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계장핵연료 조사시험용 실튜브 레이저용접기술

김수성* · 이철용* · 김웅기* · 박근일* · 고진현** · 서준석***

*한국원자력연구소 건식공정핵연료개발부
**한국기술교육대학교 신소재공학과
***한국생산기술연구원 금속소재신뢰성평가센터

Laser Welding of Seal Tube for Instrumented Irradiation Fuel Test

Soo-Sung Kim*, Chul-Yong Lee*, Woong-Ki Kim*, Geun-Il Park*, Jinh-Yun Koh** and Jun-Seok Seo***

*Dept. of Dry Process Nuclear Fuel Development, Korea Atomic Energy Research Institute, Daejon 305-600, Korea
**Dept. of Materials Engineering, Korea University of Technology & Education, Chonan 330-860, Korea
***Reliability Assessment Center for Metallic Materials, Korea Inst. of Industrial Technology, Chonan 330-825, Korea

Abstract

This work was carried out to obtain sound welds and to select a most suitable binary metal joint among three different dissimilar binary metal combinations such as Zr-4/Ta, Mo/Ta and Ti/Ta(seal tube/sensor sheath) joints for the instrumented nuclear fuel irradiation test. To do this, Taguchi experimental method was employed to optimize the experimental data. In addition, metallography, micro-focus x-ray radiography and hardness test were conducted to examine the welds. From the weld bead appearance, penetration depth and bead width as well as weld defects standpoint, Zr-4/Ta joint is suggested for the circumferential joining between a seal tube and a sensor sheath. The optimized welding parameters based on Zr-4/Ta joint are suggested as well.

* Corresponding author : sskim7@kaeri.re.kr (Received October 5, 2005)

Key Words : Dissimilar metals, Nd:YAG Laser welding, Metallography, Micro-focus X-radiography, Nuclear fuel irradiation test

1. Introduction

Laser beam welding technology is widely used to fabricate some parts of nuclear fuel in the nuclear industry. Especially, the laser welding has become one of the key technologies not only for the fabrication of precise products in nuclear fuel but also for the fuel irradiation test. It is also important for us to secure laser welding technology to perform various instrumentations for the fuel irradiation test.

The instrumented fuel irradiation test at a research reactor needs capsules to evaluate the performance of the developed nuclear fuels[1,2]. The capsule is assembled into the instrumented fuel elements. The fuel elements are designed to measure the centerline temperature of fuel pellets during the irradiation test by using temperature sensors[3]. The thermal sensor is composed of a thermocouple and a sensor sheath. In addition, the assembly which includes fuel elements and temperature sensor has to be designed soundly not to be broken and not to leak fission gases from fuel elements during the irradiation test[4]. Laser welding system which is designed and manufactured for this study was adopted to seal between a seal tube and a thermocouple sheath of 0.15 mm in thickness.

This study was carried out to seal between a thermocouple wire and a seal tube with laser welding. The optimum welding parameters and a suitable joint of dissimilar binary metal combination among Ta/Ta, Mo/Ta, Ti/Ta and Zr-4/Ta joints were chosen. These binary metal combinations are known to have good weldability in terms of solid solubility[5]. The penetration and the soundness of weld specimens were investigated by metallography and microfocus X-radiography. Hardness variation across joints were measured by hardness test. Moreover, Taguchi experimental method was employed to analyze weld specimens and the optimization of the experimental results of dissimilar metal welds was done by Taguchi experimental method.

