# Study of laser welding of brachytherapy capsules by x-ray microtomography

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This study investigated laser welding of capsules containing a radioactive material used for brachytherapy, in an attempt to optimize the welding parameters for capsule sealing. Welding was performed using a Nd:YAG laser (1064 nm, 20 Hz, 2.5 ms). Scanning electron microscopy and x-ray microtomography were used to investigate the quality and thickness of the capsule's weld seam. X-ray microtomography provided detailed three-dimensional imaging of the internal structure of the capsule and weld seam, not available using other methods.

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*Keywords*: Capsules, Laser welding, Radioactive material, X-ray microtomography

## 1. Introduction

Laser welding is a technique with fabrication opportunities that are difficult or impossible using other welding methods [1–4]. It is used mainly for joining components that require high welding speeds, thin seams, and low thermal distortion. Laser welding is used widely in modern manufacturing, due to its high throughput, easy automation, and enhanced control for improved product quality [5]. As such, laser welding is more efficient than other welding methods [6] and has been adopted by the automotive [7] and aircraft [8] industries.

Laser welding can be used to seal capsules used for material storage, although relatively few studies have investigated this application. One study reported on laser welding of stainless steel capsules for medical purposes [9]; specifically, the authors investigated metal loss, radiation penetration depth, and the welding area size and showed that increasing the laser spot size from 0.77 to 0.95 mm initiated crack/pore formation in the weld seam [9].

In this study, we investigated the quality of the seal produced by laser welding of brachytherapy capsules used for storing radioactive material. The radioactive material was encapsulated by laser welding the capsules in a hot chamber using an optical fiber for laser beam transport. Several of the experimental parameters associated with the laser welding process were varied, including the energy per pulse and beam focus. The resulting weld seam was evaluated using a nondestructive technique based on x-ray microtomography and scanning electron microscopy (SEM), in terms of the quality of its surface, the presence of cracks or porous structures, and the thickness of the seam.

## 2. Experimental

Fig. 1 shows a cross-sectional, three-dimensional (3D) view of the capsule used in the welding procedure (stainless steel, Type 10 TiNiCr 180).

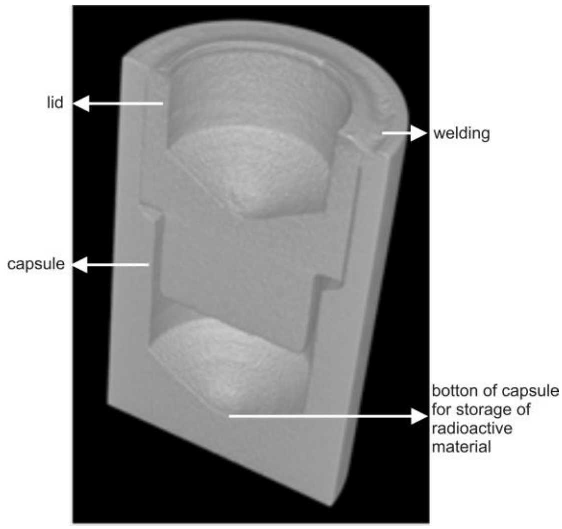



*Fig. 1. Three-dimensional (3D) x-ray microtomographic image of the capsule cross-section.*

The laser beam was directed to the capsule using an optical fiber that was sufficiently flexible to enable guidance to the position inside the hot chamber where welding was to take place. The laser welding process consisted of the follow steps: 1) adding the radioactive material to the capsule, 2) covering the capsule with the lid, and 3) welding initiation by capsule rotation. The welding seam, a butt-joint type, created a seal between the lid and capsule. The lid diameter was smaller than the capsule. The diameter of the capsule was 6 mm.

Fig. 2 shows a block diagram of the welding system: the laser, command/control system, a charge-coupled device (CCD) camera, welding head, positioning system, optical fiber, connections, and data acquisition system, as described in the patent report [10].

