THE PRECISE X-RAY INSPECTION FOR DUPIC FUEL ELEMENTS WELDED BY Nd:YAG LASER

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ABSTRACT

DUPIC (Direct use of spent PWR fuel in CANDU reactors) nuclear fuel is a CANDU fuel fabricated remotely from spent PWR fuel materials at hot cell. The soundness of the end closure welds of nuclear fuel element is an important factor for the safety and performance of nuclear fuel. To evaluate the soundness of the end closure welds of DUPIC fuel element, a precise X-ray inspection system was developed using a micro-focus X-ray inspection system with an image intensifier and a real time camera system.

The fuel elements made of Zircaloy-4 and stainless steel by an Nd:YAG laser welding and a TIG welding were inspected by the developed inspection system. The soundness of the welds of the fuel elements was confirmed by the inspection system, and the irradiation test of the fuel elements has been successfully completed at the HANARO research reactor.

1. INTRODUCTION

DUPIC (Direct use of spent PWR fuel in CANDU reactors) is a dry process to remotely fabricate CANDU nuclear fuel from spent PWR fuel at hot cell without separation of sensitive nuclear materials. By utilizing DUPIC fuel some benefits, such as reuse of the spent PWR fuel in a proliferation resistant way and reduction of radioactive wastes, can be expected[1]. Since the end closure welding of DUPIC fuel would be performed remotely by either TIG welding or laser welding techniques at hot cell[2, 3], a proper inspection system for evaluation of the soundness of the end closure in a remote manner should be developed.

In order to evaluate the weld quality of the nuclear fuel element, non-destructive tests, such as a helium leak test, eddy current test, ultrasonic test and X-ray radiography and destructive tests, such as a metallurgical examination and mechanical tests of the weld areas are typically performed[4, 5, 6]. Based on the evaluation of each inspection method for the capability of the detection of internal micro-defects and the remote operability of the inspection process at hot cell, micro-focus X-ray radiography was chosen for a remote non-destructive inspection of the end closure welding area of DUPIC fuel element at hot cell. The inspection system consists of the micro-focus X-ray generator, high resolution image intensifier and a video camera. By using the developed inspection system, Zircaloy-4 fuel element welded by an Nd:YAG laser, and stainless steel fuel element welded by a laser and a TIG have been inspected.

2. DEVELOPMENT OF THE X-RAY INSPECTION SYSTEM

The X-ray inspection system is composed of a micro-focus X-ray generator, image intensifier tube with a video camera, an image processing system and a shielded cabinet including the fuel element handling tools. A block diagram of the X-ray inspection system is shown in Figure 1. The developed X-ray inspection system is shown in Figure 2.

The X-ray generator is composed of a high vacuum X-ray tube, vacuum pumping system, high voltage supplier and controller. The X-ray generator is model FXE160.23K of FEINFOCUS. The basic operating parameters of the X-ray generator are ; a target voltage of 20 to 160 kV, a maximum electron beam current of 1 mA, and a minimum spot size of 10 μm. The X-ray image is converted to an optical image by the image intensifier. The diameter of the X-ray detector of the image intensifier is 220 mm, and the resolution is 40□60 lines/cm. The converted image is captured by a video camera and displayed on a CRT monitor. The X-ray image usually includes much random noise, and the intensity distribution is irregular. Therefore, the original image is enhanced by the image processing system to effectively inspect micro-defects. The resolution of the image processing board is 512x512x8 bit.

X-ray images of the end closure weld are shown in Figure 3. Since the original images have much random noise as shown in the figure, it is difficult to observe the defects. However, it is easy to detect the defects in the processed image by average and histogram equalization.

