247-06

Internal attachment of laser beam welded stainless steel sheathed thermocouples into stainless steel upper end caps in nuclear fuel rods for the LOFT Reactor.

Richard K. Welty/Raymond D. Reid

Exxon Nuclear Company, Inc. 2101 Horn Rapids Road, Richland Washington 99352

Abstract

The Exxon Nuclear Company, Inc., acting as a subcontractor to EG&G Idaho Inc., Idaho National Engineering Laboratory, Idaho Falls, Idaho, conducted a laser beam welding study to attach internal stainless steel thermocouples into stainless steel upper end caps in nuclear fuel rods.

The fuel rods and thermocouples are used to test simulated loss-of-coolant-accident (LOCA) conditions in a pressurized water reactor (LOFT reactor, Idaho National Laboratory).

The objective of this study was to determine the feasibility of laser welding a single 0.063 inch diameter stainless steel (304) sheathed thermocouple into a stainless steel (316) upper end cap for nuclear fuel rods.

A laser beam was selected because of the extremely high energy input in unit volume that can be achieved allowing local fusion of a small area irrespective of the difference in material thickness to be joined.

A special weld fixture was designed and fabricated to hold the end cap and the thermocouple with angular and rotational adjustment under the laser beam.

A commercial pulsed laser and energy control system was used to make the welds.

Process tests were performed and evaluated. Results indicated that successful welds could be made using the laser system.

A process qualification was written specifying laser energy, spot size and weld overlay.

This program was successfully concluded by welding seventeen (17) centerline fuel rods for the LOFT reactor.

Introduction

The LOFT reactor (Loss-of-fluid-test) located at the Idaho National Engineering Laboratory, Idaho Falls, Idaho is an experimental reactor whose purpose is to:

1) Evaluate the capability of analytical methods that predict the loss-of-coolant-accident (LOCA) responses of large pressurized water power reactors, the performance of engineered safety systems, and the margins of safety in the safety systems performance.

2) Identify any unexpected events or thresholds not presently accounted for in the analysis of reactor response or in the design of engineered safety systems.[1]

To accomplish these objectives, test instrumentation is required in the reactor core. One of the primary instrumentation items used is thermocouples attached to the outside of zircaloy clad fuel rods. This program was discussed in an earlier paper entitled "External attachment of titanium sheathed thermocouples to zirconium nuclear fuel rods for the LOFT reactor". When the external thermocouple program was completed, an advanced instrumentation study was initiated to investigate the feasibility of laser welding a single 0.063 inch diameter stainless steel sheathed thermocouple into a stainless steel upper end cap. These thermocouples which are inserted into the center of the fuel rod will be used to measure the internal nuclear fuel temperature during testing in the LOFT reactor (See Figure 1). Attachment of this small thermocouple into the center of the end cap presents an extremely difficult welding task due to the small attachment areas available, and thin wall of the thermocouple material. Since extensive equipment, instrumentation, and experience had been developed for welding the external titanium thermocouple, it was decided to apply these same techniques to the centerline thermocouples.

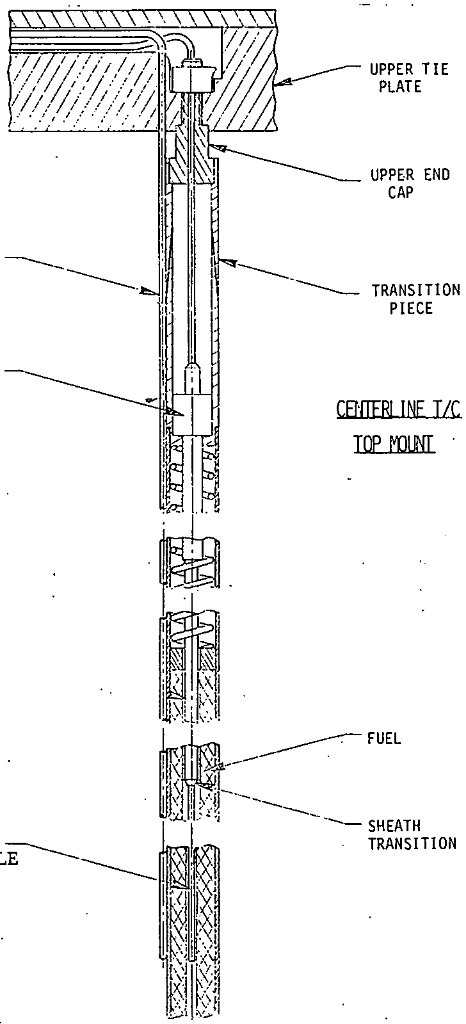


Figure 1. LOFT centerline thermocouple fuel rod.

