Laser Welding of Ta Sheath for a Thermocouple Wire for an Instrumented Fuel Irradiation Test (LAMP2006)

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

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1. Introduction

Laser beam welding technology is widely used to fabricate some parts of a nuclear fuel in the nuclear industry. Especially, a laser welding has become one of the key technologies not only for the fabrication of precise products in a 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 fuels1,2. The capsule is assembled into the instrumented fuel elements. The fuel elements are designed to measure the centerline temperature of the fuel pellets during the irradiation test by using temperature sensors3. The thermal sensor is composed of a thermocouple and a sensor sheath. In addition, the assembly which includes fuel elements and a temperature sensor has to be designed soundly so as not to be broken and not to leak fission gases from the fuel elements during the irradiation test4. Laser welding system which is designed and manufactured for this study was adopted to weld between a seal tube and a thermocouple sheath of 0.15 mm in thickness.

This study was carried out to investigate a weld between a thermocouple wire and a seal tube with laser welding. The optimum welding parameters and a suitable joint of a 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 a good weldability in terms of a solid solubility5. The penetration and the soundness of the weld specimens were investigated by metallography and a microfocus X-radiography. Hardness variations across the joints were measured by a hardness test. Moreover, the Taguchi experimental method was employed to analyze the weld specimens and the optimization of the experimental results of dissimilar metal welds was also done by the Taguchi experimental method.

2. Experimental method

2.1 Specimens preparation

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

2.2 Test Procedures

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

3. Results and discussion

3.1 Optimization of a seal tube welding

It is well known 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), a lack of fusion and other defects occur in a circumferential welding of dissimilar metal combinations. This impairs seriously the quality of the weld joints. In this experiment, the Taguchi experimental method was employed to reduce the experimental data to produce, and to secure a 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 defect points of view.

Based on the Taguchi experimental method, the orthogonal array for $L_8 2^7$ and the welding parameters such as the 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 the Ti/Ta and Zr-4/Ta joints in terms of two variables. It can be seen that the laser power has the steepest slope when compared with the other welding parameters such as the pulse width, defocus and materials. It means that it has the most effect on the penetration depth among the welding parameters chosen in this experiment.

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

Table 3 lists the welding results by the metallography and X-ray radiography in terms of the defects, bead width and penetration depth with a variation of the welding parameters such as the laser power, pulse width and defocus. In the Ta/Ta and Mo/Ta weld specimens, a weld penetration is almost not happening, on the other hand, the Ti/Ta and Zr-4/Ta weld specimens show a good penetration and bead appearance.

In a secondary experiment to secure a verification of the weld specimens by the Taguchi method, it is concluded that the sound welds are of a good penetration and bead appearance as shown in Fig. 5. Figs. 5 (a) and (b) show a 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 a 120° notch configuration as shown in Fig. 1 is the most desirable design for a seal tube welding. At this part the weld penetration depth of the Zr-4/Ta joint is approximately 0.24mm.

3.2 Metallographic examination of dissimilar welds

Rough bead appearance and a spattering took place at 50W to 60W of the laser powers when the Ta/Ta and Mo/Ta joints were used for a seal tube. This seems to be due to the higher melting points of Ta and Mo when compared with Zr-4 and Ti, and the different thicknesses of the seal tube and sensor sheath. This also seems to cause the metal vapors to scatter as fine oxides on the seal tube surface. The smooth bead appearances of the Ti/Ta and Zr-4/Ta joints were generally observed at 40W of a laser power, and a spattering was not observed in the welds. Fig. 6 shows the microstructure of the Zr-4/Ta weld joint, in which a fairly good penetration, and defects are also not revealed.

3.3 Welds inspection by a micro X-ray radiography

To find the weld defects and to confirm the soundness of the weld joints, a micro-focus X-ray radiography was conducted. Even though a little problem is expected for a welding of the same metals, dissimilar binary metal combinations such as Ta/Ta, Mo/Ta, Ti/Ta and Zr-4/Ta joints require different laser powers to obtain sound welds because of the different melting points and a thin thickness. In addition, this unfortunately causes burn-through in the welds due to the thin sheath of Ta thermocouple wire, so it becomes more sensitive to a variation of the laser powers. Fig. 7 (a) shows two parallel lines in the middle of a tube corresponding to the lines of the temperature sensors. The sound weld is confirmed by an X-ray transmitted image for the Zr-4/Ta joint , in which the thermocouple wires are not be damaged by the high laser heat input in a short time while welding. Therefore, the soundness of a circumferential weld and the defect of a burn- through are also confirmed by the X-ray transmitted images in Fig. 7 (a) and (b). In order to obtain a sound weld between a seal tube and a thermocouple wire based on the experimental results, metallography and an X-ray radiography of the welds, it can be suggested that a laser power of 30 W, a pulse width of 3 ms, a defocus distance of-0.5 mm and a welding speed of 5 rpm with the Zr-4/Ta metal combination are the optimized welding parameters for the joint design in Fig. 1. These properties are satisfied with the requirements of the fuel elements and the seal tube specimens for the irradiation test at the HANARO research reactor.

