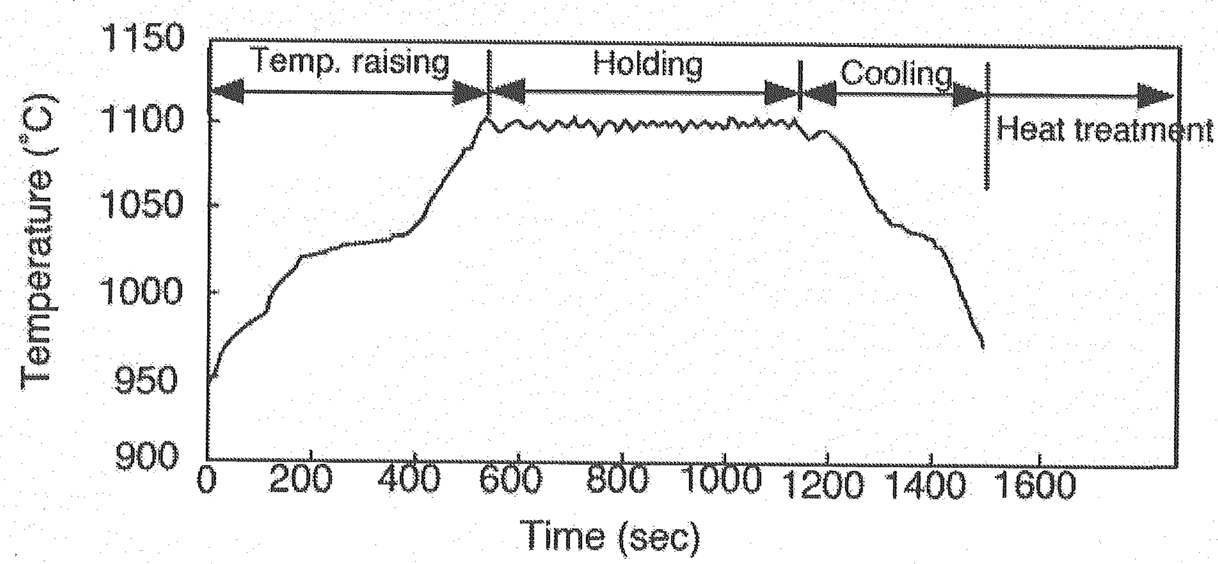


Fig.2 Temperature history in casting process for fabrication of CuCrZr/SS316LN-IG joint.

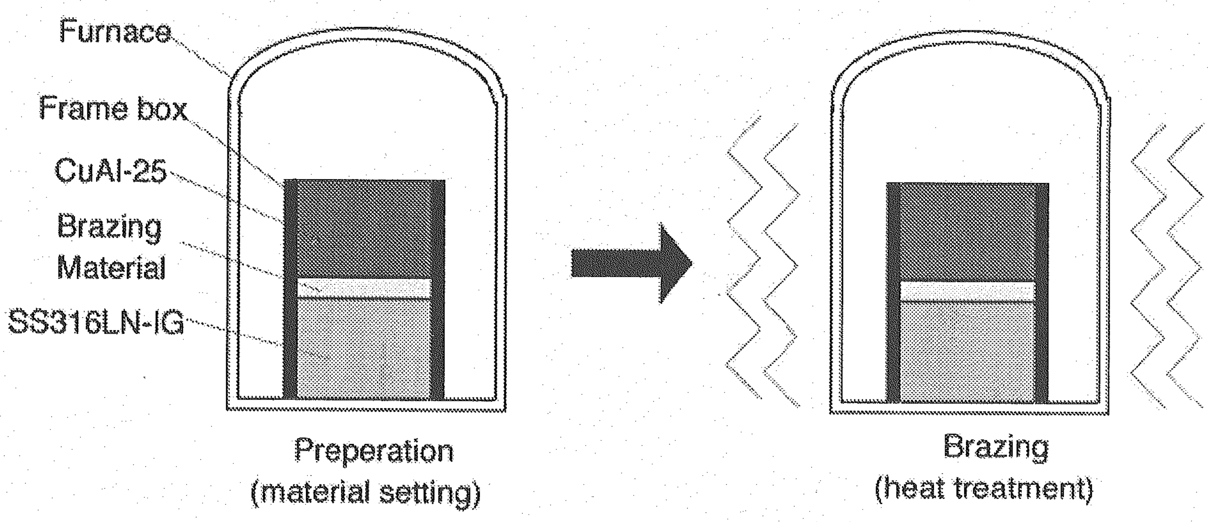


Fig. 3 Fabrication procedure of brazing Joints.

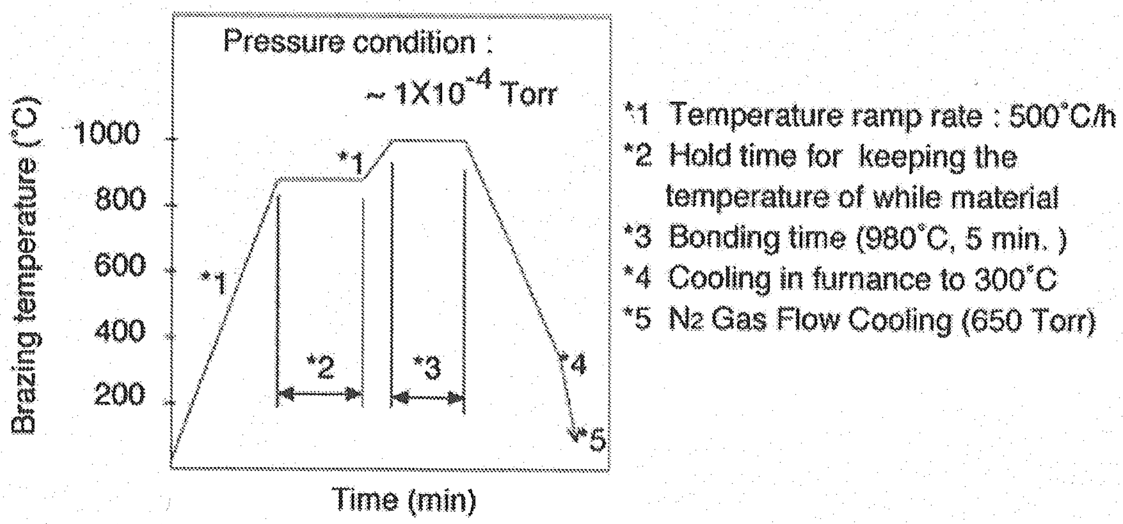


Fig.4 Temperature history in brazing joint process for the fabrication of CuAl-25/SS316LN-IG joint.

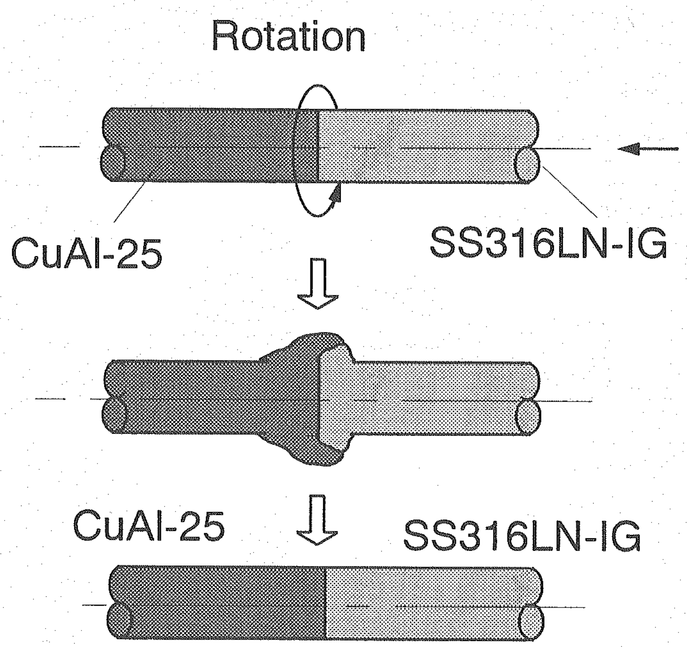


Fig. 5 Fabrication procedure of friction welding joints.