2. Experimental method

2.1 Specimens preparation

Fig. 1 shows the joint design of a weld specimen to seal between the Ta thermocouple wire and the seal tube with metal combinations. A weld specimen consists of 0.15mm thick of Ta thermocouple wire and one of seal tubes(0.2mm) of Ta, Mo, Ti and Zr-4, in which a Ta thermocouple wire is inserted into a seal tube for circumferential welding. The thermocouple wires are embedded in MgO insulator, which is also included in a sensor sheath of thermocouple wire. In order to remove impurities and dusts on the surface of a specimen before laser welding, seal tubes were cleaned in aceton for 30 min. and dried in oven at 70℃. Specimens were welded by a laser welding system with 150W pulsed Nd:YAG laser and 400㎛ SI optical fiber transmission. In order to optimize the welding parameters and select a most suitable combination of dissimilar metals, laser power, pulse width and defocus were varied. In order to weld the specimens with the metal combinations, the shielding box using an optical fiber transmission was made as shown in Fig. 2.

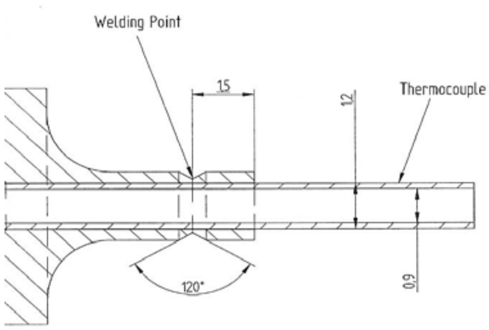

Fig. 1 Joint design of weld specimen for seal tube

2.2 Tests of weld specimens

The weld penetration depth and the bead width were metallographically investigated after cut and polishing of specimens by light microscope and micro-focus X-ray inspection. Weld defects were also examined by the light microscope and the micro-focus X-ray inspection as well. The micro-hardness variation across a weld was measured by vickers tester with a load of 300g.

3. Results and Discussion

3.1 Optimization of seal tube welding

It is known well that it is not easy to weld the dissimilar metals containing fine Ta thermocouple wires. Owing to their high melting points such as Ta (M.P.=2996°C), Mo (M.P.=2610°C), Ti (M.P.=1688°C) and Zr-4 (M.P.=1852°C), the lack of fusion and other defects in the circumferential welding of dissimilar metal combinations are to be occurred. This impairs seriously the quality of the weld joints. In this experiment, Taguchi

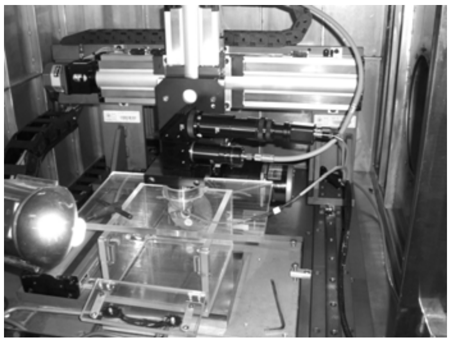

Fig. 2 Photograph of laser welding system with optical fiber transmission

experimental method was employed to reduce the experimental data to produce, and to secure reproducibility of the experimental results at the same time. By doing so, the optimized process parameters were established by the Taguchi method. Furthermore, the effect of the optimized parameters on the weldability of dissimilar metals can be discussed from the weld penetration depth and the weld defects.

Based on the Taguchi experimental method, the orthogonal array for $L_8 2^7$ and the welding parameters such as laser power, pulse width and defocus can be suggested for the seal tube welding as listed in Table 1 and Table 2.

Fig. 3 shows a plot of the experimental results by using the scattering distribution value of 0.05 for both Ti/Ta and Zr-4/Ta joints in term of two variables. It can be found that laser power has the steepest slope compared with other

Table 1 The welding conditions for Taguchi experiment method

Factor / Level	Joint Description [A]	Laser Power(W) [B]	Pulse Frequency(Hz) [C]	Defocus (mm) [D]
1	Ta × Ta	42 (pulse E14J)	3	0
2	Mo × Ta	60 (pulse E14J)	5	-0.5
3	Ti × Ta	24 (pulse E 8J)	3	0
4	Zr-4 × Ta	40 (pulse E 8J)	5	-0.5