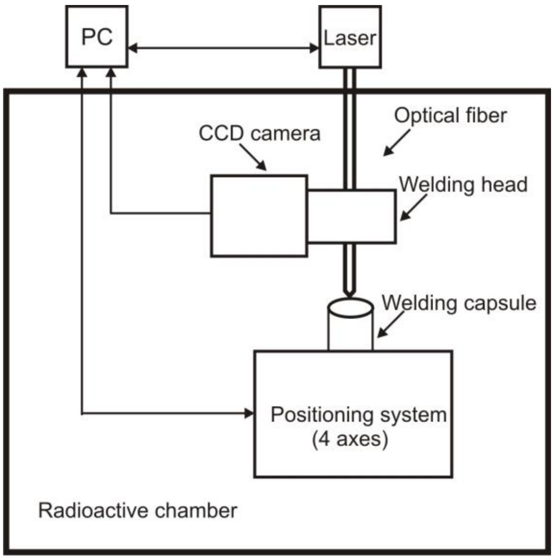



*Fig. 2. Welding system.*

*Table 1. Laser parameters for welding stainless steel capsules.*

| Laser | Wavelength(nm) | Pulse duration (ms) | Frequency (Hz) | Energy/pulse (J) | Average power (W) | Peak power (kW) |
|---|---|---|---|---|---|---|
| Nd:YAG | 1064 | 2.5 | 20 | 0.9-1.66 | 19.9-33.1 | 0.6-1 |

A Nd:YAG laser (wavelength 1064 nm; StarPulse 90 model, ROFIN/Germany) was used. The laser-welding parameters are listed in Table 1. Welding of the stainless steel capsules required 104 laser pulses and a capsule rotation speed of 0.2 rotations per second. The entire welding system was computer-controlled. A motorized system with four degrees of freedom was used to ensure correct positioning of the capsule. The XY translation stage had a range of 155 mm and a maximum speed of 90 mm $s^{-1}$. The Z stage had a range of 26 mm and a maximum speed of 20 mm $s^{-1}$. The visualization system consisted of a charge-coupled device (CCD) camera and a computer-adjustable electronic reticle for precise positioning of the laser beam. Experiments examined two positions of the laser beam focus: (1) on the capsule surface (focused position) and (2) at a focal point 2.5 mm beneath the capsule surface (defocused position). After welding the capsule seam, the weld quality was evaluated using x-ray microtomography and SEM (FEI Inspect S; resolution 3 nm at 30 kV, accelerating voltage 200 V–30 kV, current ≤ 2 µA). X-ray microtomographic experiments were performed using the high-resolution x-ray microtomography system at the National Institute of Lasers, Plasma, and Radiation Physics (NILPRP; EURATOM-MEdC, Bucharest,Romania (http://tomography.inflpr.ro).

The main component of the x-ray microtomography system is an open-type nanofocus x-ray source (a W target on a Be or diamond window (maximum high voltage 225 kV @ 30 W maximum power)).

X-rays were detected using high-resolution complementary metal–oxide–semiconductor (CMOS) flat-panel sensors. The detection system was housed on a high-precision motorized stage, with vertical and transverse adjustment capabilities. The sample to be imaged was placed on a four-axis motorized manipulator to ensure a high degree of freedom in sample positioning.

Microradiographic analysis provides sub-micron feature recognition. In this study, 3D tomographic image reconstructions were obtained using a proprietary, highly optimized computer code based on a modified Feldkamp-type algorithm. This algorithm was parallelized for the processing of large image matrices (1944 × 1536 pixels) for reconstructing very large volumes (2048 × 2048 × 2048 voxels). Using a 64-bit personal computer with 12 central processing units (equipped with 3.80-GHz cores) and 1440 projections as input data, reconstruction of the 2048 × 2048 × 2048-voxel volume required a processing time of 12 min. Note that the reconstruction software used was designed to be hardware-independent and included several features for visualization and virtual navigation within the 3D reconstructed volume; for example, in addition to fan-beam and cone-beam scanning configurations, a host of state-of-the-art tomographic artifact compensations were also coded.

Importantly, the approach described here is the first implementation of multi-material, multi-energy techniques using microtomography.

The non-invasive visualization of the inner structure of laser-welded radioactive-material containers demonstrated here would be especially useful for defectoscopic studies, as well as quantitative 3D analysis of various internal structures.

### 3. Results and discussion

Fig. 3 shows SEM images of a sealed capsule (energy per pulse 0.99 J, peak power 0.6 kW, average power 26.5 W); the images show that a focused beam with a circular shape produced a well-sealed capsule. Overlapping welds (weld diameter 400 µm), approximately equal distances apart, were observed (Fig. 3); the weld was smooth and of high quality, with no evidence of cracks or porous features.