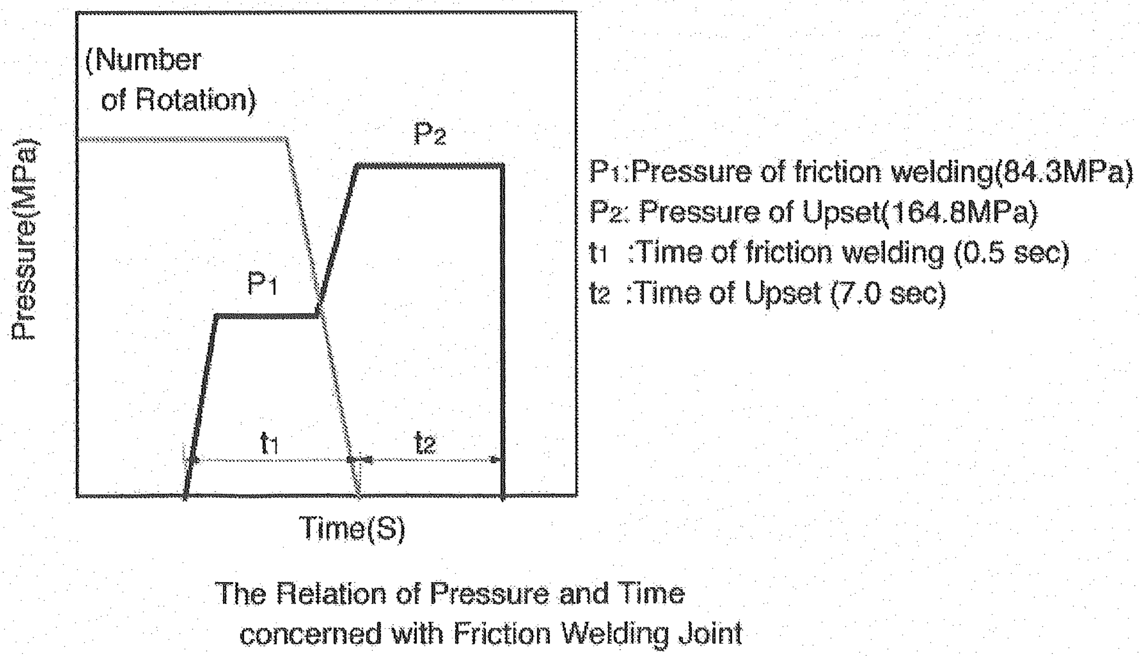
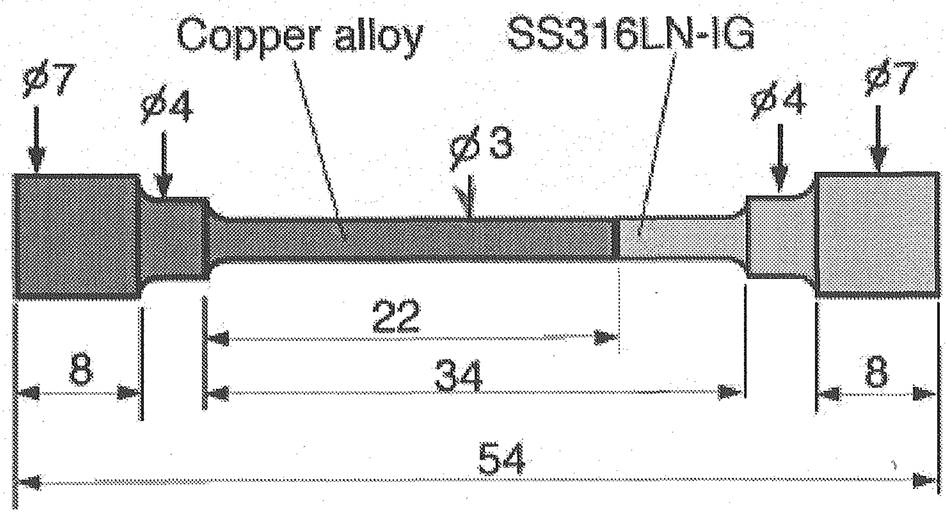
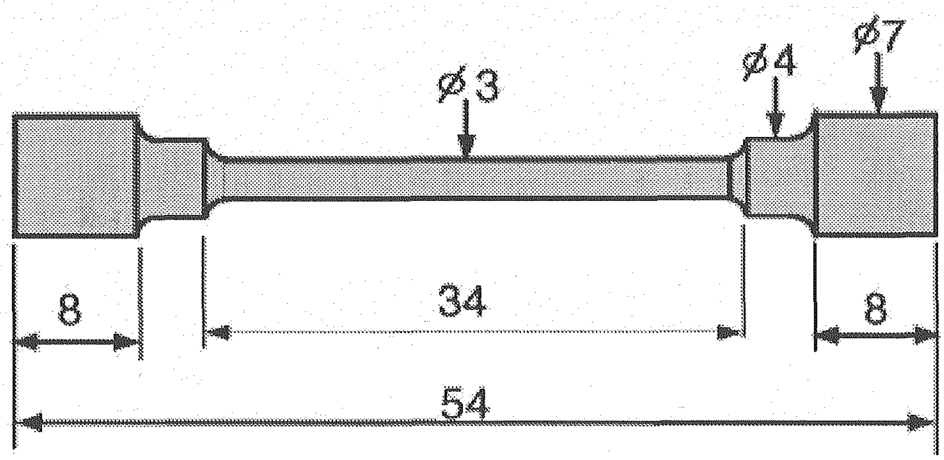


Fig.6 Detail procedure on the fabrication of CuAl-25/SS316LN-IG joint during friction welding.



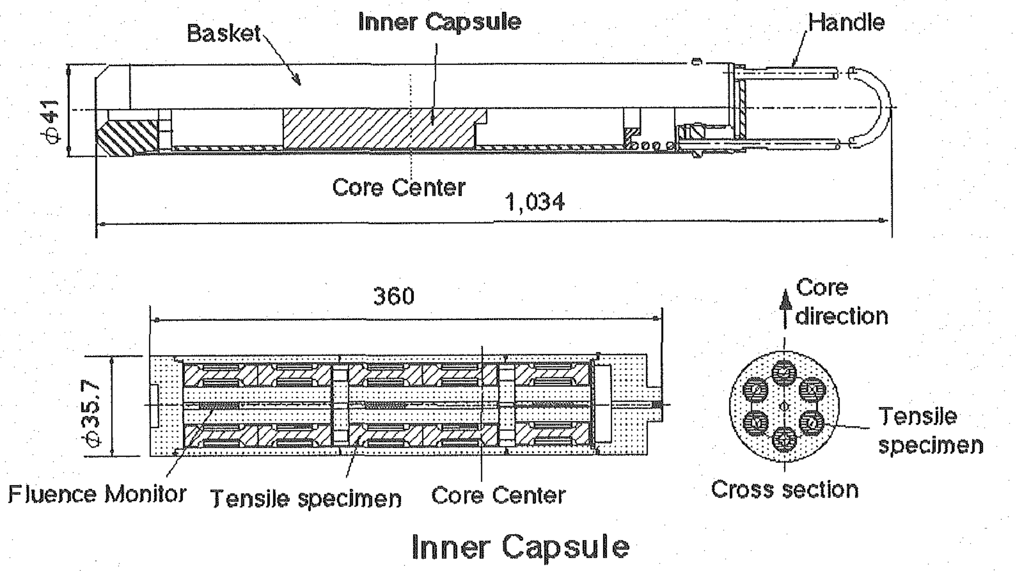
(a) Joint specimen



(b) Base material specimen

(Unit:mm)

Fig.7 Dimension of tensile specimens.



(unit:mm)

Fig.8 Structure of neutron irradiation capsule.

