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POTENTIAL USES OF LASER WELDING AND CUTTING IN THE NUCLEAR FUEL CYCLE

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ABSTRACT

This paper summarises some of the possible uses of high power lasers in the nuclear fuel cycle:- (a) In Fuel Fabrication: fuel canning, including fixing end-caps to pins; attaching wear-resistant pads on to wrappers. (b) At the Reactor: fabrication of power plant sub-assemblies; sealing of flasks for transport of irradiated fuel. (c) For Reprocessing: process plant fabrication; opening of storage and transport flasks.

Two specific equipment developments related to laser welding at powers up to 10kW are then discussed. The first is a gas shield arrangement which provides plasma control and shrouding of the weld bead. The second is a prototype moving focus head capable of welding circumferentially around a fixed horizontal pipe.

Finally, investigations of the laser welding of Zircaloy and stainless steel are described. In the former, material thickness of 4mm and powers of up to 5kW were used and emphasis was placed on control of weld geometry and microporosity. The stainless steel welding, at powers of 5 and 10kW, concerned work of relevance to chemical process plant in wall thicknesses up to 10mm, and a sample weld from this work has been incorporated in such plant for testing.

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INTRODUCTION

Lasers offer the possibility of remote operation in hostile environments and a range of potential applications of laser cutting and welding in the nuclear industry are now recognised[(1)]. Many are under investigation internationally, and in some cases, lasers are being used in production and pre-production operations. Within the context of this paper, we first summarise some of these areas and then describe three relevant topics of work carried out in the Laser Applications Group at Culham Laboratory.

The nuclear fuel cycle is illustrated schematically in Figure 1 which shows several potential laser applications. They can be divided into three main areas as follows:-