The size of the shield cabinet for shielding the X-ray radiation is about 70x90x180 cm, the shield material is Pb of 3 mm thickness and Fe of 2 mm thickness. The cabinet is a tower type to have a small bottom space. The cabinet can be separated into two parts, an upper part and a lower part, to be easily handled at hot cell. The X-ray generator with a linear motion system for adjusting the distance from the X-ray tube and the target screen is installed on the lower part. A cylinder type shield is installed for shielding the radiation from fuel rod to protect the X-ray generator, image intensifier and fuel rod handler on the lower center part. The thickness of the cylinder shield is 7 cm of Pb. On the upper part, the image intensifier and the video camera are installed.

3. INSPECTION OF END CLOSURE WELD OF DUPIC FUEL ELEMENTS

3.1 End closure welding

Three kinds of fuel elements are prepared for the irradiation test of DUPIC nuclear fuel. One is fabricated with Zircaloy-4 with a 49.3 cm long, 13.2 mm in diameter and 0.4 mm wall thick tube. This element is welded by laser welding. The dimensions are almost the same as a typical CANDU fuel element. Another is fabricated by stainless steel with a 20 cm long, 12.7 mm in diameter and 0.89 mm wall thick tube welded by TIG welding. This mini-element has been used for irradiation tests of the simulated DUPIC fuel pellets. The other is fabricated with Zircaloy-4 with a 20 cm long, 10.6 mm in diameter and 0.66 mm thick tube welded by laser welding. This mini-element has been used for irradiation tests of DUPIC fuel pellets fabricated in a hot cell. As an example, the dimensions of the stainless steel fuel element are shown in Figure 4. The end closures are made of the same materials as the tubes. Laser welding was performed using the Nd:YAG laser beam with a 1.06 μm wavelength, which is transmitted by an optical fiber in a helium atmosphere chamber. The typical surface features of the laser and TIG weld area are shown in Figure 5. The conceivable weld defects are cracks, porosity, and lack of fusion, which can usually be detected by a destructive metallurgical examination.

3.2 X-ray inspection of end closure weld

The depth of X-ray penetration during inspection is set up as about 6 mm for Zircaloy-4 fuel element, about 4.7 mm for stainless steel mini-element, and about 4.5 mm for Zircaloy-4 mini-element, considering their outer and inner diameters. The detectable size of the defect is about 1 percent of the depth of penetration. Therefore, the detectable sizes of defects for the X-ray incident direction are 60 μm, 47 μm, and 45 μm for Zircaloy-4 fuel element, stainless steel mini-element, and Zircaloy-4 mini-element, respectively. In order to evaluate the size of the defects, a copper wire with a 62.5 μm diameter is attached to the weld surface for a reference.

For inspection, the fuel element was first installed in the inspection chamber. The element can be rotated over a 360 degree by the rotator. The X-ray penetration image was displayed on a high resolution monitor for real time inspection. The X-ray images can be stored on a computer hard disk and processed for precise inspection of the existence of defects. Figure 6 shows the schematic structure of the precise X-ray inspection of a fuel element end closure weld using the micro-focus X-ray inspection system. The distance from the X-ray generator to the element is adjusted to 20 mm. The distance from the X-ray generator to the screen of the image intensifier is 450 mm. So the magnification ratio was 22.5. The target voltage and beam current were adjusted to 140□150 kV and 50 μA to obtain optimum X-ray images. The spot size of the X-ray generator is shown in Figure 7. The target material of the X-ray generator was tungsten, and the maximum X-ray power was 7.5 W. The spot size of X-ray generator was less than 10 m under the inspection conditions.

3.2.1 X-ray inspection of Zircaloy-4 fuel element

The target voltage and beam current were adjusted to 140 kV and 50 μA to obtain a focused and uniformly distributed intensity image. The inspected images of the weld area are shown in Figure 8. The horizontal white line at the bottom of the image is a copper wire with a 62.5 μm diameter. The white point displayed on the lower center of the X-ray image is a noise caused by a metal scrap on the surface of X-ray generator. A few porosities and a lack of fusion in the laser welded Zircaloy-4 fuel element were detected under non-optimum welding conditions. However, under optimum conditions, there was no defect detectable.

