기술논문

# 조사연료봉 봉단마개의 레이저용접기술

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## Technology of the End Cap Laser Welding for Irradiation Fuel Rods

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### Abstract

Various welding methods such as Gas Tungsten Arc Welding(GTAW), magnetic force electrical resistance welding and Laser Beam Welding(LBW) are now available for end cap closure of nuclear fuel rods. Even though the resistance and GTA welding processes are widely used in manufacturing commercial fuel rods, they can not be recommended for the remote seal welding of fuel rods in the hot cell facility due to the complexity of the electrode alignment, the difficulty in replacing parts in a remote manner and the large heat input for the thin sheath. Therefore, the Nd:YAG laser system using optical fiber transmission was selected for the end cap welding of irradiation fuel rods in the hot cell.

The remote laser welding apparatus in the hot cell facility was developed using a pulsed Nd:YAG laser of 500 watt average power with an optical fiber transmission. The weldment quality such as microstructure and mechanical strength was satisfactory. The optimum conditions of laser welding for encapsulating irradiation fuel rods in the hot cell were obtained.

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## 1. Introduction

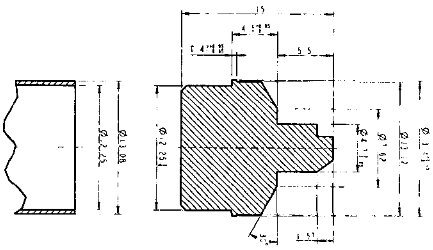
Various studies have been conducted to develop new fuels and to manufacture capsules for the irradiation test. In such studies, a remote welding technique has been required in a highly radioactive hot cell for manufacturing the irradiation fuel rods[1,2]. Meanwhile, the laser has been considered to be one of the most appropriate candidate tools for the remote welding technique, since the laser beam transmission by an optical fiber can be easily applied to end cap welding in a shielded facility. This study is also a technical challenge to secure a higher quality of laser weldments. In the fuel rod manufacturing process, end cap closure is the welding of Zircaloy-4 cladding tube, which is loaded with pellets, with an end cap. Such a seal welding requires high reliability. If there were any defects along the circumference of the welds, they would cause the radioactive fission products to leak out during irradiation of the nuclear fuels, and consequently bring about serious safety problems[3]. This study was carried out to investigate the feasibility of the LBW application in the sealing of end caps and Zircaloy-4 cladding tubes in a remote manner and to obtain the optimum conditions for the laser welding and to evaluate the performance of the seal welds for the irradiation of fuel rods.

## 2. Experimental Procedure

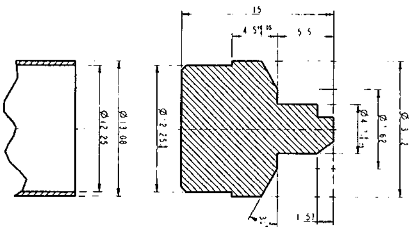
The material used in this study was Zircaloy-4. The chemical composition and mechanical properties of the specimen are given in Table 1 and its the schematic in Fig. 1. These specimens were prepared by welding cladding tubes with end caps. For the tensile test, the specimens welded by LB and GTA were prepared as shown in Fig. 2. These specimens were ultrasonically cleaned in ethyl alcohol, and then dried.

**Table 1** Chemical compositions and mechanical properties of zircaloy-4

| 1Chemical Compositions | | | | |
|---|---|---|---|---|
| Element | Sn | Fe | Cr | Zr |
| wt. % | 1.2 - 1.7 | 0.18 - 0.2 | 0.07 -0.1 | Bal. |
| Mechanical Properties | | | | |
| Tensile Streng (Mpa) | Yield Strength (0.2%offset, MPa | Elongation (%) | | |
| 440 | 345 | 32.0 | | |



(A type)



(B type)

**Fig. 1** A schematic of zircaloy-4 specimens

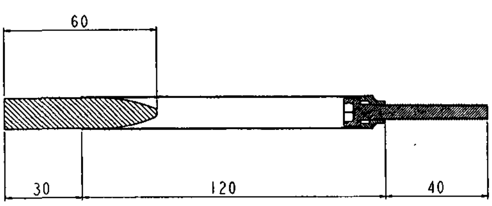



**Fig. 2** Configuration of tensile specimen

In order to weld the end cap of the fuel rods in the hot cell, the remote chamber using the Nd:YAG laser with an optical fiber transmission system was made as shown in Fig. 3. The chamber comprised of a body, a rotary driving part, an end cap inserting part, an optical fiber as well as a coupler part. When the beam oscillating from the laser generator was transmitted, the optical fiber, which was very flexible, thin and long, was utilized for transmission. Since the distance between the welding chamber inside the hot cell and the laser generator outside the hot cell was about 20m, an optical coupler was required to connect the chamber with the optical fiber. As illustrated in Fig. 4, the optical coupler was manufactured in such a way that the optical fiber, the optical fiber connector and the coupler could be easily replaced in a remote manner.