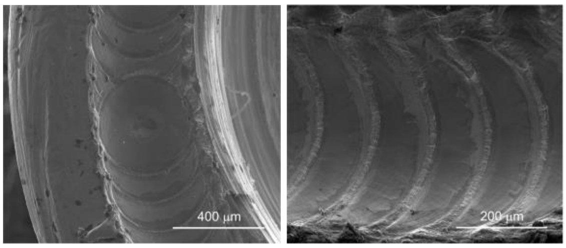
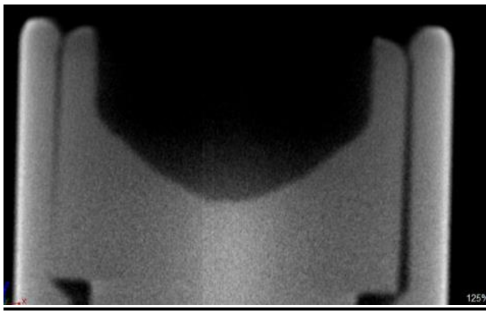



*Fig. 3. Scanning electron microscopy (SEM) images of the welded capsule.*

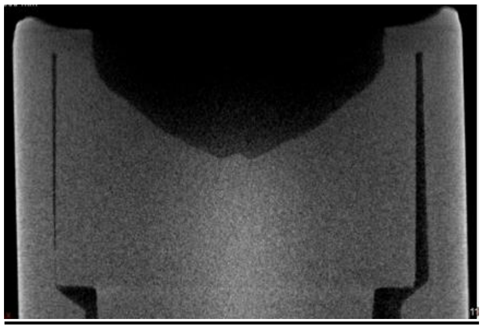
Fig. 4 shows x-ray microtomographic images of capsules subjected to laser welding at three laser energies per pulse (0.99, 1.32, and 1.66 J per pulse), using a defocused laser beam.

For laser beams with low energy per pulse, x-ray microtomographic imagery showed that the capsule was not welded. As the energy per pulse increased, the quality of the weld and weld thickness improved. Fig. 5 shows the butt-joint penetration of the seam as a function of the laser energy per pulse and lid–capsule separation distance. The weld thickness depends on the separation distance between the lid and capsule.

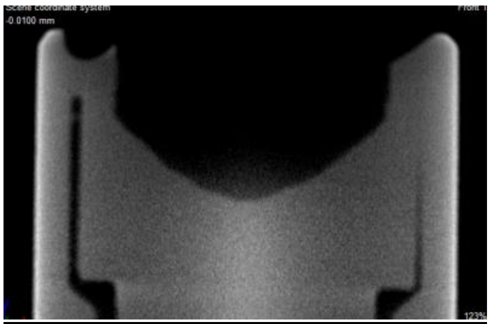
As a function of laser energy, linear fitting of the experimental data indicated a decreasing tendency for the weld thickness as the separation distance between the lid and capsule increased. For example, for a lid–capsule separation of >0.1 mm, a focused, low-energy beam (0.99 J) produced an incomplete weld seam; a defocused beam with the same energy (0.99 J) produced incomplete welds with smaller separation distances (>0.07 mm). Increasing the energy per pulse to 1.32 J for both cases (focused and defocused laser beams) resulted in welded capsules at greater lid–capsule separation (0.13 mm for the focused beam and 0.12 mm for the defocused beam). An increase in the laser energy per pulse to 1.66 J produced good-quality welds at a maximum lid–capsule separation of 0.12 mm, regardless of the beam focus.



(a) 0.99 J



(b) 1.32 J



(c) 1.66 J

*Fig. 4. X-ray microtomographic images.*

Regarding the weld thickness, at a low energy (0.99 J), the focused beam produced a 0.3-mm-thick weld for a lid–capsule separation of 0.08 mm. For a similar lid–capsule separation distance, the defocused laser beam was unable to weld the capsule. At a higher energy per pulse of 1.32 J, the weld thickness was nearly the same for both the focused and defocused beams, producing 0.3-mm-thick welds for a lid–capsule separation of 0.08 mm. Using 1.66 J, 0.35- and 0.4-mm-thick weld seams were produced by focused and defocused beams, respectively, with a lid–capsule separation of 0.08 mm. Therefore, the weld seam thickness increased significantly with the laser energy per pulse.

