Fundamental Study of Tandem Electron Beam Welding for Nuclear Fusion and Fission Reactors

著者	Suzuki Tsutomu, Kohyama Akira, Abe Nobuyuki
journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	45
number	1
page range	143-147
year	1997-03-28
URL	http://hdl.handle.net/10097/28717

Sci. Rep. RITU A45 (1997) pp. 143-147
No. 1, March 1997

Fundamental Study of Tandem Electron Beam Welding for Nuclear Fusion and Fission Reactors

Tsutomu Suzuki[a], Akira Kohyama[a] and Nobuyuki Abe[b]

[a] Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611, Japan
[b] Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka, Japan

(Received March 28, 1997)

As the important part of the life extension program for nuclear fission reactors and that of the maintenance scheme of blanket of fusion reactors, repair welding technique of neutron damaged materials is recognized to be one of the most urgent subjects to be established. This work provides the potentiality and the critical issues of "Tandem electron beam welding technique" when it is applied to heavily neutron damaged materials. Where mechanical property degradation due to the displacement damage and helium production from (n, α) reaction makes it very difficult to produce sound welded joint.

This paper presents the preliminary results to see the elementary characteristics of the welded joints produced by Tandem electron beam welding technique. Not only for the stainless steel nor high-nickel alloys, also for stainless steel to high-nickel alloy welded joints were studied. The tandem electron beam welding was done at JWRI, Osaka University. By optimizing the drilling effect from the leading electron beam and the weld defect suppression effect from the secondary electron beam , weld defect free welded joints were obtained with the excellent joint strength and ductility. The weld bead shape and penetration characteristics are also provided. The present results are quite promising to apply "Tandem electron beam welding" to heavily neutron damaged metallic structures and components.

KEYWORDS: tandem electron beam welding, weld bead characteristics, mechanical properties

1. Introduction

Metallic structures and their components with excellent heat resisting properties are essentially necessary for energy production and conversions systems and also for energy utilization systems operated at very high temperatures or with high heat flux exposures. The most typical and the most important examples are components of first wall and blanket for controlled thermo-nuclear fusion reactors, internals of light water nuclear fission reactors and those of propulsion engines for Super Sonic Transports (SST) and Hyper Sonic Transports (HST).

Especially for the case of nuclear fission and fission reactors, the properties of welds and welded joints are the key factors which limit the service conditions including their end-of-life. Where, an availability of reliable repair welding techniques is strongly required in order to improve cost of electricity through , so called, plant life extension. One of the most difficult and the unique characteristic, of which the repair welding has to overcome, is the radiation damaged microstructure including nuclear transformed gaseous atoms, such as helium atoms form the (n, a) and hydrogen from the (n,p) reaction[1,2].

The objective of this research is to clarify the potentiality and the critical issues of "Tandem electron beam welding technique" (Tandem EBW) when it is applied to heavily neutron damaged materials. Where mechanical property degradation due to the displacement damage and helium production from (n, a) reaction makes it very difficult to produce sound welded joint. The unique advantage of the Tandem EBW is the wide ranged flexibility to control "drilling action" and "mixing action" of welds There have been many studies on Tandem electron beam welding method in JWRI of Osaka University and other research institutes. This work is based on the accomplishments in JWRI/Osaka University where excellent deep penetration characteristics and controllability of bead shape under high speed welding have been presented[3].

2. Experimental Procedures

The materials used were 304, 316SS, Inconel 706 and Inconel 718. The chemical composition of the materials used is shown in Table 1. The size of the plates applied to the electron beam welding was 10 mm (thickness), 50 mm (width) and 100 mm (length). The electron beam welding

Table 1. Chemical Composition of the Materials Used : wt%

	C	Cr	Ni	Ti	Al	B	Mo	Cb	Si	Mn	Nb+Ta	Fe Co
SUS304	0.05	19.5	10.9		0.001		0.16		0.74	1.74		Bal
SUS316	0.03	16.74	13.9				22.0		0.02	0.24		Bal
In.706	0.02	16.0	40.0	1.7	0.3	0.004		2.75				Bal
In.718	0.04	19.0	52.5	0.9	0.5	0.005	3.05	5.3	0.163	0.1	5.22	Bal

Table 2. Electron-beam Parameters

	Eb-1	Eb-2
Beam Energy : KW	30	6
Acc. Voltage : KV	70	60
Beam Current : mA	430	100
Cathode Size : mm	4	2

facility used was a low accelerating voltage and high vacuum type EBW machine, the "Tandem Electron Beam Welding Facility" of JWRI/Osaka University. The electron beam parameters are shown in Table 2.