If the beam coming from the laser generator is directly emitted, its degree of positional freedom becomes poor and it is inconvenient to use the beam in a narrow space. Therefore, a flexible and thin optical fiber was used. The optical fiber transmission consisted of an optical inlet coupler, an optical fiber and an optical outlet coupler. The optical inlet coupler was in a section where the beam was connected with the core of the optical fiber by an incident lens. The optical fiber, which was quartz glass of pure $SiO_2$, was made up of a core part having a wide refractive index

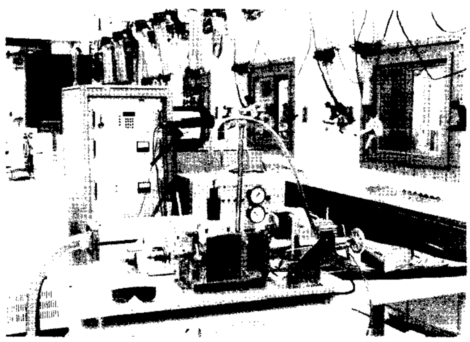


**Fig. 3** Photograph of laser system with optical fiber transmission.

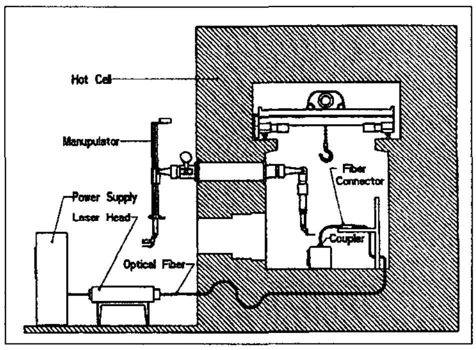


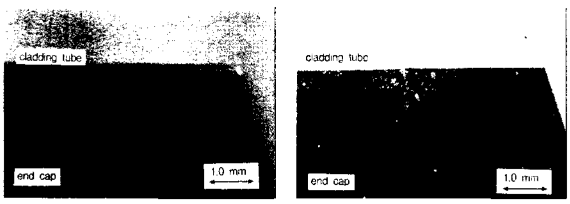

**Fig. 4** Schematic illustration of fiber delievery system in hot cell

and a cladding part having a narrow refractive index, whose diameters to the core were 800 ㎛. The Step Index(SI) was multi-mode type, and the Numerical Aperture(NA) of the optical fiber was 0.22. The focusing lens of the coupler used in this experiment was ultraviolet grade fused silica.

Microhardness was determined under a 100 g load at 0.2 mm intervals across the welds, the Heat Affected Zone(HAZ) and the base metal. A series of Vickers hardness numbers was measured across several welded specimens. Tensile tests were performed according to the ASTM standard E8 using an universal test machine and five specimens were tested for every geometry type. The crosshead speed for weld tensile specimens was 0.001 mm/s and the gauge length was 25 mm. Closed-end burst test specimens were sealed with Swagelock pressure fitting and then they were connected to the oil pressurization system. Internal pressurization was applied at a speed of 0.23 MPa/sec until the specimen ruptured. The microstructure of the weld specimens was observed by an optical microscope. All specimens were polished and etched using the etchant of $H_2O$ 45 %, $HNO_3$ 45 %, HF 10 %(vol.%). Microstructures of the overall weld zone including the weld metal, the HAZ and the base metal were obtained.

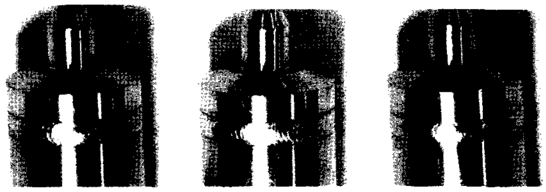
## 3. Results and Discussion

It is evident that the joint geometry of the end cap and the cladding tube has a significant effect on the seal welding of the irradiation fuel rods. Any modification and improvement of the weld joint geometry may be an advantage to the autogenous welding processes. If the weld metal is solidified only in one direction during welding, the modified part of the weld joint geometry can be easily melted by the weld metal. Due to the high density energy of the beam, LBW produces a molten pool in the material easier than GTAW, and a much deeper penetration can be obtained by a laser. Fig. 5 shows the typical weld-sections of end cap welds with the cladding tube made by GTAW and LBW. As shown in Fig. 6, LBW was found to have a much smaller HAZ than GTAW. Moreover, it is well known that GTAW generally has a larger melting volume than LBW which is a high density energy welding process.