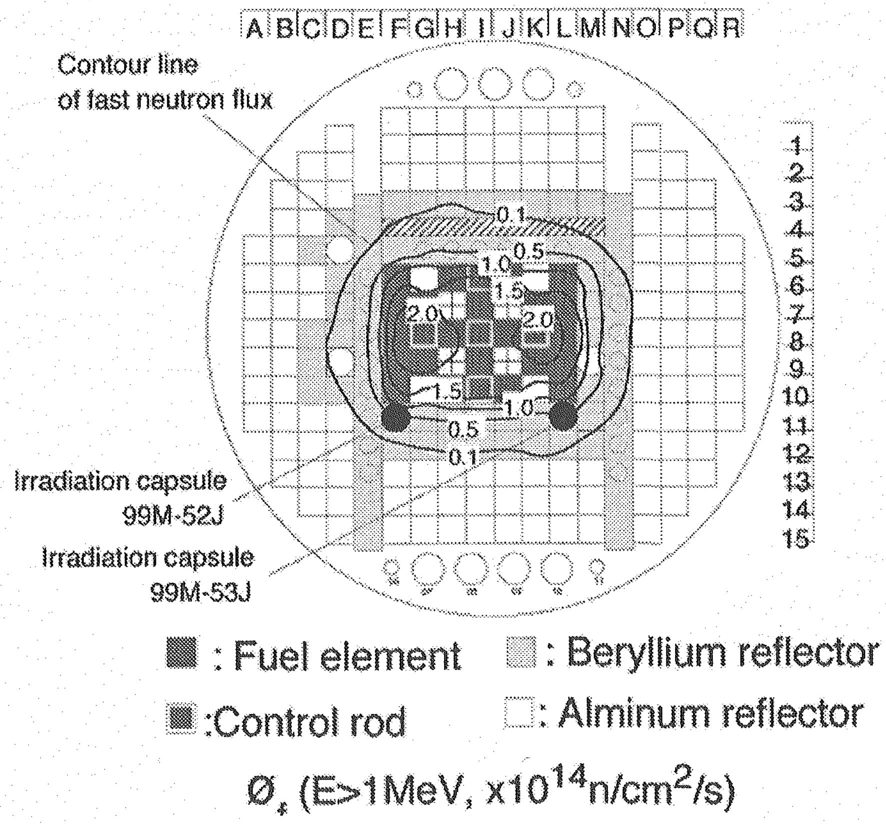
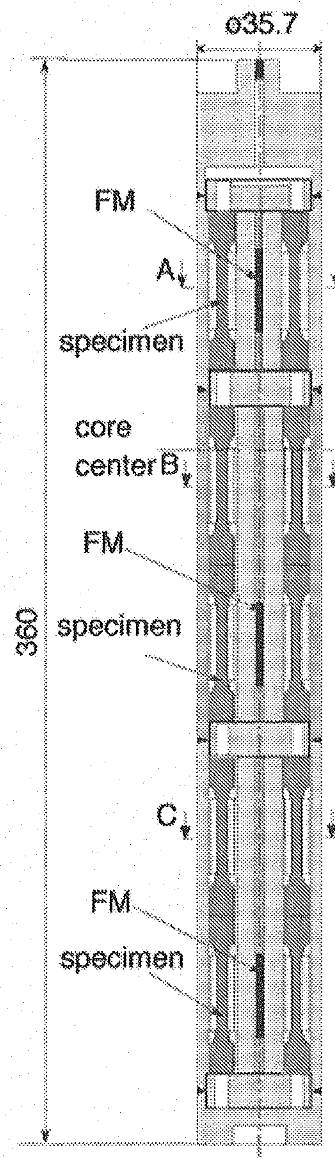


Fig.9 Irradiation holes of capsules for neutron irradiation in JMTR.



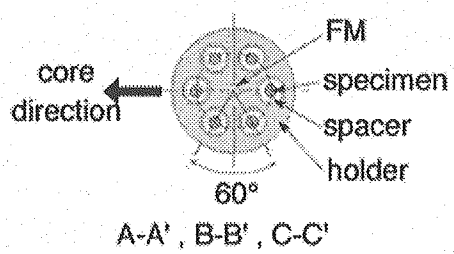
Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
126.5 °C	0.38dpa	$2.3x10^{24}$ n/m^2

Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
128.0 °C	0.40dpa	$2.3x10^{24}$ n/m^2

Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
132.1 °C	0.40dpa	$2.4x10^{24}$ n/m^2

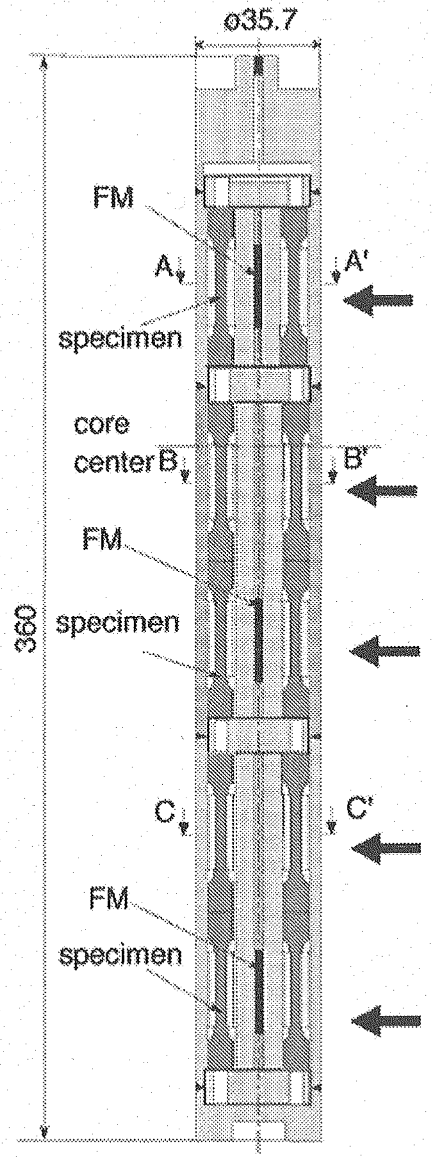
Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
128.0 °C	0.39dpa	$2.3x10^{24}$ n/m^2

Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
126.5 °C	0.35dpa	$2.1x10^{24}$ n/m^2



(FM: Fluence monitor)

Fig.10 Detail of irradiation condition of each specimen in 99M-52J capsule



Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
126.5 °C	0.28dpa	$1.6x10^{24}$ n/m^2

Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
128.0 °C	0.26dpa	$1.6x10^{24}$ n/m^2

Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
132.1 °C	0.27dpa	$1.6x10^{24}$ n/m^2

Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
128.0 °C	0.25dpa	$1.6x10^{24}$ n/m^2

Irradiation tempearature	Irradiation damage	Fast neutron fluence (E>1MeV)
126.5 °C	0.28dpa	$1.6x10^{24}$ n/m^2