Discussion

Laser system

The laser facility used for this project was the same one that was used for the titanium thermocouple program.

Figure 2 is a photograph of the overall system. The principal items in the photograph are: (a) the laser head, (b) optical viewing, (c) tooling fixture to hold the thermocouple and end cap.

Figure 3 is a photograph of the laser head showing: (a) back reflector, (b) laser cavity (Xenon gas filled helical flashlamps are used), (c) front reflector, (d) negative lens, and (g) focusing lens.

This particular laser was used previously for attaching the external titanium thermocouples to the fuel rods.

For this application, the laser machine was not modified, different tooling was designed to hold the end cap and thermocouple in position under the laser beam with angular and rotational capability (See Figure 4).

Little or no process development had to be done. The experienced gained from the exterior titanium thermocouple welding was applied successfully to this program. Most of the effort was centered on weld development.

Weld development

Initial attempts to weld the 304 sheathed thermocouple into the 316 end cap resulted in cracks at the weld interface. Figure 5 is an example of cracking in the weld joint. In this photograph the thermocouple sheath is on the left and the end cap weld prep area on the right.

This problem persisted, so an analysis was made to try determine potential causes. Since it is known that 3 to 15 percent delta ferrite is required in the weldment to suppress hot cracking, a Schaeffler Constitution diagram was used to try and estimate the percent ferrite in the weld. The actual ferrite would have to be analyzed with a magna-gage or other ferrite meters because the rapid cooling rates associated with this type of weld alter the predicted values in the Schaeffler diagram. Figure 6 is an Expanded Schaeffler Constitution diagram for stainless steel weld metal. The delta ferrite in 316 stainless with 18 percent chromium and 12 percent nickel falls very close to the 0 percent ferrite region. (The actual values are chromium equivalent equal to 21.04 and nickel equivalent to 14.75)

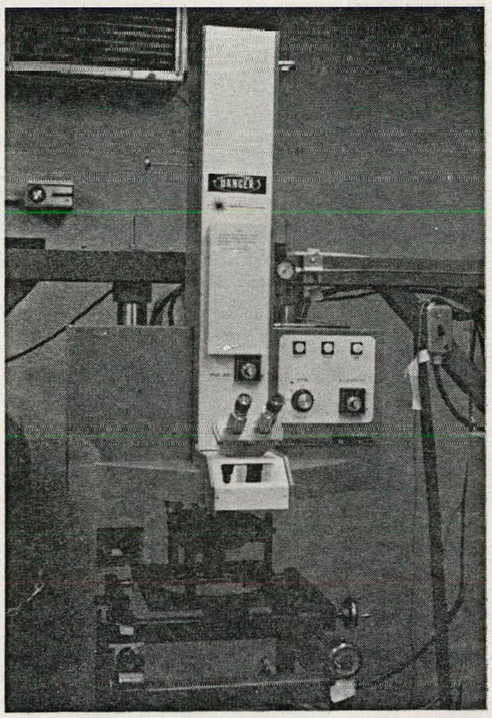


Figure 2. Laser system for centerline T/C welding.

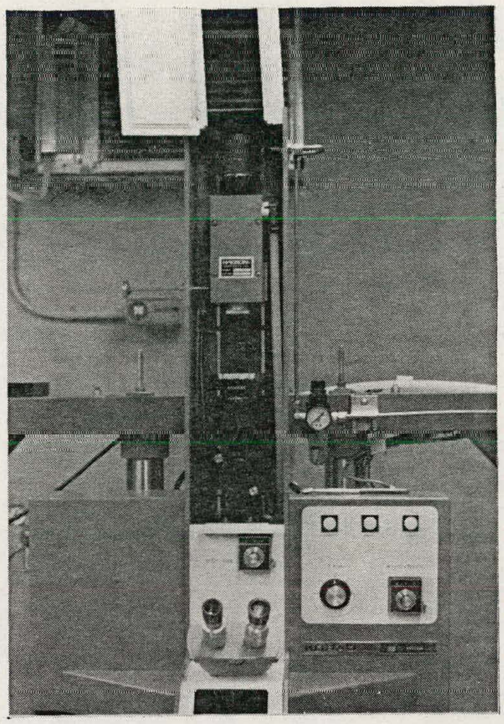


Figure 3. Laser head for centerline T/C welding.