(a) GTAW (b) LBW

**Fig. 5** Cross sectional views by remote welding performance. (×20)



(a) $D_o$=13.12mm (b) $D_o$=13.5mm (c) $D_o$=13.87mm

**Fig. 6** Bead shapes with Do=13.12mm, 13.5mm, 13.87mm of end caps and laser power 280W. (×2.5)

In order to assemble the bundle in the fuel fabrication process, it is required that the outer diameter of fuel rods after end cap welding is less than 13.20 mm. The effect of dimensional geometry of the end cap for LBW was investigated by changing the outer diameter ($D_o$) of the end caps and laser powers. Fig. 6(a), (b) and (c) show typical appearances of the welded specimens using 13.12 mm, 13.4 mm and 13.87 mm of $D_o$ of the end caps (including filler size). Fig. 7, Fig. 8 and Fig. 9 show the relationship

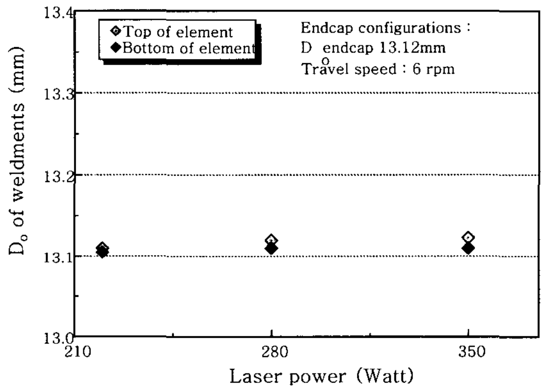



**Fig. 7** Results of dimensional measurements using $D_o$=13.12mm

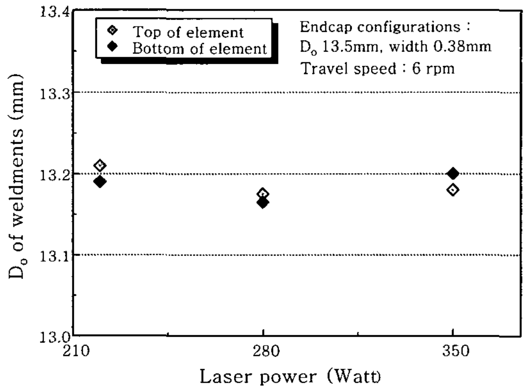



**Fig. 8** Results of dimensional measurements using $D_o$=13.5mm

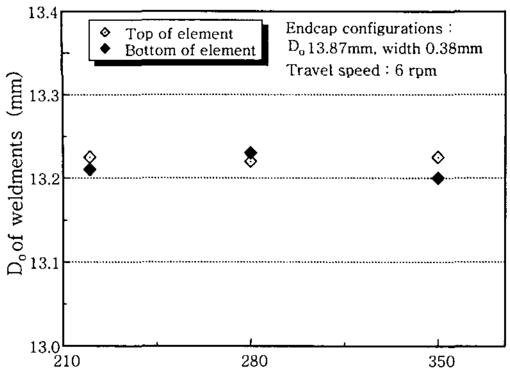



Fig. 9 Results of dimensional measurements using $D_o$ of 13.87mm

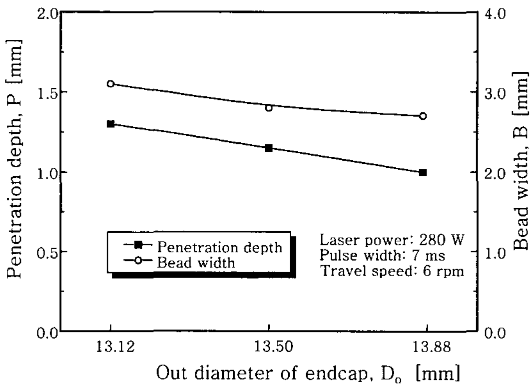



Fig. 10 Comparison of bead width and penetration depth on $D_o$ of end caps

between the $D_o$ of the end caps and laser power using the 800 μm optical fiber at Focal Length (FL)= 95 mm. In the case of 13.12 mm, $D_o$ of the end caps of the fuel rods without the filler part was found to be from 13.10 mm to 13.13 mm. In the case of 13.4 mm with a filler part, the $D_o$ of the end caps of the element was found to be from 13.15 to 13.20 mm, and in the case of 13.87 mm with a filler part, the $D_o$ of the end caps of the element was found to be from 13.20 mm to 13.24 mm. Therefore, it was found that the optimum $D_o$ of the end cap before laser welding would be from 13.4 mm to 13.5 mm to keep a max. 13.20 mm of $D_o$ of the end cap after laser welding. In addition, Fig. 10 and Fig. 11 show the relationship between the bead width and the penetration depth using the $D_o$ of the end caps of the fuel rods and laser powers, respectively. As for the effect of $D_o$ on the end caps of the fuel rods, it was found that the bead width and the penetration depth of the welds decreased with increasing the $D_o$ of the end cap. In the effect of the laser powers on the end caps of the fuel rods, it was found that the penetration depth increased remarkably by increasing the laser power, whereas the bead width increased slightly with the laser power.