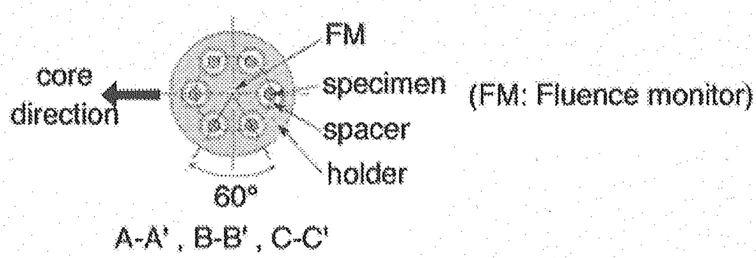


Fig.11 Detail of irradiation condition of each specimen in 99M-53J capsule

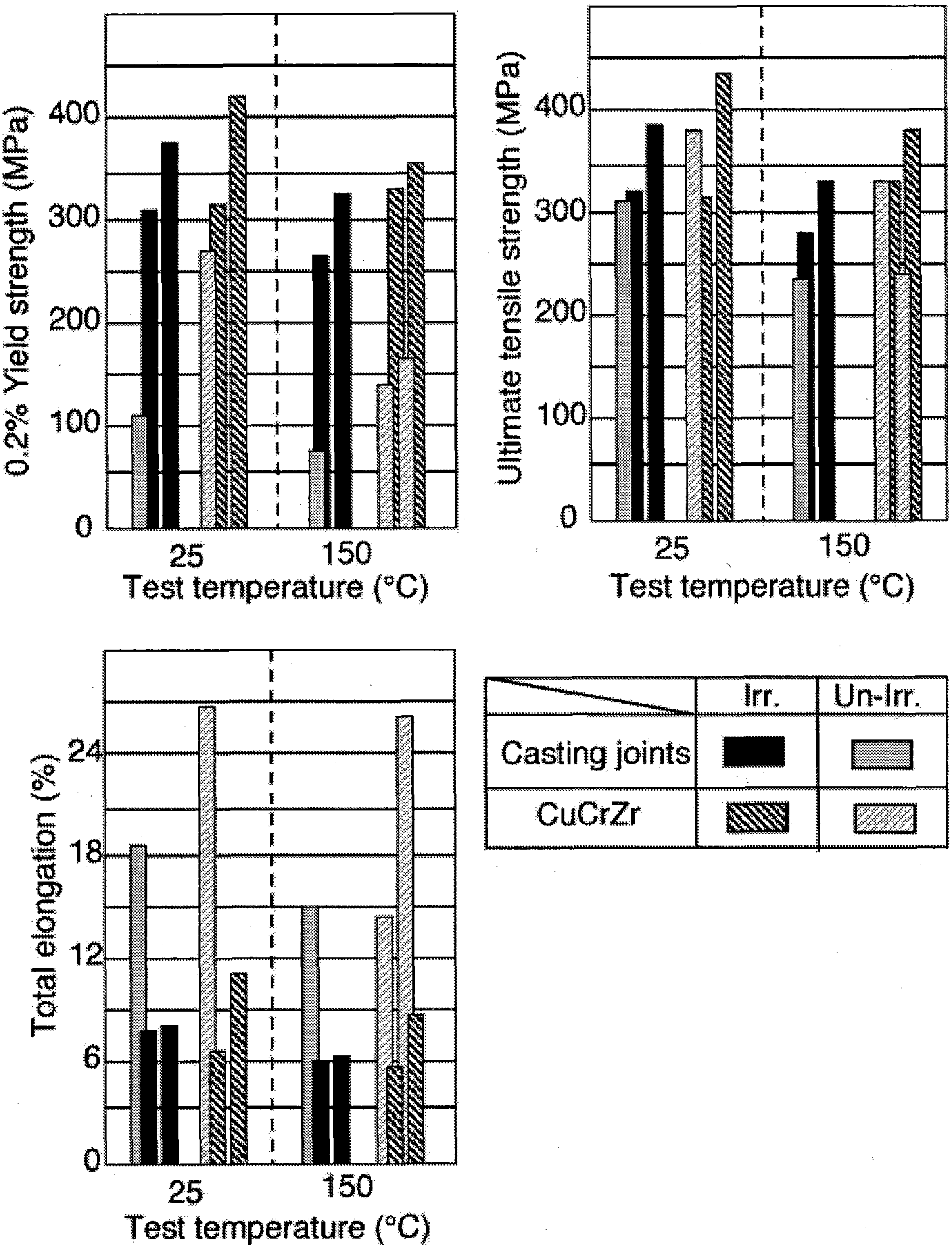


Fig.12 Results of tensile tests on CuCrZr/SS316LN-IG joint by casting and CuCrZr base material.

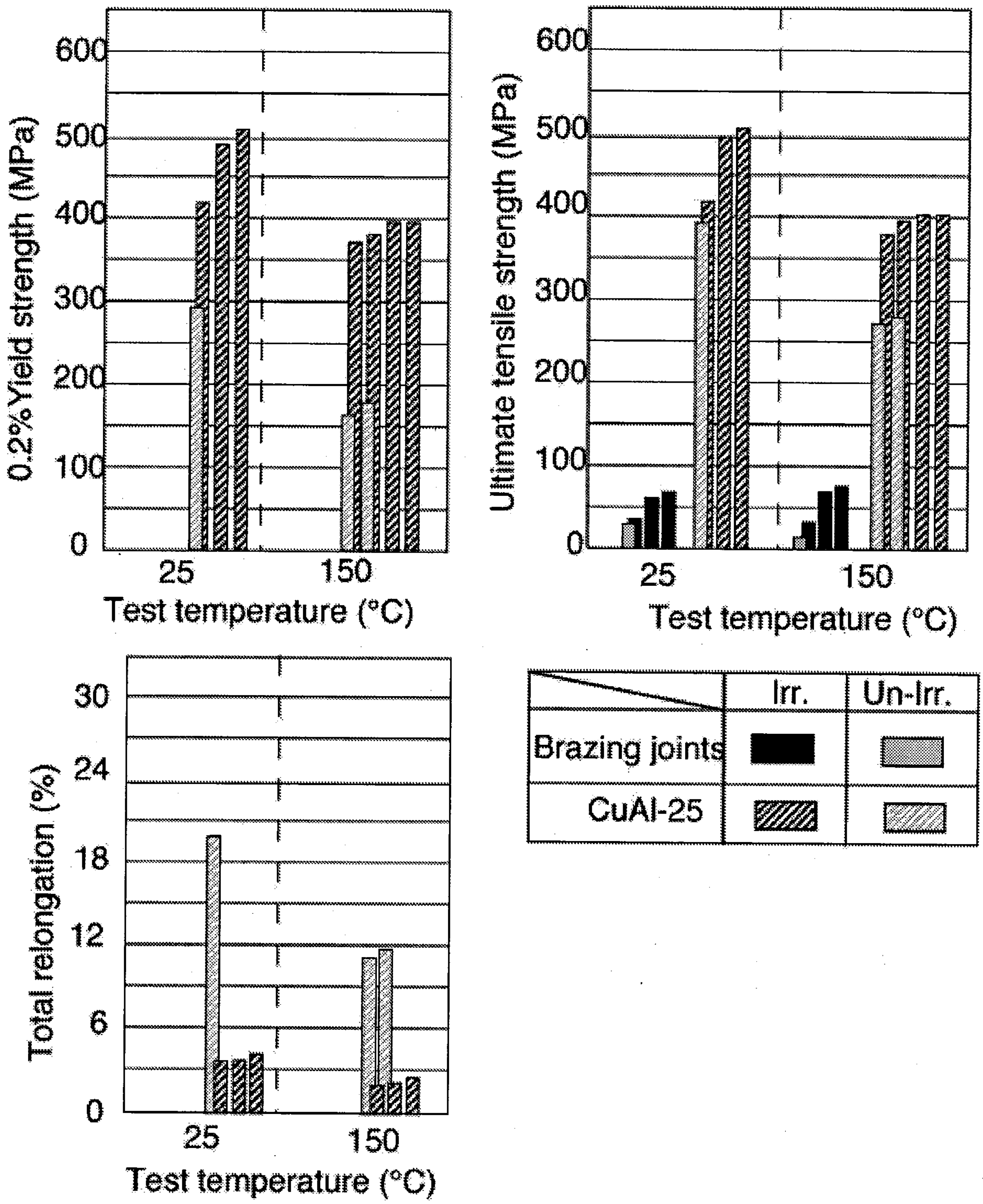


Fig.13 Results of tensile tests on CuAl-25/SS316LN-IG joints by brazing and CuAl-25 base material.