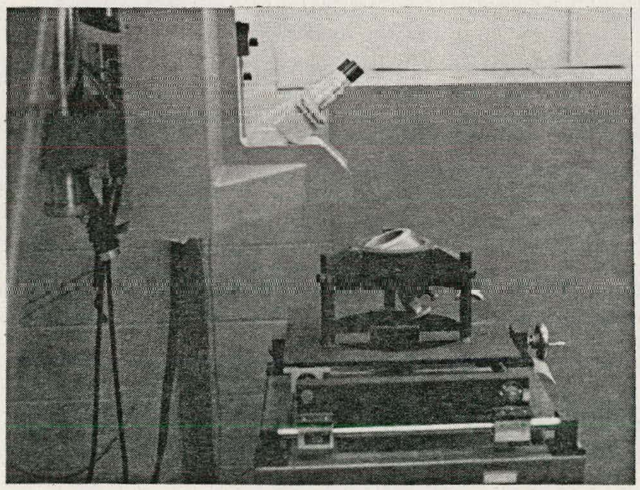


Figure 4. Rotational and angular tooling for centerline T/C welding.

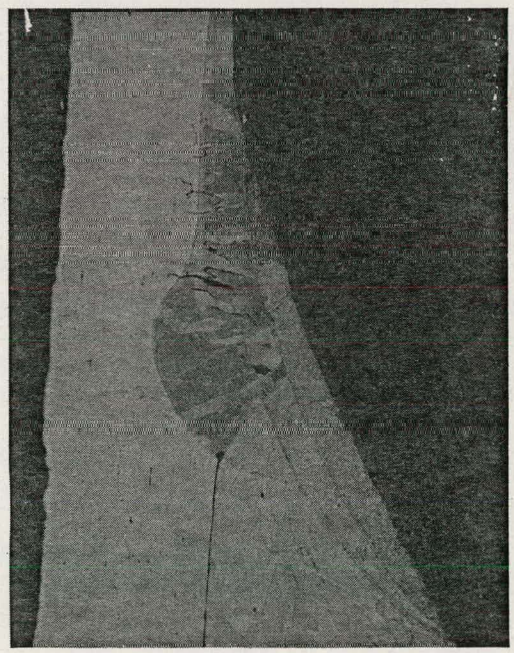


Figure 5. Weld crack - LOFT centerline stainless steel thermocouple.

Two tests were performed, first, nickel filler wire was added to the weld to drive the weld into the austenite phase. This resulted in severe cracking of the weld, which was predicted. Next, the end cap was chrome plated to increase the ferrite percentage. This technique was successful in producing crack free welds, an example of which is shown in Figure 7.

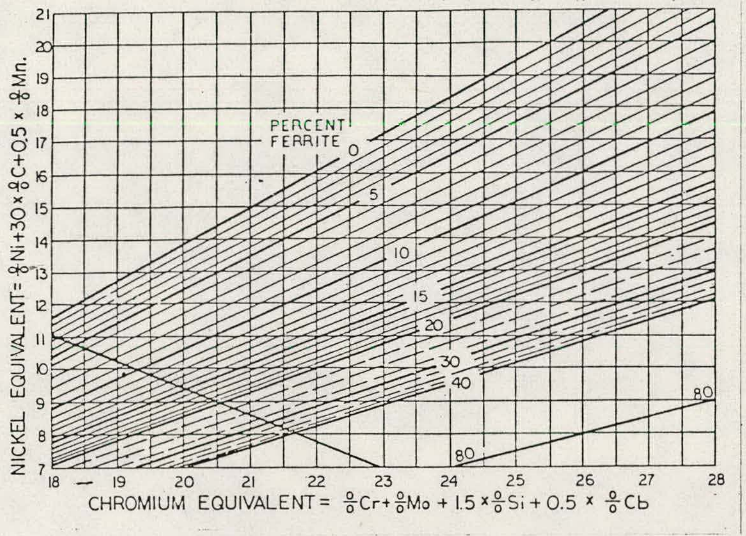


Figure 6. Expanded Schaeffler constitution diagram for stainless steel weld metal.