Table 2 List of Orthogonal Array for $L_8 2^7$

Factor / Trial No	[A]	[B]	[C]	[D]
1	1	1	1	1
2	1	1	2	2
3	1	2	1	1
4	1	2	2	2
5	2	1	1	2
6	2	1	2	1
7	2	2	1	2
8	2	2	2	1
1	3	3	3	3
2	3	3	4	4
3	3	4	3	3
4	3	4	4	4
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6	4	3	4	3
7	4	4	3	4
8	4	4	4	3
	a	b	c	a × c

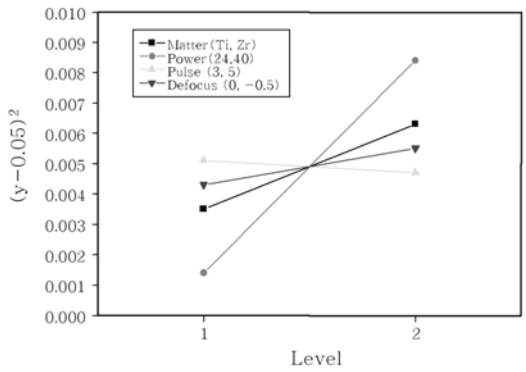


Fig. 3 Scattering distribution for a comparison of the welding parameters on Ti/Ta and Zr-4/Ta joints

welding parameters such as pulse width, defocus and materials. It means that it has the most effect on the penetration depth among welding parameters chosen in this experiment.

The primary goal in this work is to investigate proper weld penetration and soundness in the weld joint of a metal combination for the seal tube welding. The metals which have high melting points such as Ta/Ta and Mo/Ta made by laser power 60W, remarkably revealed incomplete penetration such as the lack of fusion. However, the metal combinations such as Ti/Ta and Zr-4/Ta made at laser power 40W showed over-fused penetration such as the burn-through. From the primary welding experiment by Taguchi method, it is found that Ti/Ta and Zr-4/Ta joints show similar penetration depths and bead widths as listed in Table 3. Fig. 4 (a) and (b) show the relationship between weld penetration and bead width at the pulse width and laser power. Pulse width was varied from 3ms and 5ms, and laser power was also changed depending upon metal combinations.

Table 3 lists the welding results by the metallography and X-ray radiography in terms of defects, bead width and penetration depth with the variation of welding parameters such as laser power, pulse width and defocus. In Ta/Ta and Mo/Ta weld specimens, weld penetration is almost nothing, on the other hand, Ti/Ta and Zr-4/Ta weld specimens show a good penetration and bead appearance.

Table 3 Results of welding experiment

	A	B	C	D	Radiography Test			Metallography Test	
					Conditions		Defects	Bead Width (mm)	Penetration depth(mm) seal tube t=0.2
					V(kV)	A(μA)			
1	Ta/Ta	42	3	0	150	15	L.F.	0.70	0.20
2	Ta/Ta	42	5	-0.5	150	15	L.F.	0.74	0.20
3	Ta/Ta	60	3	0	150	15	×	0.82	0.22
4	Ta/Ta	60	5	-0.5	150	15	L.F.	0.87	0.20
5	Mo/Ta	42	3	-0.5	150	16	L.F.	0.68	0.20
6	Mo/Ta	42	5	0	150	16	L.F.	0.72	0.20
7	Mo/Ta	60	3	-0.5	150	16	L.F.	0.77	0.20
8	Mo/Ta	60	5	0	150	16	L.F.	0.82	0.20
1	Ti/Ta	24	3	0	150	3	×	0.66	0.24
2	Ti/Ta	24	5	-0.5	150	3	×	0.70	0.22
3	Ti/Ta	40	3	0	150	3	×	0.75	0.28
4	Ti/Ta	40	5	-0.5	150	3	B.T.	0.83	0.28
5	Zr-4/Ta	24	3	-0.5	150	10	×	0.80	0.24
6	Zr-4/Ta	24	5	0	150	10	×	0.84	0.22
7	Zr-4/Ta	40	3	-0.5	150	10	B.T.	0.87	0.32
8	Zr-4/Ta	40	5	0	150	10	B.T.	0.85	0.30