3.2.2 X-ray inspection of stainless steel mini-element

The target voltage and beam current were adjusted to 140 kV and 50 μA to obtain a focused and uniformly distributed intensity image. The inspected images of the weld area are shown in Figures 9 and 10. Cracks, porosities, and a lack of fusion have often been detected in stainless steel mini-elements welded by a laser. The defects are confirmed by a metallurgical examination. One of the causes of the defects inferred from the experimental results is the abrupt thermal transfer in the stainless steel structure.

TIG welding was used to weld stainless steel mini-elements in addition to laser welding. There were a few lack of fusion defects in TIG welded elements due to mis-alignment of the weld line and a lack of energy. The defects were also confirmed by the metallurgical examination. Through trial and error, the optimum welding conditions have been found. There was no defect under the optimum conditions. Therefore, the stainless steel mini-elements containing simulated DUPIC fuel for irradiation tests are welded by TIG welding. There was no defect in the three mini-elements for the irradiation test. The mini-elements were irradiated successfully at the HANARO research reactor at KAERI. Table 1 shows the results of the experiment for stainless steel mini-elements.

3.2.3 X-ray inspection of Zircaloy-4 mini-element

The target voltage and beam current were adjusted to 150 kV and 50 μA to obtain a focused and uniformly distributed intensity image. The inspected images of the weld area are shown in Figure 8. The Zircaloy-4 mini-elements to be used for irradiation tests of DUPIC fuel fabricated at hot cell were remotely welded by a laser welding system installed at hot cell. The Zircaoy-4 mini-elements containing DUPIC fuel pellets are so highly radioactive that one end of element was tested by X-ray inspection before the DUPIC pellets were inserted in the elements. A lot of elements with dummy pellets were welded by the laser welding system at hot cell for process qualification. Based on the results, the optimum conditions were found for laser welding of Zircaloy-4 mini-elements. There was no defect under the optimum welding conditions. The laser welding process for Zircaloy-4 mini-elements was also confirmed by a metallurgical examination, mechanical test, and helium leak test. One end of the Zircaloy-4 mini-element was tested by X-ray inspection. There was no defect in the three mini-elements for the irradiation test. Table 2 shows the results of experiment for Zircaloy-4 mini-elements. The elements were successfully irradiated for performance test at the HANARO reactor.

4. CONCLUSIONS

The X-ray radiography inspection method is applied to evaluate the soundness of DUPIC fuel element end-cap welds. A 10 μm spot size of a micro-focus X-ray inspection system is developed to precisely inspect small defects in the end closure weld area. Using the X-ray inspection system, Zircaloy-4 CANDU fuel elements welded by the Nd:YAG laser, stainless steel mini-elements containing SIMFUEL for irradiation tests welded by the laser and the TIG, and Zircaloy-4 mini-elements containing DUPIC fuel pellets for irradiation tests welded by the Nd:YAG laser have been tested. The main experimental results are found as follows.

- There was no defect in Zircaloy-4 CANDU fuel element under the optimum welding conditions.
- Cracks, porosities, and a lack of fusion have often been detected in stainless steel mini-elements welded by a laser. Therefore, TIG welding is used to weld stainless steel mini-elements instead of laser welding.
- There was no defect under the optimum conditions for the TIG welded stainless steel mini-elements containing simulated DUPIC fuel for irradiation tests at the HANARO research reactor at KAERI. The mini-elements have been successfully irradiated at HANARO.
- One end of the Zircaloy-4 mini-element containing DUPIC fuel pellets was tested by X-ray inspection. There was no defect in the three mini-elements to be irradiated at HANARO.

Therefore, Zircaloy-4 CANDU fuel element, stainless steel mini-element, and Zircaloy-4 mini-element can be successfully inspected by the X-ray inspection method. The soundness of the laser welded Zircaloy-4 CANDU fuel element containing DUPIC pellets to be fabricated at hot cell will be inspected by using the X-ray inspection system in the future.