The tandem EBW method uses two electron beams with the distance of L_b (Tandem gap), where the 1st beam is larger in beam current to get sufficient "drilling action" and the 2nd beam has a role to suppress weld defects especially on bead shape. For this purpose, the 2nd beam was oscillated (1kHz, circular oscillation) to use a benefit of "mixing action".

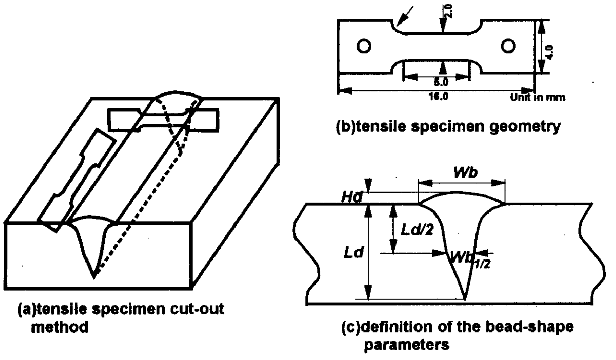
To obtain weld bead penetration characteristics, bead on plate test was done with 10 mm thick back-up plate. For mechanical property testing of the welded joints, I-butt welding was done.

Specimens for tensile tests, microstructure inspections and micro-Vickers hardness test were cut-out from the I-butt welded joints by a multi-wire sawing machine. The specimens cut-out were, then, surface polished to remove deformation zone introduced while specimen cut-out process. The tensile test specimen cut-out method is schematically shown in Fig.1, together with the definition of the weld bead shape parameters. As shown in Fig.1, Tensile specimens were cut out from welded joints both parallel and perpendicular to the welding direction. The specimen geometry was selected to be the standard mini-sized tensile specimen used in the Japan/USA collaboration program on fusion reactor materials. For tensile test, full automated tensile test machine (MATRON) was used.

3. Results and Discussion

3.1 Weld Bead Characteristics

In order to compare the bead shape characteristics for single- and tandem electron beam welding, bead on plate test on 304 SS was performed. As shown in Fig.2, Bead width was nearly constant for the case of Tandem EBW, although for the case of single EBW it became smaller with increasing the beam current. This means the stability of weld bead shape was improved by Tandem-EBW with the trade-off of a slight reduction of weld bead penetration depth as much as the beam current of 10 mA for the case of single EBW compared with the Tandem EBW with 2mm tandem gap. The effect of Tandem gap value on bead shape characteristics, for the case of 316 SS is shown in Fig. 3. With increasing the tandem gap, weld bead penetration depth became smaller but the bead width and bead height were nearly constant, showing an excellent bead shape stability in this welding condition. Whereas for the case of 304 SS, as shown in Fig.4, the trend of the Tandem gap effect on bead shape characteristics was completely to the contrary with the case of 316 SS. In this case, weld bead penetration was increased with increasing the tandem gap and bead width and bead height were decreased and increased with increasing the tandem gap, respectively. This can be qualitatively understood by the enhancement effect of weld metal flaw by the 2nd electron beam with increasing the tandem gap for the case of 304 SS but the origin of the differences with the case of 316 SS cannot be figured out, presently. This is suggesting the importance of the flaw characteristics of molten metals and thermal