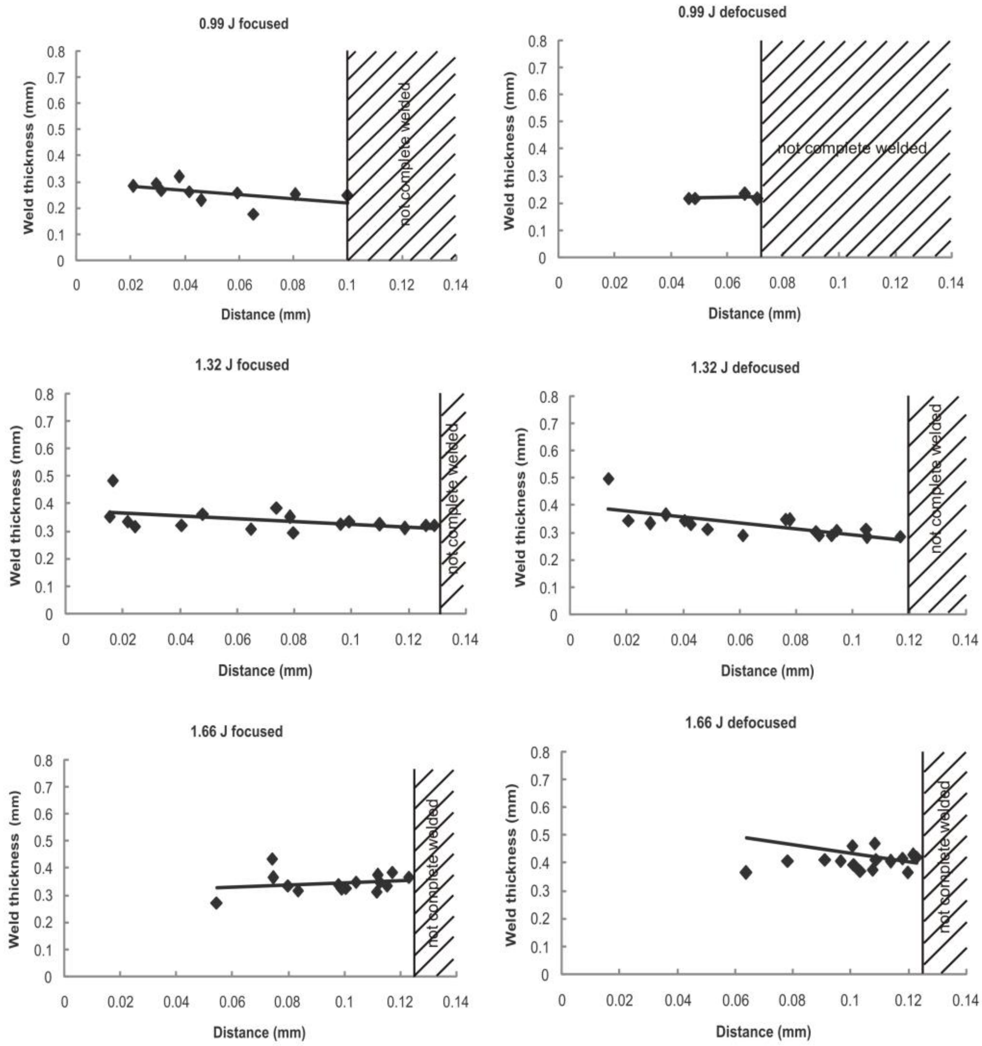



*Fig. 5. Weld (seam) thickness as a function of distance, degree of focus, and energy per pulse.*

## 4. Conclusions

Using a nondestructive method based on x-ray microtomography and SEM, we studied the weld quality of a laser-welded capsule dedicated to the storage of radioactive material. High-quality welds, smooth without cracks or porous features, were observed. The weld seam thickness increased with the laser energy. Given the same separation distance between the lid and capsule and the same laser energy per pulse, the best quality weld was produced using a focused beam, as opposed to a defocused beam.

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