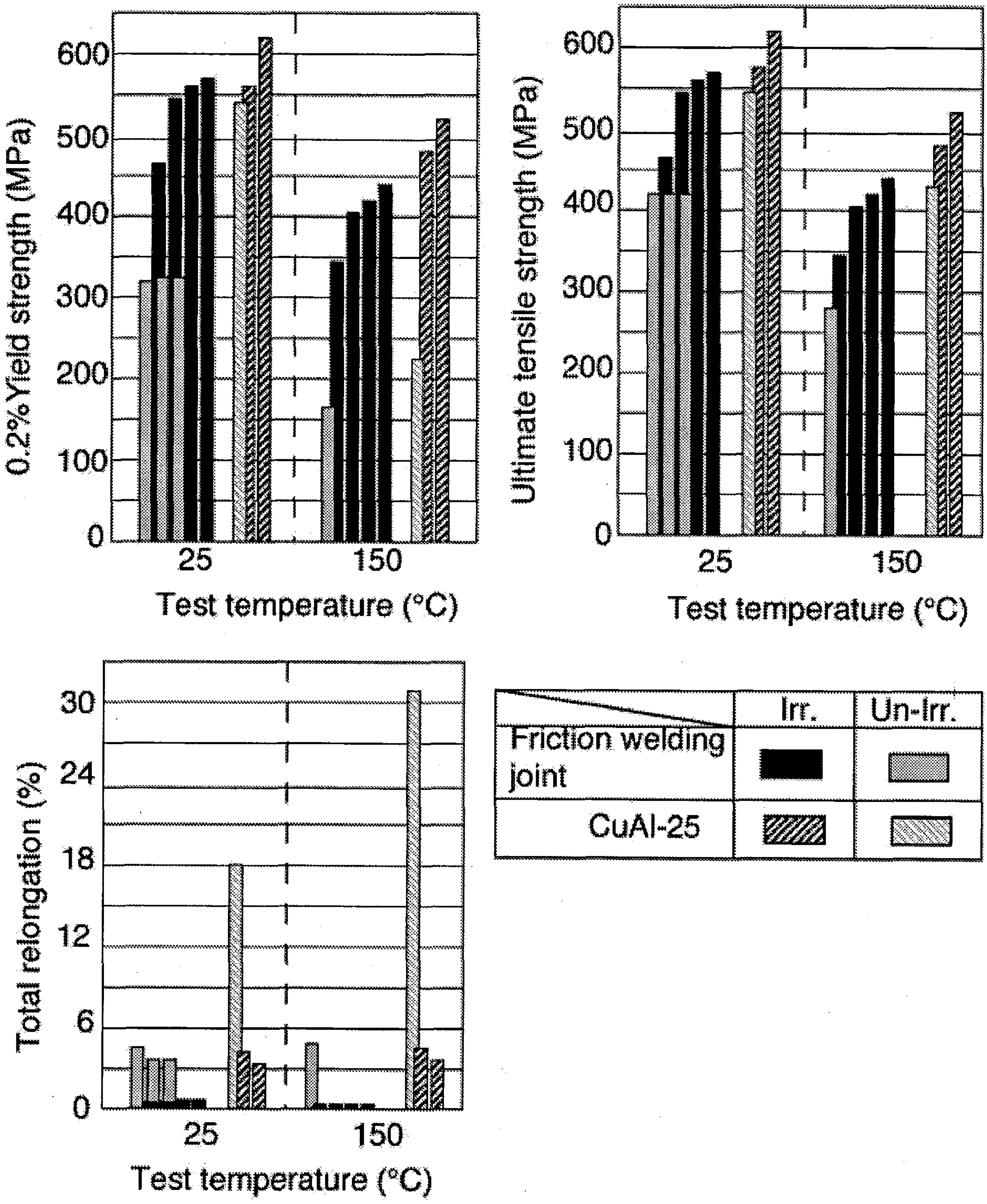


Fig.14 Results of tensile tests on CuAl-25/SS316LN-IG joints by friction welding and CuAl-25 base material.

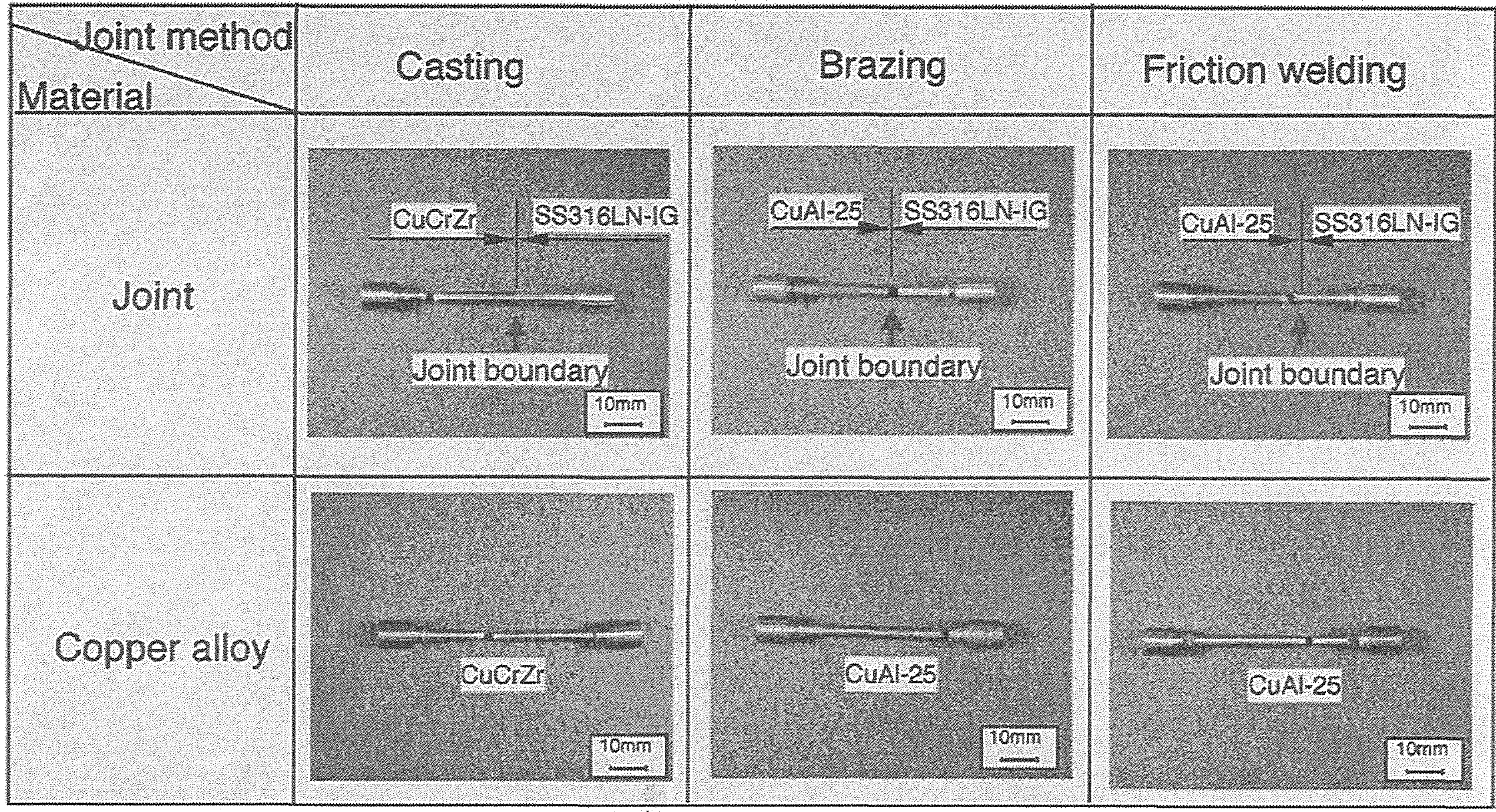


Fig.15 Photographs of un-irradiated specimens after tensile test at 150°C.