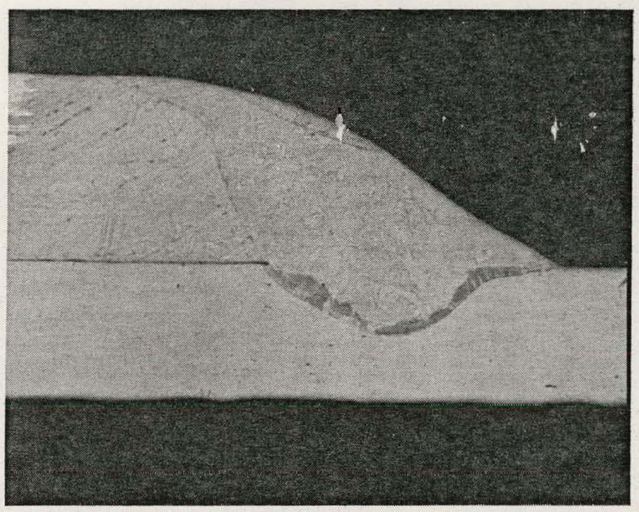


Figure 7. Crack-free weld - LOFT centerline stainless steel thermocouple.

The results of this work tend to support the accepted role of ferrite in contributing to weld soundness.[2]

- o Delta ferrite islands in an austentic matrix dissolve more of the impurities than austenite can.

- o Delta ferrite islands provide interphase boundaries with more surface over which to distribute the undissolved low melting particles. With small amounts of ferrite these boundaries are discontinuous, thus interrupting any cracking path.

Laser burn pattern characterization

A very important technique that has been developed in the laser programs for the external titanium and internal stainless steel thermocouple welding is characterization of the laser beam.

Since the wavelength of neodymium is invisible to the human eye, it is difficult to characterize the laser beam. These types of welds are very sensitive to misalignment, so it is necessary to see the energy density within the beam and to observe circularity of the laser beam perimeter. Circularity of the laser beam is very important as it indicates when the reflectors are perpendicular to the laser rod resulting in uniform beam energy.

Initially, the laser beam was observed by radiating the beam onto an exposed sheet of Polaroid film. This is an acceptable technique except that the edges of the laser beam pattern on the film "run" or burn unevenly from excess heat in the laser beam, resulting in a difficult to interpret beam pattern.

Since July 1975, an improved technique has been employed using "Footprint" paper. Footprint paper is a carbon deposited, front surfaced paper which burns very evenly in the laser beam, leaving the white paper background exposed. The carbon vaporization is very sensitive and small energy variations within the laser beam can be observed.

Use of this paper has permitted a highly refined technique to be used for alignment of the laser reflectors and has contributed directly to the success of the LOFT thermocouple laser welding programs.

An example of how the burn patterns can be used to avert potential welding difficulties is shown in Figures 8 and 9.

The burn patterns in Figure 8 show a shaded or darkened area in the top portion of the beam. The mirrors were re-collimated and another set of burn patterns taken (Shown in Figure 9). The energy increase that resulted from this adjustment was 0.2 of a joule at a lower pumping voltage. The objective in production welding is to maintain constant output energy at the lowest possible pumping voltage. (Low pumping voltages prolong flashlamp life).

Another example of burn pattern characterization is shown in Figures 10 and 11. These samples are not representative of normal welding parameters. (As examplified by the deep penetration in the weldment.) They were made to demonstrate the unbalanced front to back welds which can occur when the laser reflectors are misaligned. This is shown by the shaded areas of the burn patterns in Figure 10. The weld, in this case, has low penetration on the right side of the sample. The reflectors were collimated and new burn patterns made which are shown in Figure 11. The weldments in this case are reasonably balanced in front and back penetration.

All of the other welding parameters were kept constant during this test so that the net difference in weld penetration was contributed to the alignment of the mirrors.