3.4 Micro-hardness test of weld specimens

Fig. 8 shows the hardness variations across the base metal, HAZ (heat affected zone) and a weld metal of the Zr-4/Ta joint. Hardness values of the base metal (BM), HAZ and the weld metal (WM) are 175-210 Hv, 225-375 Hv and 400-450 Hv, respectively. Hardness values of the HAZ and WM obtained in this experiment are much higher when compared with the 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 the hardness between the autogeneous welds of the Zr-4 and Zr-4/Ta joints by a laser beam welding is due to a rapid cooling and the formation of hard phases in the Zr/Ta joints based on the Zr-Ta binary diagram[7]. It seems that a further study is necessary to analyze the constituents formed in the weld joints such as the intermetallic compounds by electron microscopies and other advanced analysis tools

4. Conclusions

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

A Nd:YAG laser welding system with a 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 a dissimilar binary metal combination of Zr-4/Ta was selected for a seal tube to Ta thermocouple wire joining in terms of the penetration and sound welds, in which the welding parameters optimized by the Taguchi method were employed. The laser power was found to have the most dominant effect on the penetration depth among the welding parameters used in this experiment.

Acknowledgments and Appendixes

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References

[1] O. Arrestad : Fuel Rod Performance Measurements and Re-Instrumentation Capabilities at HALDEN project, In-Core Instrumentation Proceeding, (1996)
[2] S. C. Wilkins : Experimental Coaxial Mo-Zr-4 Fuel Cladding Surface Thermocouple, (1978)
[3] A. M. Eatom : LOFT Fuel Rod Surface Temperature Measurment Testing, CONF-781105-3, (1978)
[4] S. C. Wilkins : Embedded Zircaloy Sheathed Cladding Temperature, NUREG/CR-0271, (1978)
[5] C. Dawes : Laser Welding, Abington Publishing, (1992) 51-55
[6] J. H. Koh, S. S. Kim : A Study on Effects of Parameters on Beads by Plasma Arc Welding for Zircaloy-4, Journal of KWS, 15-6, (1977), 549-551
[7] D. L. Douglass : The Metallurgy of Zirconium, IAEA, (1971), 170-174

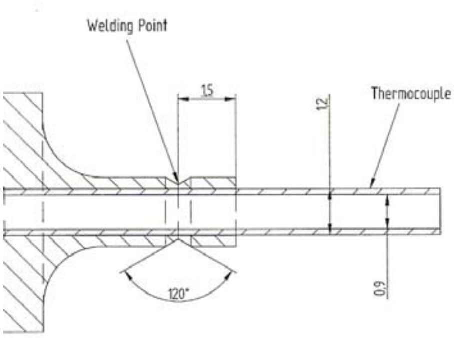


Fig. 1 Joint design of weld specimen.

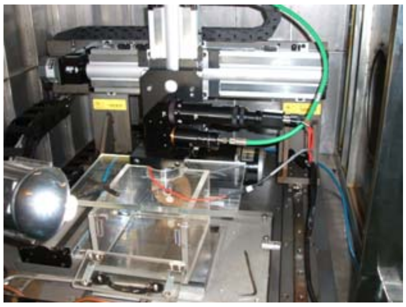


Fig. 2 Photograph of laser welding system.

Table 1 The welding conditions for Taguchi method.

Factor Level	Joint Description [A]	Laser Power (W) [B]	Pulse Frequency (Hz) [C]	Defocus (mm) [D]
1	Ta x Ta	42 (E 14J)	3 5	0 -0.5
2	Mo x Ta	60 (E 14J)	3 5	0 -0.5
3	Ti x Ta	24 (E 8J)	3 5	0 -0.5
4	Zr-4 x Ta	40 (E 8J)	3 5	0 -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
5	4	3	3	4
6	4	3	4	3
7	4	4	3	4
8	4	4	4	3
	a	b	c	a × c