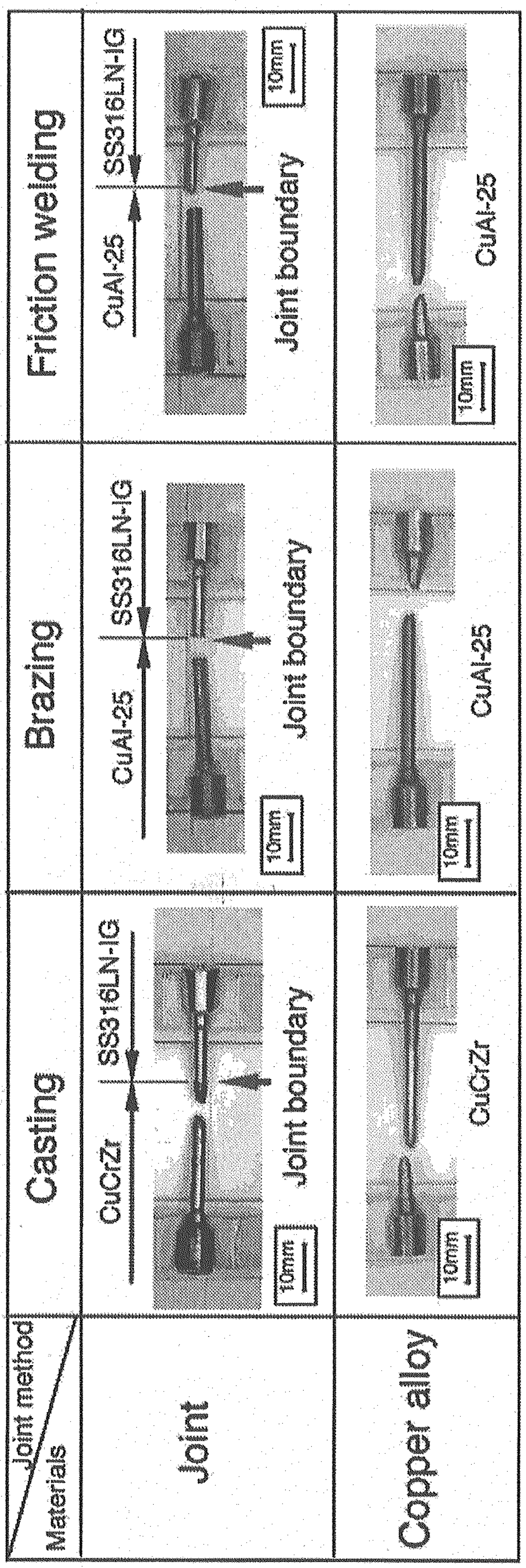


Fig.16 Photographs of irradiated specimens after tensile test at 150°C.

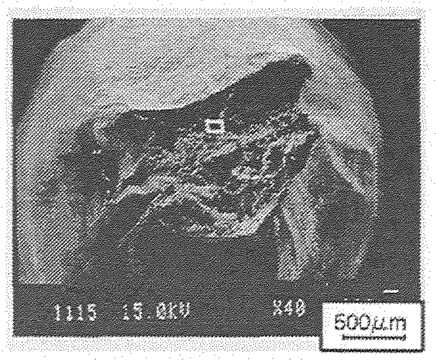
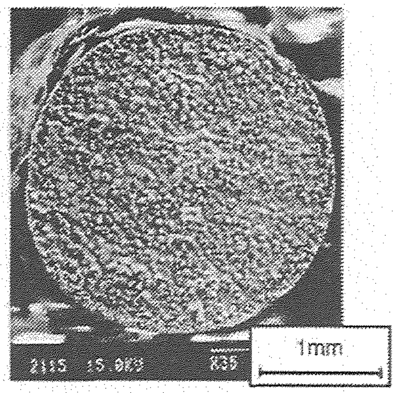
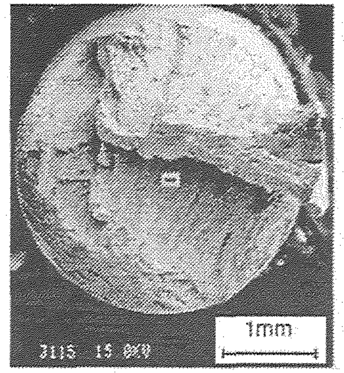
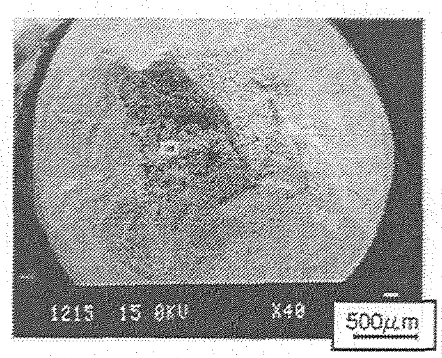
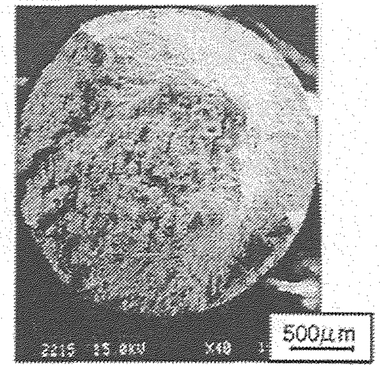
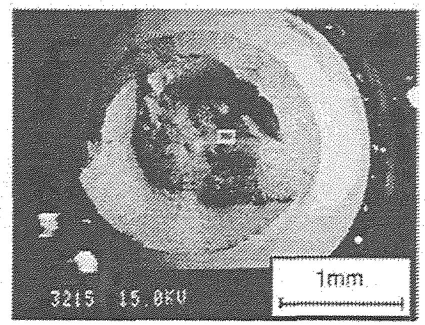
Joint method / Materials	Casting	Brazing	Friction welding
Joint			
Copper alloy			

Fig.17 Fracture surface of un-irradiated specimens after tensile test (Test temperature: 150°C).

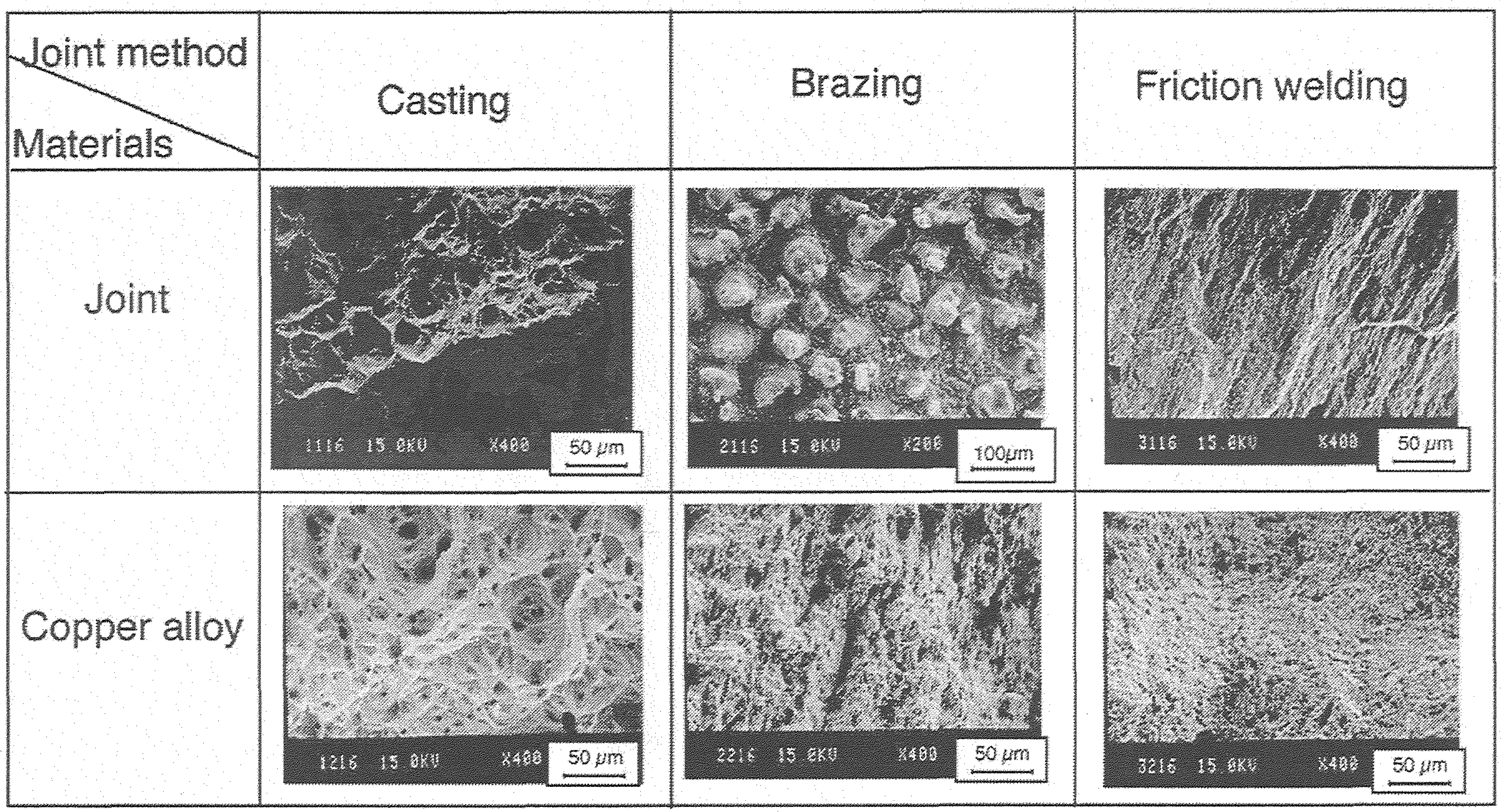


Fig.18 SEM micrographs of fracture surface of un-irradiated specimens after tensile test (Test temperature: 150°C).