[L.F.: Lack of Fusion, B.T.: Burn Through, × : No Defects]

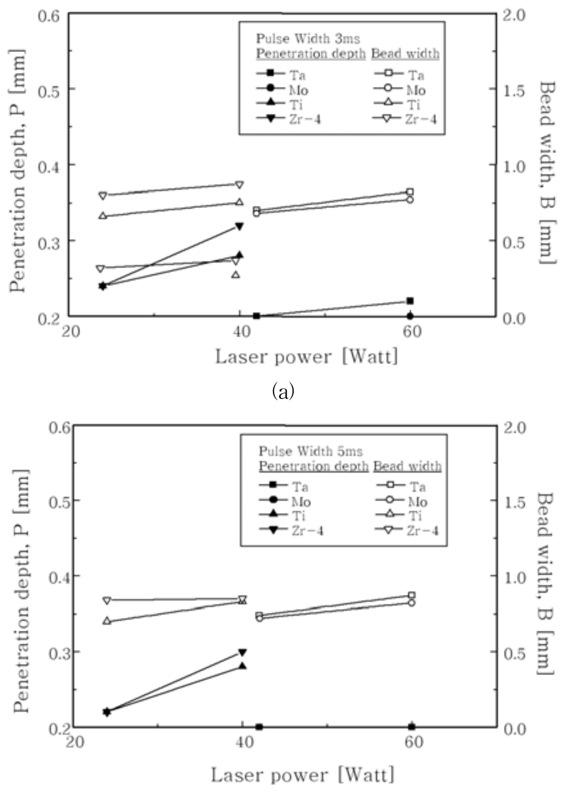


Fig. 4 Bead penetration and width as combinations of Ta, Mo, Ti and Zr-4 (a) 3ms and (b) 5ms

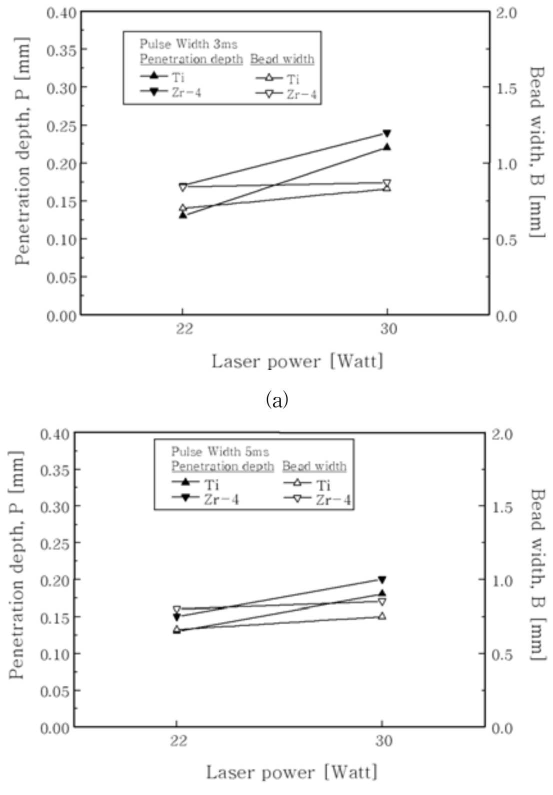


Fig. 5 Bead penetration and width as combinations of Ti and Zr-4 (a) 3ms and (b) 5ms

In secondary experiment to secure verification of weld specimens by Taguchi method, it is convinced that the sound welds of good penetration and bead appearance as shown in Fig. 5. Fig. 5 (a) and (b) show proper weld penetration with the Zr-4/Ta metal combination in pulse width (3-5ms) and laser power (20-30W). The Zr-4/Ta joint having 120° notch configuration as shown in Fig. 1 is the most desirable design for seal tube welding. At this part the weld penetration depth of Zr-4/Ta joint is approximately 0.24mm.