Fig. 12 shows the comparison of the specimens welded by GTA and LB. In the GTA and LB weld specimens, the hardness of the weld metal was found to be in the range of 180 to 210, and the hardne ss of HAZ between the weld metal and the base metal in the range of 160 to 180. The difference of the hardness of the weld metal between the LB and GTA weld specimens was not significant, but the hardness of HAZ of the GTA weld specimens were slightly higher than that of the LB weld specimens. The closer to the top of the end cap, the higher and the harder GTA and LB weld specimens were found. It was therefore considered that the hardness of the GTA weld specimens was high because the weld zone of the end cap underwent fast cooling and quenching from the overheated condition by the weld thermal cycle. Also, the weld metal and the HAZ of the LB weld specimens were found to be narrower compared with those of the GTA weld specimens.

Table 2 shows the yield strength, tensile strength and elongation obtained from the tensile tests in terms of the differences in the geometrical configurations of the GTA and the LB weld specimens, i.e., A type (with filler joint as

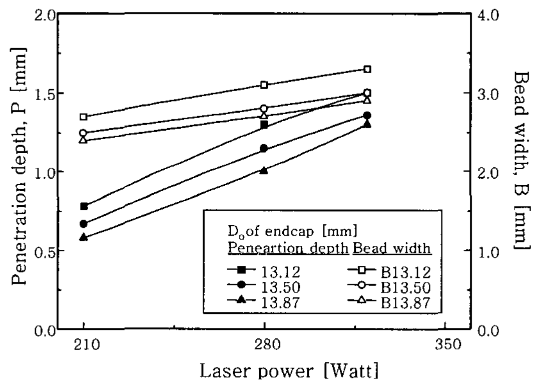



Fig. 11 Comparison of bead width and penetration depth on $D_o$ of end caps and laser powers

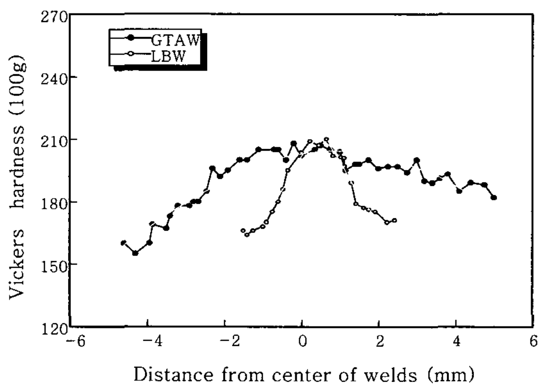



Fig. 12 Variations in the microhardness along the sheath-HAZ-end cap in GTAW and LBW

shown Fig.1) and B type (without filler joint as shown Fig.1). The tensile strengths of the GTA and the LB weld specimens were higher than those of the base metal. The elongation of the LB weld specimens showed a little higher than that of the GTA weld specimens. No significant difference could be found between the A and B types in the tensile properties of the weld specimens. The failure of the transverse weld tensile specimens occurred in the base metal far away from the welds.

The ultimate burst elongation of the LB weld specimens were found to be an average 36 %, which was much higher than that of the GTA weld specimens. Also, based on the geometrical configuration of the weld zone, the mean value

**Table 2** Tensile properties of GTA and LB welded specimens

| Specimen Types | | Cladding Tube Dimensions | 0.2% YS (MPa) | | UTS (Mpa) | | % E in 50mm | |
|---|---|---|---|---|---|---|---|---|
| | | | Each | Ave. | Each | Ave. | Each | Ave. |
| GTAW | A | 13.08x12.24 (O.D) (I.D) | 431 | 434 | 540 | 541 | 37.2 | 37.1 |
| | | | 452 | | 552 | | 35.6 | |
| | | | 420 | | 530 | | 38.5 | |
| | B | | 406 | 408 | 520 | 529 | 35.7 | 36.3 |
| | | | 424 | | 532 | | 36.5 | |
| | | | 396 | | 535 | | 36.7 | |
| LBW | A | | 397 | 423 | 520 | 520 | 40.2 | 39.7 |
| | | | 449 | | 532 | | 39.4 | |
| | | | 423 | | 509 | | 39.4 | |
| | B | | 398 | 427 | 535 | 533 | 36.2 | 37.3 |
| | | | 457 | | 540 | | 35.8 | |
| | | | 426 | | 523 | | 39.9 | |