ACKNOWLEDGEMENTS

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TABLES

TABLE 1. X-RAY INSPECTION OF STAINLESSSTEEL MINI-ELEMENTS CONTAINING SIMFUEL FOR IRRADIATION TEST

X-ray generator : Feinfocus(Germany) FXE-160.23K
X-ray image intensifier & detector : Balto(Belgium), Baltoscope BIX220
Results : Existence of defects

No.	Voltage, kV	Current, μA	Defects			Remarks
			lack of fusion, μm	Crack, μm	Porosity, μm	
1-1	140	50	0	0	0	PASS
1-2	140	50	0	0	0	PASS
2-1	140	50	0	0	0	PASS
2-2	140	50	0	0	0	PASS
3-1	140	50	0	0	0	PASS
3-2	140	50	0	0	0	PASS

TABLE 2. X-RAY INSPECTION OF ZIRCALOY-4 MINI-ELEMENTS CONTAINING DUPIC PELLETS FOR IRRADIATION TEST

X-ray generator : Feinfocus(Germany) FXE-160.23K
X-ray image intensifier & detector : Balto(Belgium), Baltoscope BIX220
Results : Existence of defects

No.	Voltage, kV	Current, μA	Defects			Remarks
			Lack of fusion, μm	Crack, μm	Porosity, μm	
1	150	50	0	0	0	PASS
2	150	50	0	0	0	PASS
3	150	50	0	0	0	PASS