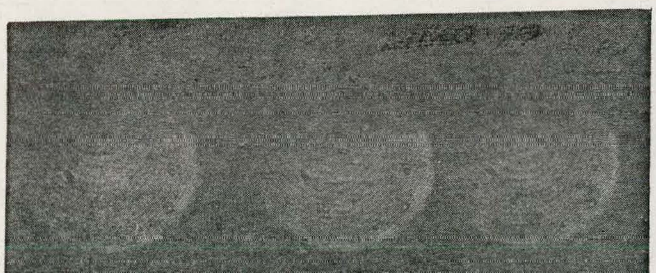


Figure 8. Misaligned burn patterns.

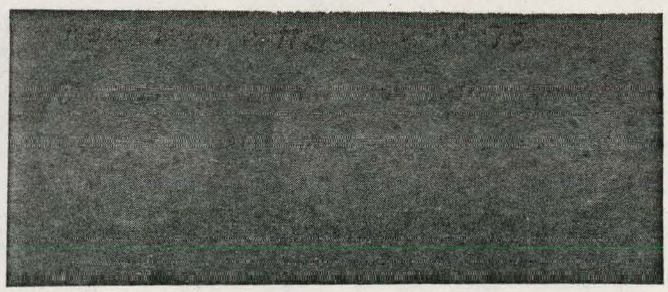
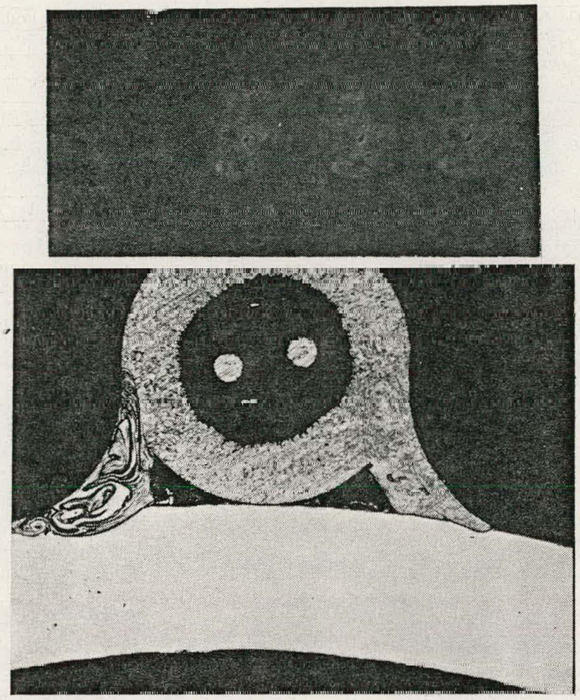


Figure 9. Aligned burn patterns.



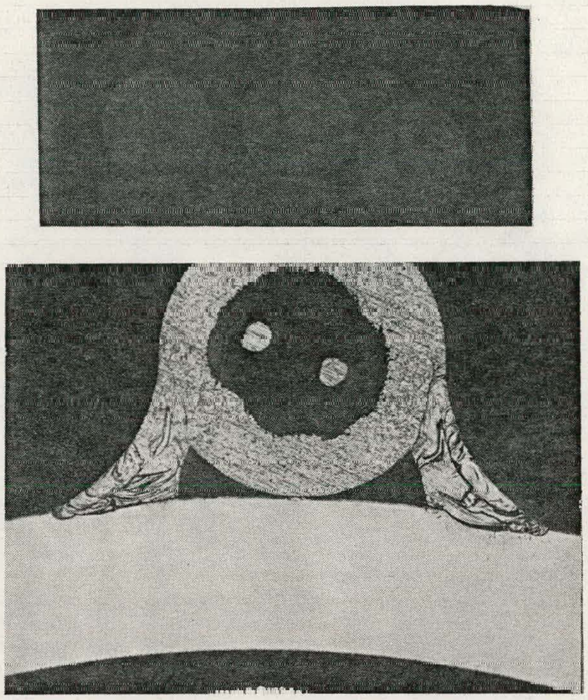


Figure 10. Unbalanced burn patterns and welds. Figure 11. Balanced burn patterns and welds.

Figures 12 and 13 are examples of how the burn patterns can be used for a different type of analysis, namely irregularities in the laser beam (burned areas on the lenses, mirrors, laser rod, weld splatter on the cover glass, etc.)

Figure 12 is a burn pattern taken before welding of an external thermocouple. Very few spotted areas occur within the laser beam burn pattern.