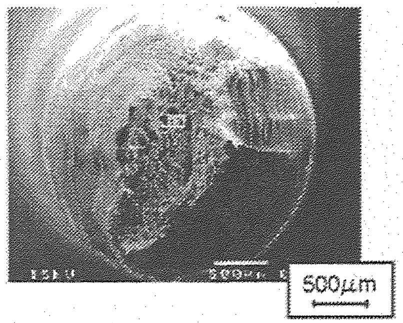
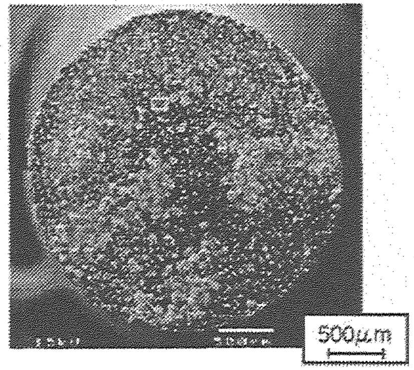
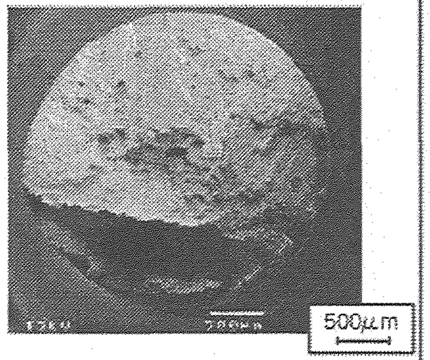
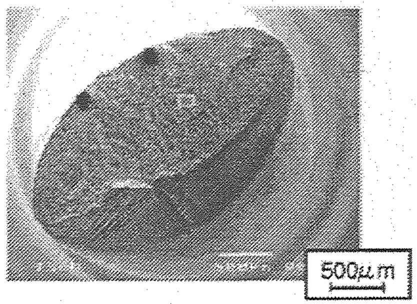
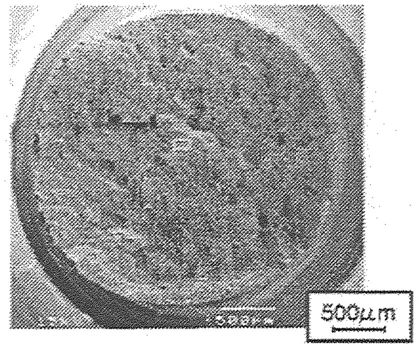
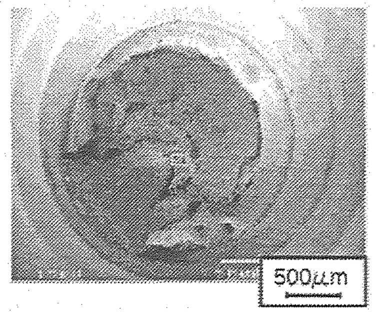
Joint method / Materials	Casting	Brazing	Friction welding
Joint			
Copper alloy			

Fig.19 Fracture surface of irradiated specimens after tensile test (Test temperature: 150°C).

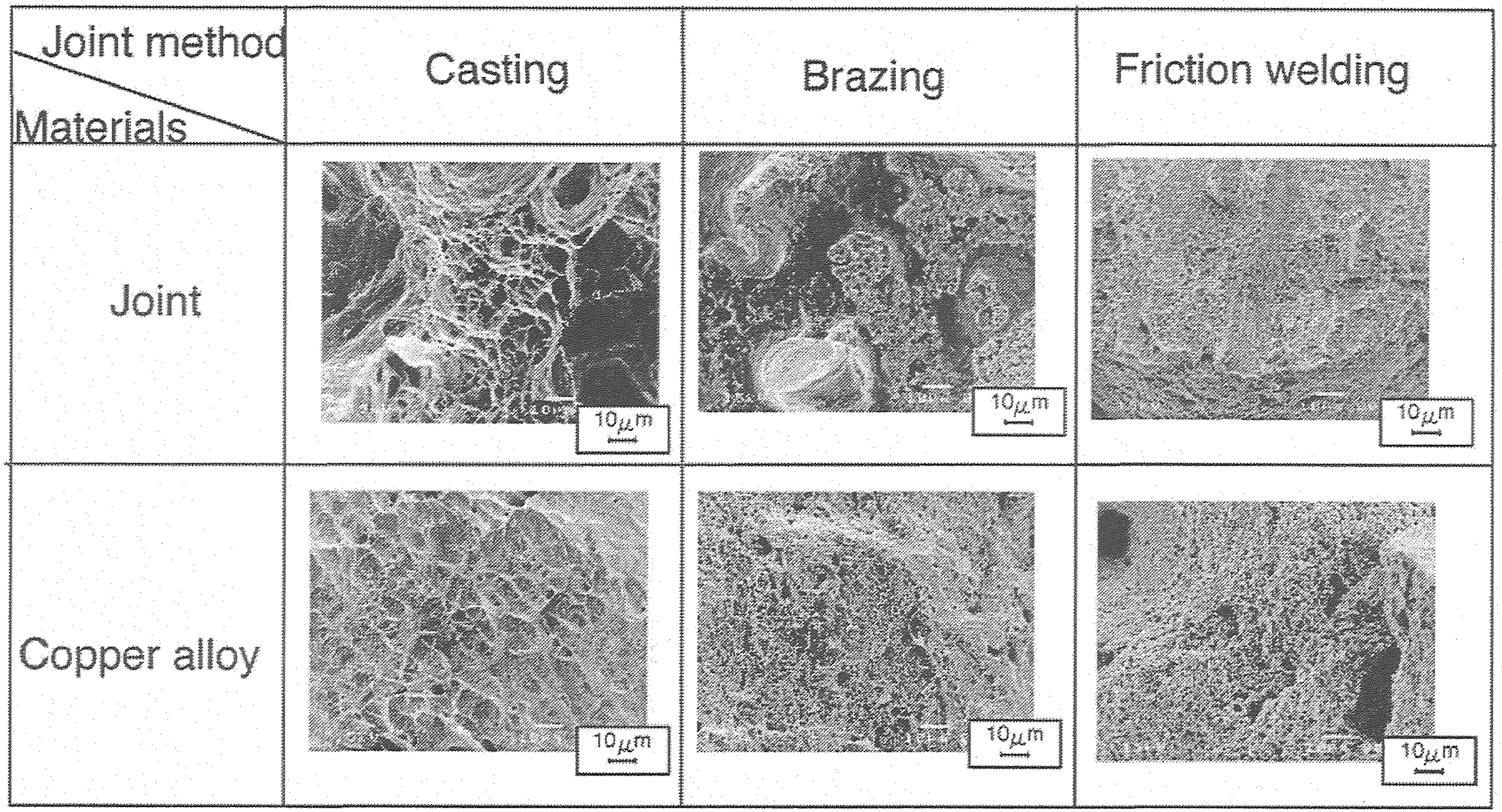


Fig.20 SEM micrographs of fracture surface of irradiated specimens after tensile test (Test temperature: 150°C).