(a)tensile specimen cut-out method

(b)tensile specimen geometry

(c)definition of the bead-shape parameters

Figure 1. Specimen Cut-out Method and the bead shape parameters

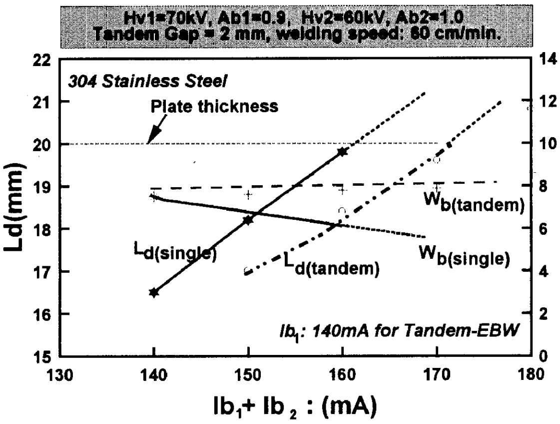


Figure 2. Bead Shape Characteristics of Single- and Tandem-EBW Methods

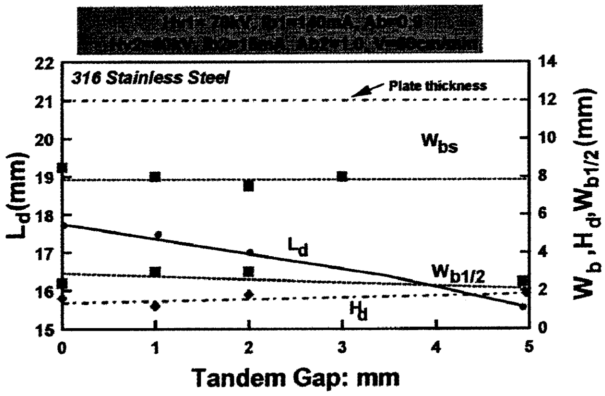


Figure 3. Effect of Tandem Gap on the Bead Shape Characteristics of Tandem-EBW

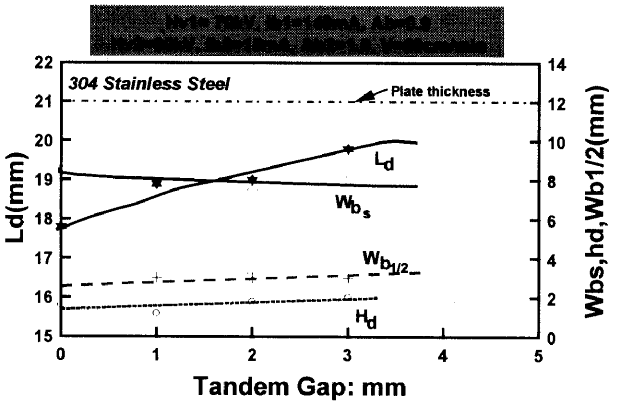


Figure 4. Effect of Tandem Gap on the Bead Shape Characteristics of Tandem-EBW

properties of the base metal in weld bead formation for the case of Tandem EBW. This is also suggested for the cases of Inconel 706 and Inconel 718, where the sound weld bead were produced by the slight reduction of weld heat input, by the reduction of the 1st electron beam current from 140 mA to 120 mA , from the cases of 304 and 316 SS, reflecting the effect of the reduction of thermal conductivity by the increase of Ni contents for the cases of Inconel alloys.

3.2 Inspections and Analysis of the Microstructure

In order to analyze the microstructure and the microchemistry, such as segregation, of the welded joints, correlating with the weld defect formation, inspection by Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray (EDX) analysis capability was carried out. For the case of single EBW of Inconel alloys, high temperature cracks in weld metal, lateral crack along weld metal solidification columns, were observed at high beam current condition. For example, in the case of Inconel 706 with the beam current of 150 mA and the constant welding speed of 60cm/min for this work, the lateral weld cracks were observed, but were not observed for the cases with the beam current smaller than 140 mA. Along the weld crack, nickel enrichment was observed but this cannot be the direct origin of the weld crack but the balance of the deep penetration bead shape and solidification behavior may cause the high temperature (solidification) lateral crack. In the case of Tandem EBW, no lateral crack was observed all conditions applied in this work, suggesting another benefit of Tandem EBW in suppressing weld crack often observed in deep penetration EBW welds.

Both for the cases of single- and Tandem- EBW, necklace cracks and root cracks near the bottom of the penetration bead were occasionally observed. These cracks were associated with sulfur and manganese enriched precipitates only when the sharp top of penetration bead was produced. This is suggesting that by optimizing the 1st beam current and beam focus position to eliminate the formation of sharp top of the penetration bead, these root cracks can be suppressed.

For the cases of dissimilar metal joints, such as Inconel 718/316SS, Inconel 706/Inconel 718, weld cracks were not observed by Tandem EBW, whereas were occasionally observed by single EBW. This may be due to the excellence in weld metal mixing and in good weld bead shape accomplished for the case of Tandem EBW. This feature may be also beneficial for the case of repair welding of heavily neutron irradiated metals, supposed to be come out from light water nuclear reactors.

3.3 Mechanical properties of Welded Joints

Mechanical properties of weld metals as a function of the distance from the center of weld metal and those of welded joints cut out from the mid-depth region of the welded joints (at L_d /2 depth position) were measured by mini size tensile test and micro-Vickers hardness test.

The I-butt welded joints for the mechanical tests were made by the following conditions;

I_{b1} : 120 mA H_{v1} : 70 kV A_{b1}: 0.9
I_{b2} : 15 mA H_{v2} : 60 kV A_{b2}: 1.0
Tandem Gap: 2 mm
Welding velocity: 60 cm/min.