FIGURES

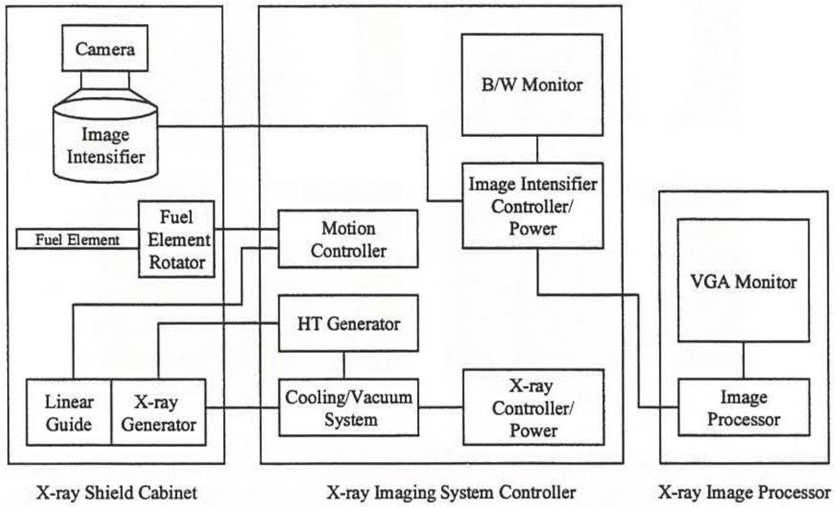


FIGURE 1. BLOCK DIAGRAM OF THE X-RAY INSPECTION SYSTEM

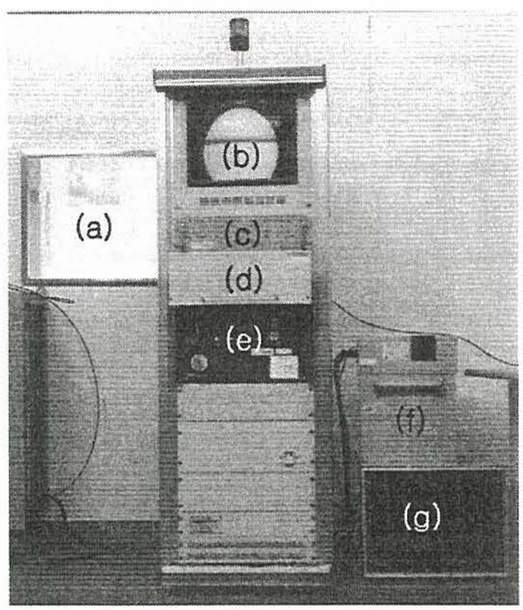


FIGURE 2. X-RAY INSPECTION SYSTEM (a)SHIELD CABINET, (b)CRT MONITOR, (c)IMAGE INTENSIFIER CONTROLLER, (d)MOTION CONTROLLER, (e)X-RAY GENERATOR CONTROLLER, (f)HIGH VOLTAGE GENERATOR, (g)VACUUM SYSTEM

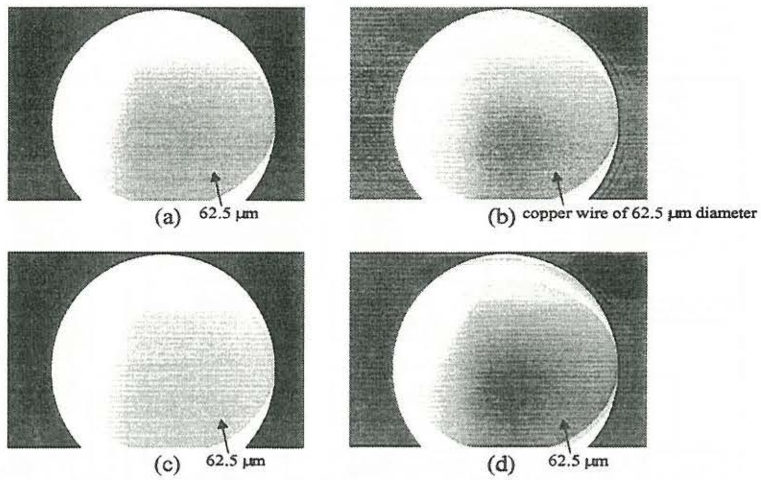
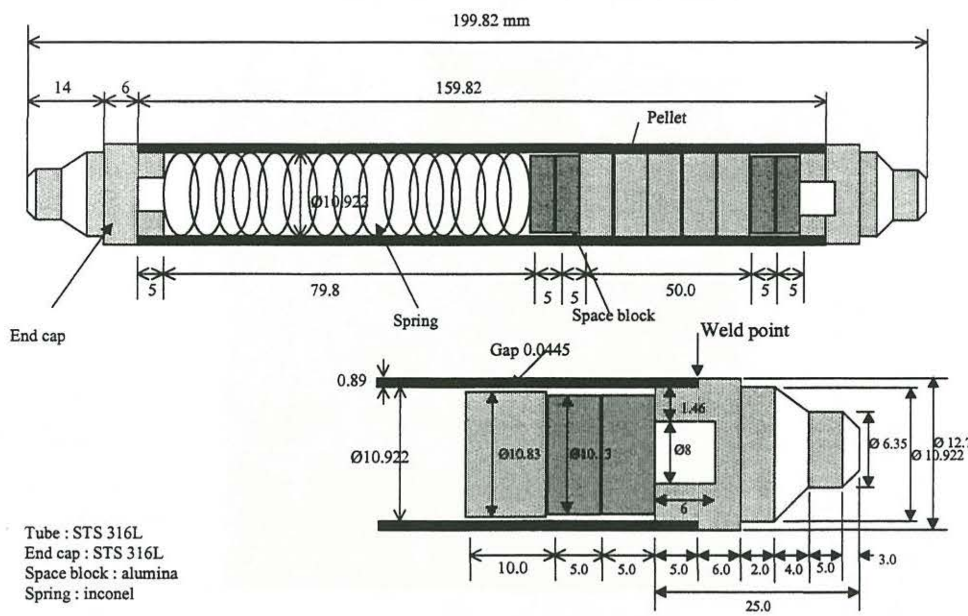
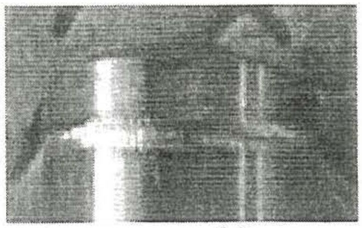