3.2 Metallographic examination of welds

Rough bead appearance and spattering took place at 60W of laser power when Ta/Ta and Mo/Ta joint were used for seal tube materials as shown in Fig. 6 (a) and (b). This seems to be due to higher melting points of Ta and Mo compared with Zr-4 and Ti, and different thickness of seal tube and sensor sheath[5]. This also seems to cause metal vapors to scatter as fine oxides on the seal tube surface. The smooth bead appearances of Ti/Ta and Zr-4/Ta joints were generally observed at 40W of laser power, and spattering was not observed in the welds as shown in Fig. 6 (b) and (c). Fig. 7 shows the microstructure of Zr-4/Ta weld joint, in which the fairly good weld penetration, and weld defects are also not revealed.

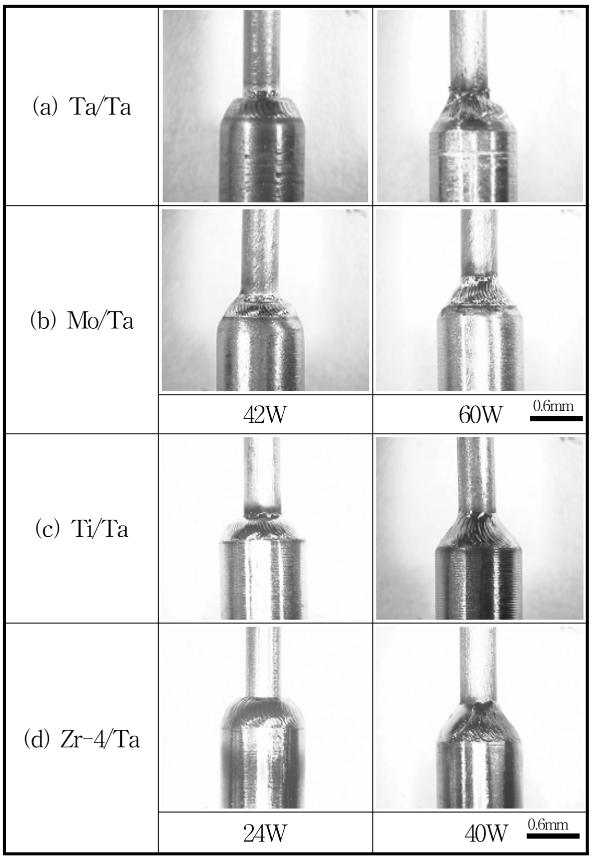
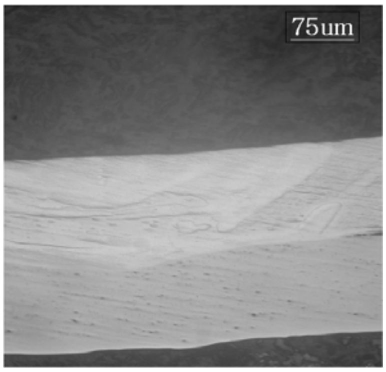


Fig. 6 Bead appearance of welds by macrography (a) Ta/Ta, (b) Mo/Ta, (c) Ti/Ta and (d) Zr-4/Ta joints

3.3 Welds inspection by micro-focus X-ray radiography

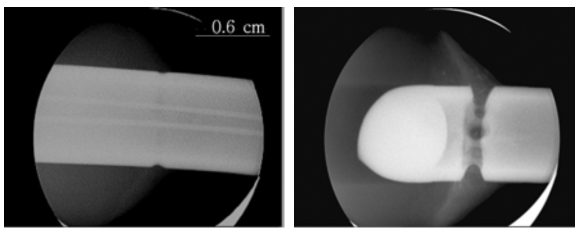
To find weld defects and to confirm the soundness of weld joints, the micro-focus X-ray radiography was conducted. Even though little problem is expected for welding of the same metals, dissimilar binary metal combinations such as Ta/Ta, Mo/Ta, Ti/Ta and Zr-4/Ta joints are required different laser powers to obtain sound welds because of different melting points and thin thickness. In addition, this unfortunately caused burn-through in the welds due to thin sheath of Ta thermocouple wire, so that it became more sensitive to the variation of laser powers.