In Figure 13, which was recorded after making the weld shown in the photograph, shows numerous spotted areas within the laser beam burn pattern. These were caused by weld splatter adhering to the objective lens cover glass. They can, and do, contribute to a loss in energy, in this case 0.1 of joule, or 2% of the available laser energy. This is demonstrated by the drop in weld penetration in the before and after process control metallurgical cross-sections.

Conclusions

The experience and techniques gained from welding external titanium thermocouples was successfully applied to welding stainless steel centerline thermocouples. The problems that arose were ones of metallurgy in that the weld had insufficient ferrite present to prevent hot cracking. This was solved by chrome plating the end caps. Seventeen centerline fuel rods were made and are now awaiting insertion into the LOFT Reactor.

Characterization of burn patterns has been a key factor in understanding the laser energy distribution within the weldment, and has contributed directly to successful thermocouple welding for the LOFT program.

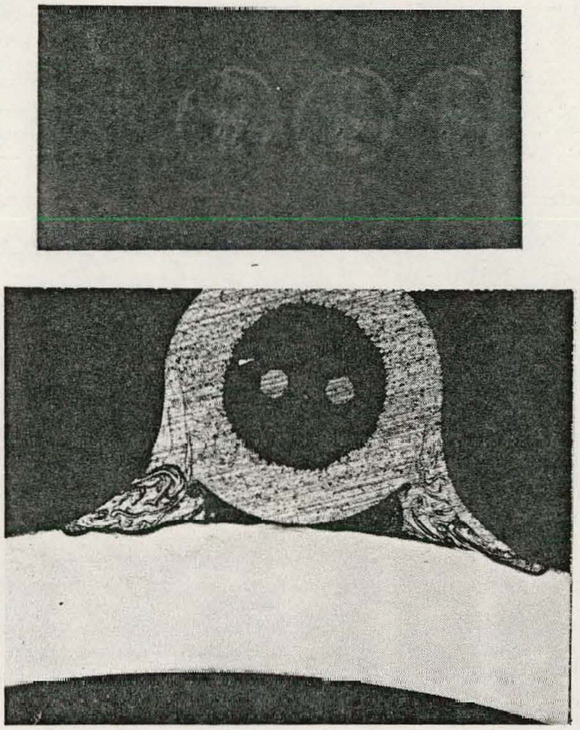


Figure 12. Typical burn patterns before welding.

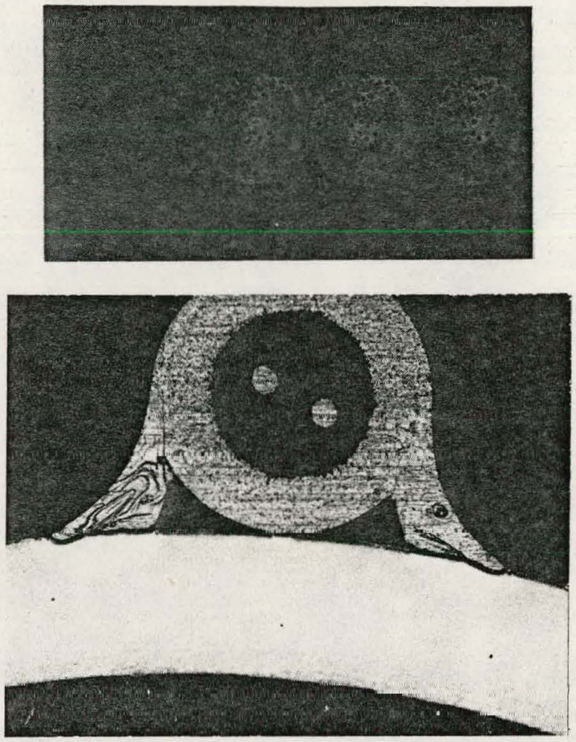


Figure 13. Typical burn patterns after welding.

Acknowledgments

The author wishes to acknowledge R. D. Reid, and E. G. Coye, Exxon Nuclear Company, Inc. for their leadership in conducting the laser welding program, and to O. L. Kruger, P. P. King and B. S. Flora, also of Exxon Nuclear Company, for their technical assistance.

References

1. Russell, M. L. "LOFT Fuel Modules Design Characterization and Fabrication Program" ANCR-1223, September 1975.

2. Campbell, H. C., Manager, Education, American Welding Society, Welding Journal, December 1975.