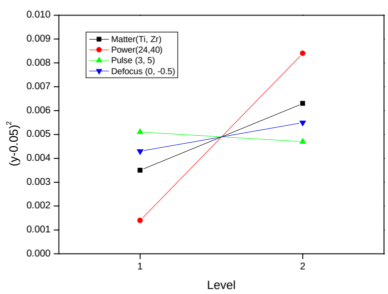
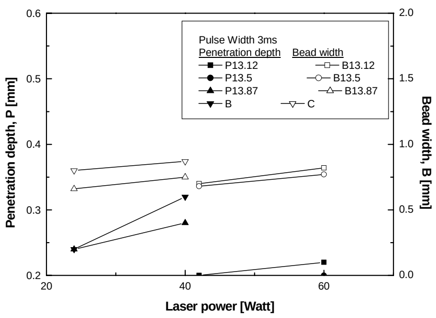


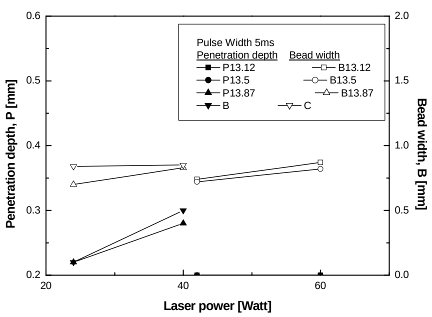
Fig. 3 Scattering distribution for a comparison of the welding parameters on Ti/Ta and Zr-4/Ta joints.

Table 3 Results of welding experiments.

	A	B	C	D	Radiography Test			Metallography Test	
					Conditions		Defects	Bead Width (mm)	Penetration depth(mm) Seal tube 0.2mm
					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	×	0.83	0.28
5	Zr/Ta	24	3	-0.5	150	10	×	0.80	0.24
6	Zr/Ta	24	5	0	150	10	×	0.84	0.22
7	Zr/Ta	40	3	-0.5	150	10	B.T.	0.87	0.32
8	Zr/Ta	40	5	0	150	10	B.T.	0.85	0.30

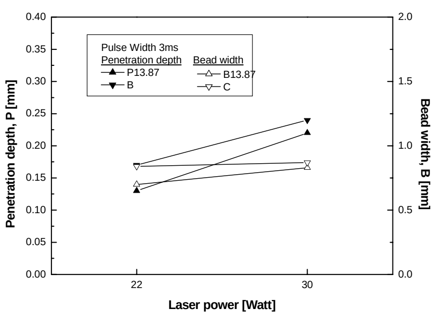


(a)

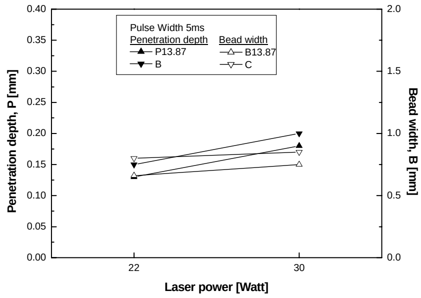


(b)

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



(a)



(b)

Fig. 5 Relationship between penetration depth and bead width as combinations of Ti and Zr-4 (a) 3ms and (b) 5ms.

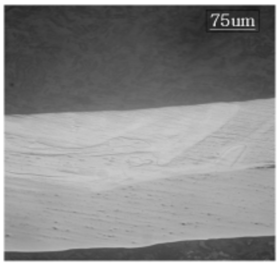
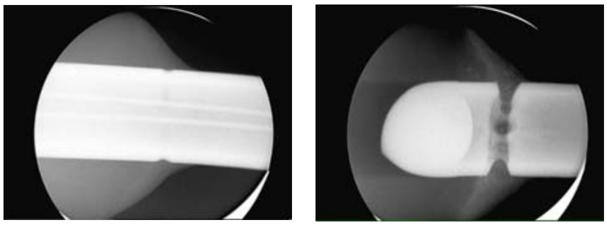


Fig. 6 Microstructure as polish of Zr-4/Ta welded specimen. (laser power 30W, pulse width 3ms, speed 5rpm)



(a) (b)

Fig. 7 RT images of Zr-4/Ta welded specimens (a) partial penetration (b) burn-through.

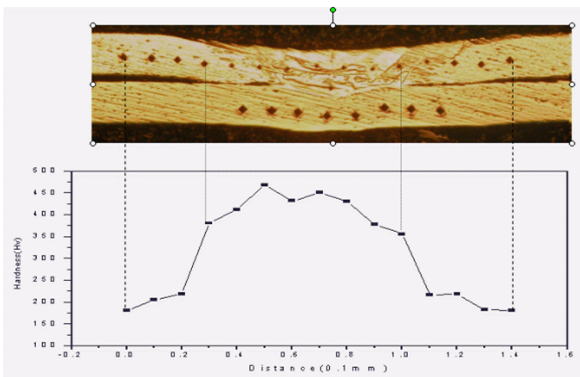


Fig. 8 Micro-hardness profile across a weld of Zr-4/Ta joint.

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