FIGURE 3. X-RAY IMAGE PROCESSING (a) ORIGINAL IMAGE, (b) HISTOGRAM EQUALIZED IMAGE, (c) AVERAGED IMAGE, (d) AVERAGED AND HISTOGRAM EQUALIZED IMAGE

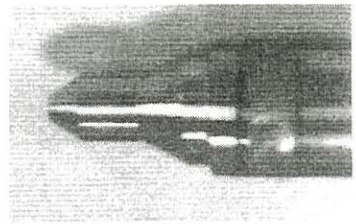


Mini-element(0.89mm tube)

FIGURE 4. STAINLESS STEEL MINI-ELEMENT FOR IRRADIATION TEST



(a)



(b)

FIGURE 5. (a) ZIRCALOY-4 ELEMENT END CLOSURE WELDED BY Nd:YAG LASER, (b) STAINLESS STEEL MINI-ELEMENT END CLOSURE WELDED BY TIG

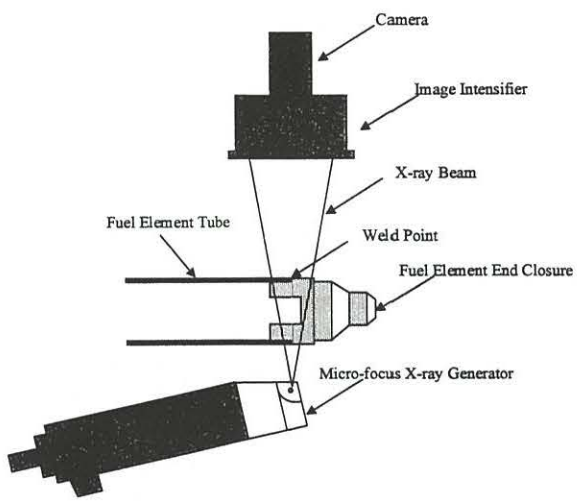


FIGURE 6. THE PRECISE X-RAY INSPECTION OF A FUEL ELEMENT END CLOSURE WELD