**Table 3** Burst properties of GTA and LB welded specimens.

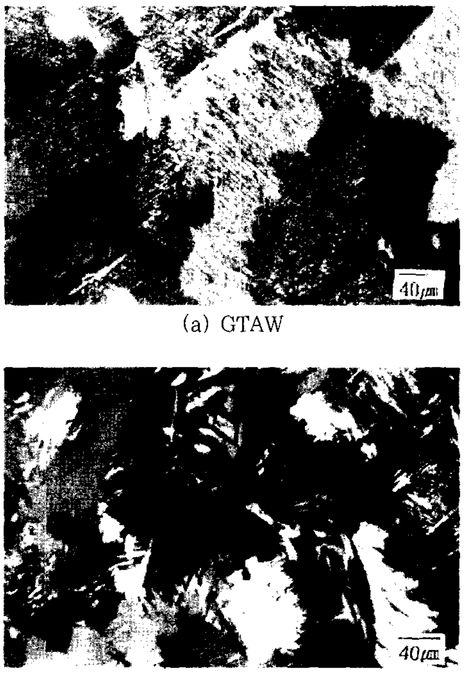
| Specimen Types | | Cladding Tube Dimensions | UBS (MPa) | | UBE (%) | |
|---|---|---|---|---|---|---|
| | | | Each | Ave. | Each | Ave. |
| GTAW | A | 13.08x12.24 (O.D) (I.D) | 530 | 528 | 28.8 | 28.5 |
| | | | 527 | | 26.4 | |
| | | | 528 | | 30.2 | |
| | B | | 532 | 527 | 28.9 | 28.2 |
| | | | 524 | | 27.5 | |
| | | | 525 | | 28.1 | |
| LBW | A | | 524 | 526 | 39.9 | 37.8 |
| | | | 526 | | 36.2 | |
| | | | 528 | | 37.2 | |
| | B | | 530 | 525 | 30.7 | 35.4 |
| | | | 520 | | 37.6 | |
| | | | 522 | | 37.8 | |

of the ultimate burst elongation of A type was found to be higher. The results of the ultimate burst strength and the ultimate burst elongation are summarized in Table 3.

Since the weld zone was locally heated and cooled to the extent of its phase boundary areas depending upon the welding parameters, it had various microstructures with different phase transformations[4]. It was observed that the $\alpha$ grains in the microstructure of the base metal of the cladding tube were longitudinally elongated, and the microstructure of the base metal of the end cap was an irregular structure with equiaxed, recrystallized $\alpha$ grains. The microstructures of the GTA and the LB weld metals are shown in Fig. 13. The GTA weld zone was composed of a structure of Widmanstätten with nonparallel $\alpha$ plates (basketweave type). The LB weld zone was also composed of a mixed structure of nonparallel Widmänstatten plates and martensite. The HAZ in the welds included a transformed $\beta$ structure with irregular grains near the weld metal. And the HAZ in the LB welds was much smaller than that of the GTA welds as shown in Fig. 5.

## 4. Conclusions

This study was conducted to develop Zircaloy-4 end cap welding, utilizing the Nd:YAG laser system including optical fiber transmission. The remote welding performance was evaluated as follows.




(a) GTAW

(b) LBW

**Fig. 13** Microstructures of welded regions (×200)

1) As a result of examining the characteristics of the dimensional configuration of end cap welding by the LB, it was found that the optimum $D_0$ of the end caps before laser welding would be at least 13.5 mm to keep a max. 13.20 mm of $D_0$ of the end caps after laser welding.

2) In the mechanical test of the Zircaloy-4 welded specimens, both the GTAW and the LBW were found to have good strengths, but the LB weld zone was found mostly to have a greater penetration depth than that of the GTA weld zone, and further to have a good weldability with the formation of fine grains.

3) The LB weld zone was smaller than the GTA weld zone, and the microstructure of the welds in both the GTA and the LB weld zones appeared to be of a mixed structure, where the martensitic $\alpha'$ structure and the Widmänstatten $\alpha$ phase in the prior $\beta$ grains were intermixed.

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