Fig. 8 (a) shows the two parallel lines in the middle of a tube corresponding to the lines of temperature sensors. The sound weld is confirmed by X-ray transmitted image for Zr-4/Ta joint, in which the thermocouple wires are not be damaged by the high laser heat input in a short



(Laser power 30 W, Pulse width 3 ms, Speed 5 rpm)

Fig. 7 Microstructure as polished of Zr-4/Ta welded specimen



(a) (b)

Fig. 8 RT images of Zr-4/Ta welded specimen (a) partial penetration (b) burn-through time while welding. Therefore, the soundness of circumferential weld and the defect of burn-through are also confirmed by the X-ray transmitted images in Fig. 8 (a) and (b).

In order to obtain sound weld between a seal tube and a thermocouple wire based on the experimental results, metallography and X-ray radiography of welds, it can be suggested that laser power of 30 W, pulse width of 3 ms, defocus distance of-0.5 mm and welding speed of 5 rpm with Zr-4/Ta metal combination are the optimized welding parameters and joint design in Fig. 1.

3.4 Micro-hardness test of Zr-4/Ta weld specimen

Fig. 9 shows the hardness variation across base metal, HAZ (heat affected zone) and weld metal of Zr/Ta joint. Hardness values of base metal (BM), HAZ and weld metal (WM) are 175-210 Hv, 225-375 Hv and 400-450 Hv, respectively. Hardness values of HAZ and WM obtained in this experiment are much higher compared with autogeneous plasma arc welds of Zr-4 in the range of 220-230 and 240-250 Hv[6], respectively. It seems that the big difference in hardness between autogeneous weld of Zr-4 and Zr-4/Ta joints by laser beam welding is due to the rapid cooling and formation of hard phases in the Zr/Ta joints based on Zr-Ta binary diagram[7]. It seems that further study is necessary to analyze the constituents formed in the weld joints such as intermetallic compounds by electron microscopies and other advanced analysis tools.

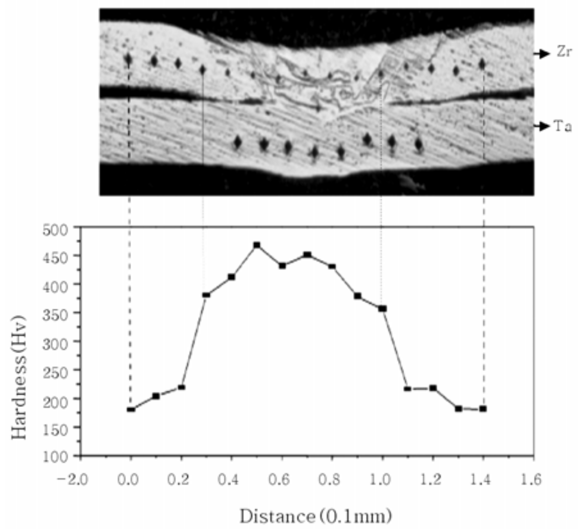


Fig. 9 Micro-hardness profile across a weld of Zr-4/Ta joint

Ⅳ. Conclusions

This work was carried out to obtain the optimum welding parameters and to select a most suitable dissimilar metal combination for joining of seal tube to thermocouple wire for the nuclear fuel irradiation test.

A Nd:YAG laser welding system with 150W pulsed and 400㎛ SI optical fiber transmission was set up to weld between the instrumented seal tube and the instrumented Ta thermocouple sheath for the fuel irradiation test. A joint of dissimilar binary metal combination of Zr-4/Ta was selected for seal tube to Ta thermocouple wire joining in terms of penetration and sound welds, in which welding parameters optimized by Taguchi method were employed. The laser power was found to have the most dominant effect on the penetration depth among welding parameters used in this experiment.

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