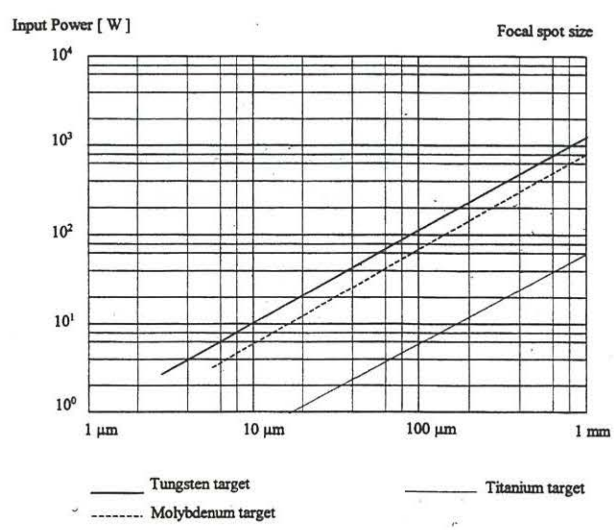


FIGURE 7. SPOT SIZE OF THE X-RAY GENERATOR

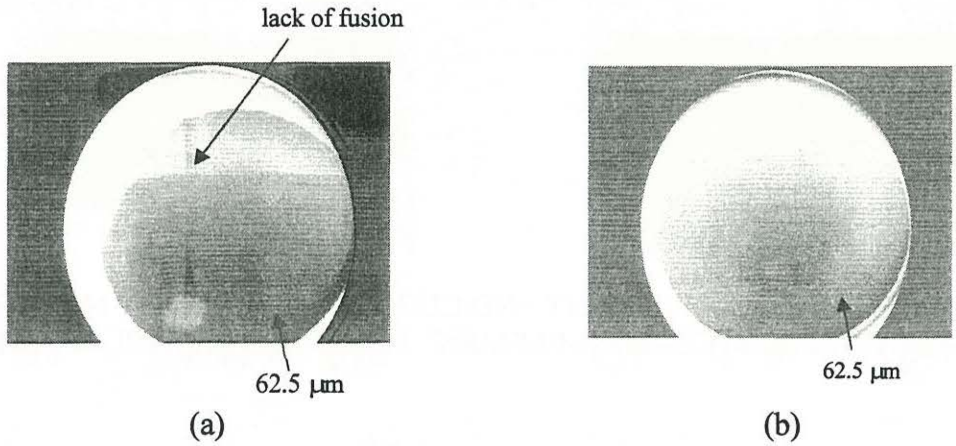


FIGURE 8. X-RAY INSPECTION OF ZIRCALOY-4 FUEL ELEMENT WELD AREA WELDED BY Nd:YAG LASER (a) LACK OF FUSION, (b) NO DEFECT

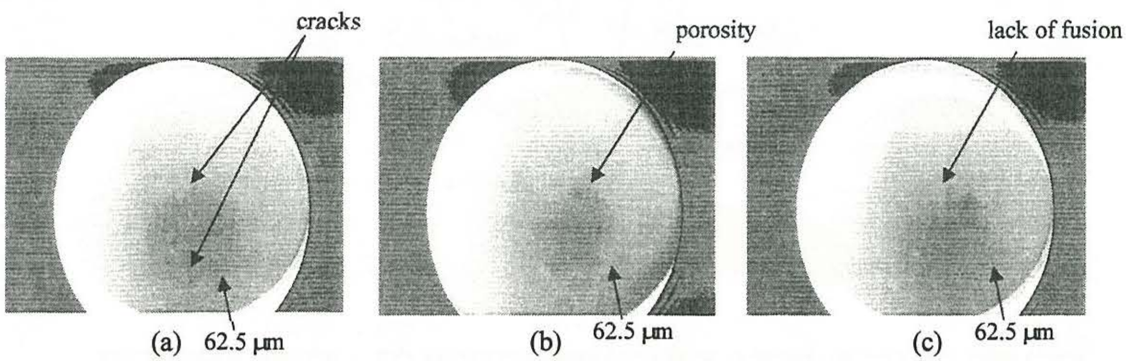


FIGURE 9. X-RAY INSPECTION OF STAINLESS STEEL MINI-ELEMENT WELDED BY Nd:YAG LASER (a) CRACKS, (b) POROSITY, (c) LACK OF FUSION

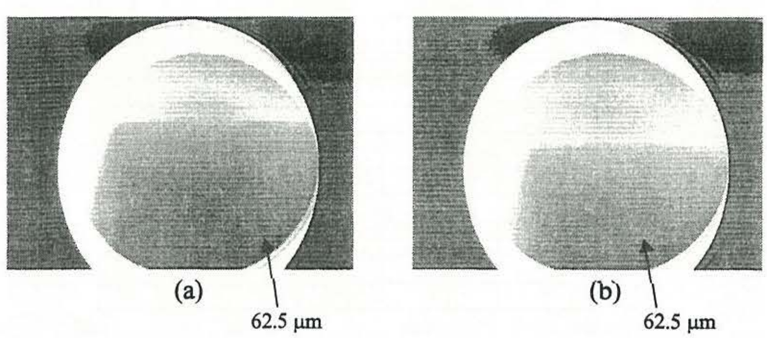


FIGURE 10. X-RAY INSPECTION OF STAINLESS STEEL MINI-ELEMENT WELDED BY TIG WELDING (a) LACK OF FUSION, (b) NO DEFECT