Figures 5 and 6 show the tensile test results of Inconel 706 welded joints for strength and for ductility, respectively. The bead width at the L_d /2 was about 2 mm, the mechanical properties at 1 mm distance from the center of the weld represented the properties at weld bond region. As shown in the figures, the strength at the weld bond was low with low ductility values. They were fractured right after yielding and almost no post yield hardening and no post uniform elongation were observed. This may include some effects on

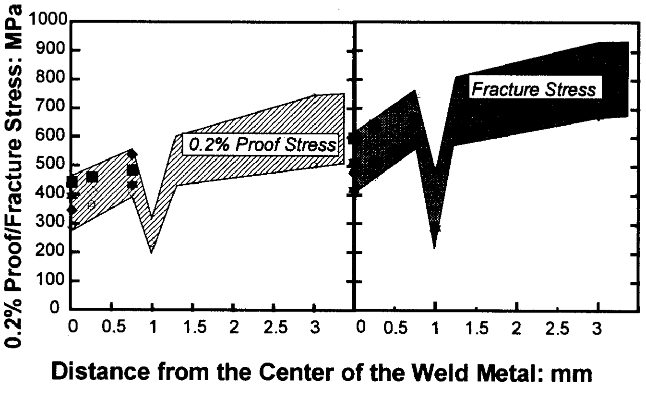


Figure 5. Positional Dependence of Tensile Properties - Ductility of Inconel 706 I-butt Joint -

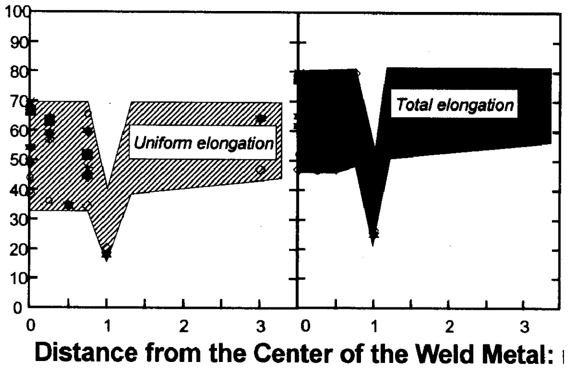


Figure 6. Positional Dependence of Tensile Properties- Ductility of Inconel 706 I-butt Joint -

small specimen size utilized in this test, but the low yield strength and low ductility at bond was indicated. This tendency was only seen in the Inconel 706 joints. Although uniform elongation in weld metal was higher than 30 %, presenting enough ductility, but yield and fracture strengths were lower than base metal simply due to the difference in grain size in the both region. These results indicates that the joint strength of Inconel 706 may determined dominantly by the strength at weld bond.

The mechanical properties of dissimilar metals joints have been tested for the cases of Inconel 706/Inconel 718 and Inconel 718/316 SS. In the both cases, the positional dependence of mechanical properties showed no indication of embrittlement caused by the joining of dissimilar metals. The results of the former case are shown in Figs. 7 & 8, as the representing data. The weld metal and the heat affected zone mechanical properties are quite reasonable considering the thermal cycling during the welding process with the fracture strength and total elongation larger than 600Mpa and 50%, respectively. These results also indicted the lack of weld defects formation harmful to the mechanical properties and the sufficient action of weld metal mixing during electron beam welding process. For the case of the latter showed the same trend with the former case.

The positional dependence of Vickers hardness has been measured by a micro-Vickers hardness method using the laterally and tangentially cut-out specimens. The hardness distribution as the function of the distance from the center of the weld metal was fully correlated with the tensile test results suggesting the soundness of the welded joints. The depth profiles of Vickers hardness at the center of the weld metals are shown in Fig. 9. As the general trend, the hardness became larger with increasing the distance from the weld surface. The width of data band is understood by the position of micro-indenter. That is, on the grain-or solidification cell-boundaries case and in the center of the large grain case can make the Vickers hardness value difference of 20, without any special consideration for these cases. These results are also indicating the excellent uniformity of the weld joint strength as the function of the depth from the weld surface.

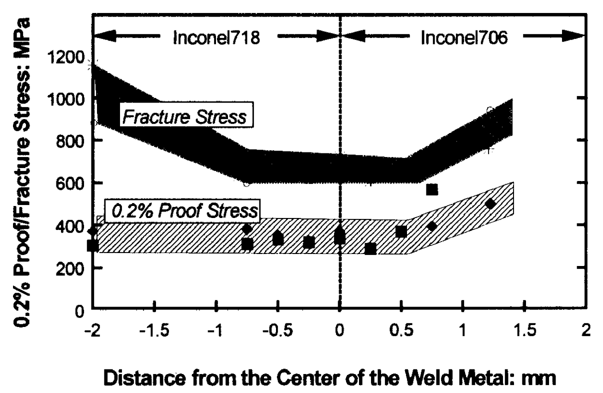


Figure 7. Positional Dependence of Tensile Properties- Strength of Inconel 718/Inconel 706 I-butt Joint -