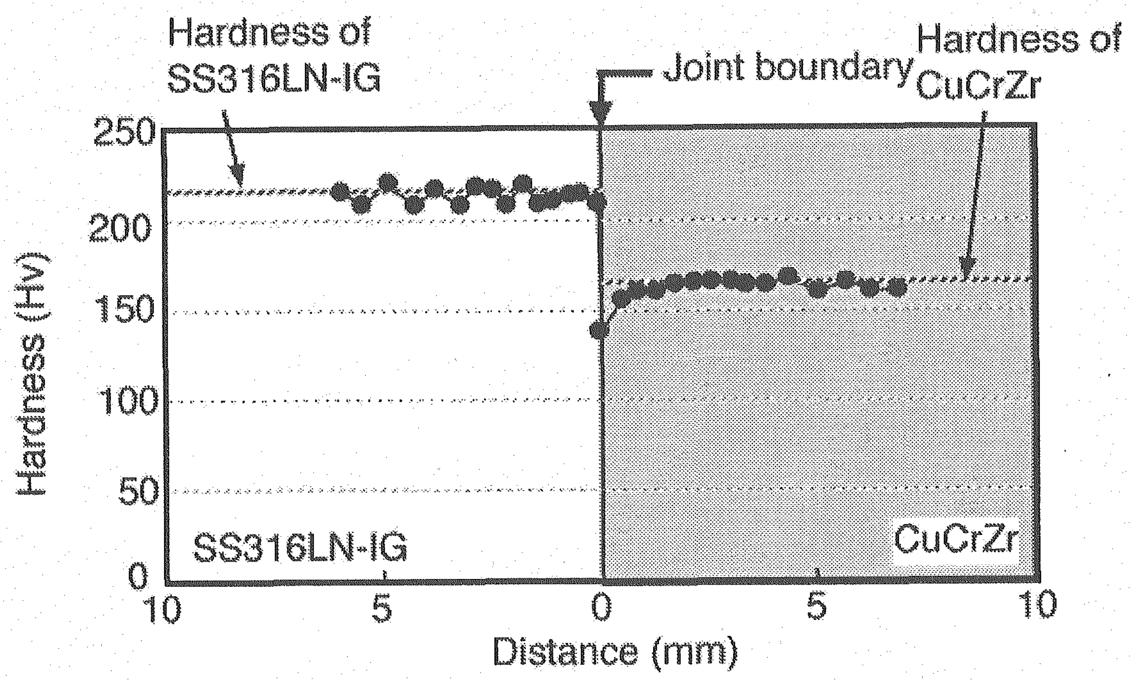


Fig.21 Hardness distribution around joint boundary of casting joint material.

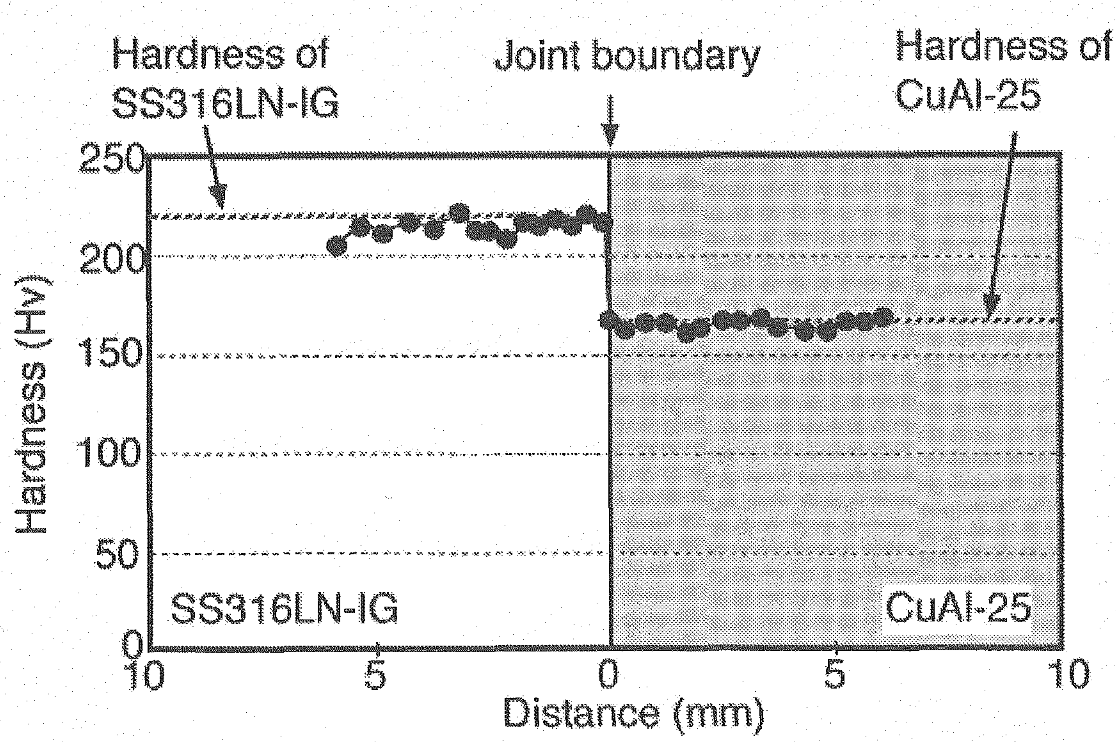


Fig.22 Hardness distribution around joint boundary of brazing joint material.

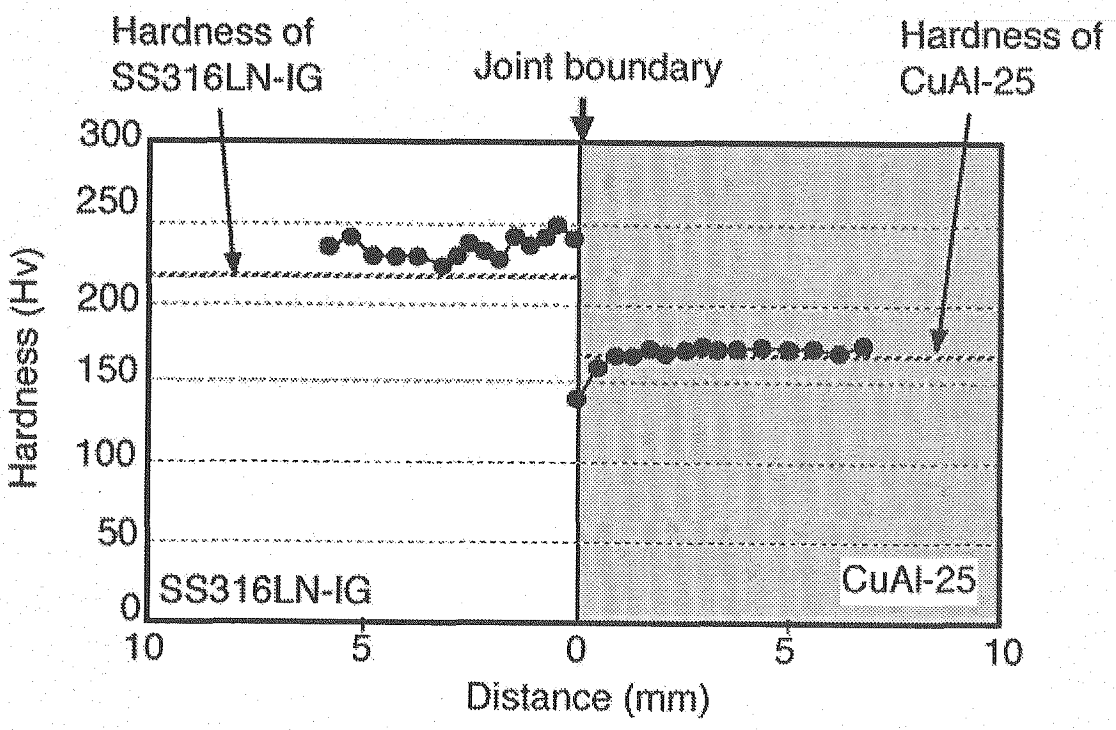


Fig.23 Hardness distribution around joint boundary of friction welding joint material.