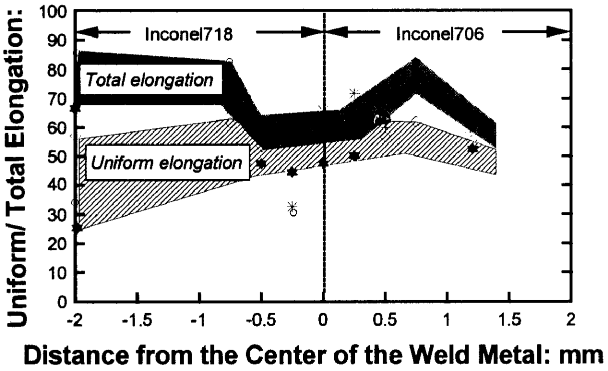


Figure 8. Positional Dependence of Tensile Properties - Ductility of Inconel 718/Inconel 706 I-butt Joint -

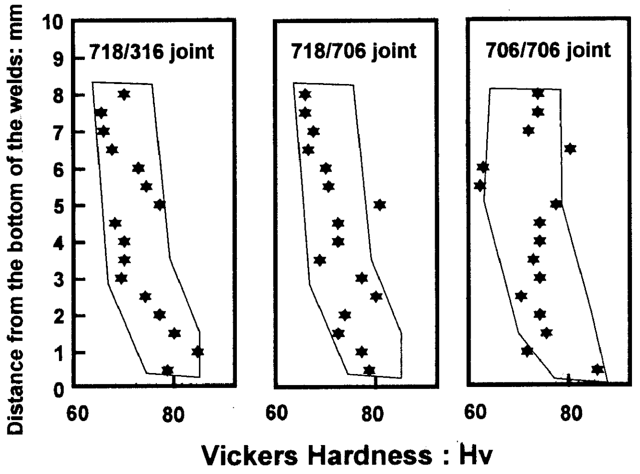


Figure 9. Depth Profile of Vickers Hardness at the Center of the Weld Metals-

The summary of the welded joint strength and ductility is shown in Fig. 10. In this figure, the data from 1/4 of L_d , where the effect of the near surface weld bead was included together with the combined effect of the specimen size and the width of the weld metal, are relatively inferior than others in strength and in ductility. Other data from 3/4 of L_d and 1/2 of L_d are well rationalized by the data shown in Figs. 5 - 9. For the case of the Inconel 706 welded joints, due to the low bond strength with brittleness near the bond, 3/4 of L_d.

4. Conclusions

In order to evaluate an applicability of Tandem EBW for maintenance of Fusion and Fission Reactors, a preliminary

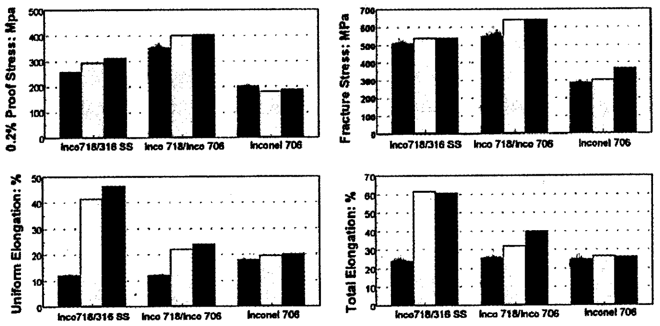


Figure 10. Mechanical properties of welded jointsby Tandem EBW

study was carried out. The major conclusions of this work were as follows;

(1) Tandem EBW presented the significant advantage in suppressing weld crackings and improving stability of bead shape. As the important welding parameters, Tandem gap and EB energy input ratio between the two electron beams were identified and the fundamental effects on welded joint properties were presented.

(2) Tandem EB welded joints of dissimilar metals, such as Inconel alloys and 316 SS, were soundly produced with enough flexibility of welding condition which suggested the potential of Tandem EBW to be applied for maintenance of fusion and fission reactors.

(3) Mechanical properties with enough ductility and uniformity to plate thickness direction.

References

1. A.F.Rowcliffe, A.Hishinuma, M.L.Grossbeck and S. Jitsukawa: J. Nucl. Mater. 179-181(1991)125.
2. C.A.Wang, H.T.Lin, M.L.Grossbeck and B.A.Chin: J. Nucl. Mater. 191-194(1992)696.
3. A.Kohyama, S.Sato, M.Tomie and N.Abe: Japan Welding Society HEB Comm. Doc.: HEB-15-94(1994)