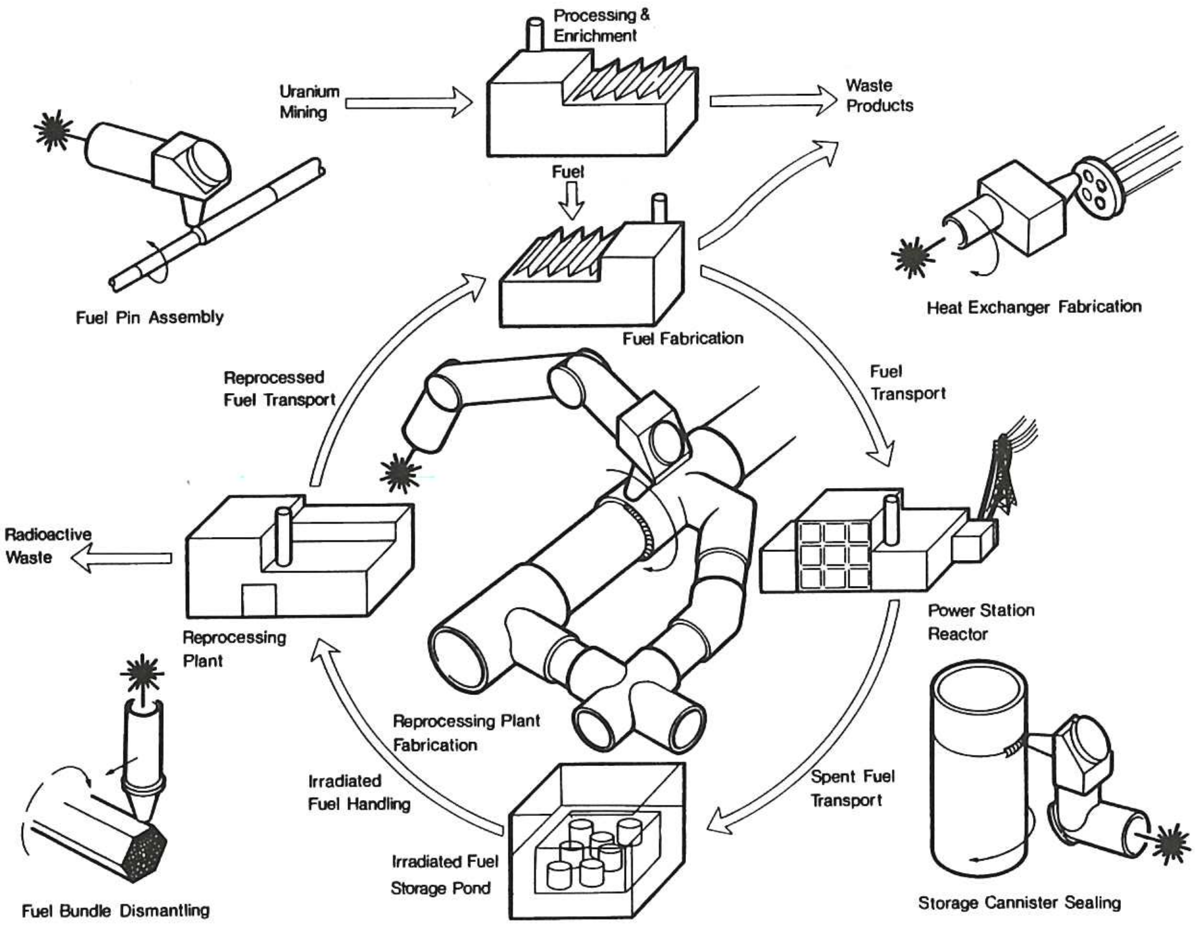


Fig. 1. Potential laser applications in the nuclear fuel cycle.

Fuel Fabrication

Fuel is 'canned' in a number of configurations and materials which depend on reactor type. For example, it may be sealed by the welding of end-caps into 'pins' consisting of tubes (~10mm diameter x <1mm wall) of stainless steel or Zircaloy. Subkilowatt pulsed NdYAG lasers and cw CO_2 lasers of ~1kW output appear to offer excellent capabilities for this welding, and a number of accounts have been published including one which describes a comparison of laser, eb and TIG welding(2). Lasers also offer potential for ancillary operations such as the fixing of wear-resistant pads on to wrappers containing bundles of fuel pins(3).

Uses at the Reactor

Much of the fabrication for nuclear power plant requires the welding of structural, pressure vessel and stainless steels. Industrially rated multi-kilowatt lasers are now capable of welding steels ≈15mm thick in a single pass(4) and multipass operation, with use of filler, can considerably extend single pass penetration(5). In parallel with assessment of laser-weldabiliy of particular material compositions, studies have been carried out for specific applications such as the sealing of flasks used to transport irradiated fuel from the reactor to the reprocessing plant(6).

Reprocessing

Here, attention has focused on two particular aspects. The first is laser dismantling of wrappers, prior to removal of pins for reprocessing. This technique is well established and is being exploited at the Dounreay Prototype Fast Reactor for fuel post-irradiation examination and reprocessing(7). The second concerns the concept of re-usable fuel transport flasks, where studies have demonstrated that laser cut edges can be re-welded by laser(8) with, if necessary, the use of filler(9).

EQUIPMENT DEVELOPMENT

Multikilowatt laser welding is a fast, deep penetration process performed by a high power density ($>1 \times 10^6 Wcm^{-2}$) focal spot which can produce full penetration welds in thick section materials in a single pass. Beam penetration depends on the formation of a capillary, or 'keyhole', filled with hot vapour and plasma which absorbs laser beam power by the inverse bremsstrahlung process. Energy thus absorbed within the keyhole is efficiently coupled to the metal for welding. However, material streaming from the keyhole into the incident beam path promotes extension of the plasma above the workpiece. Beam energy absorbed there is not efficiently used and can result in broadening of the weld crown and loss of penetration. The growth of this plasma may be controlled by directing at the interaction point a jet of inert gas having high ionisation potential (such as helium), and having flow and pressure distributions which assist with the formation of the keyhole and the convective removal of plasma energy. Although this gas jet excludes air from the interaction point, additional inert shielding must be provided above and below the welded specimen in order to prevent oxidation of the solidifying metal.

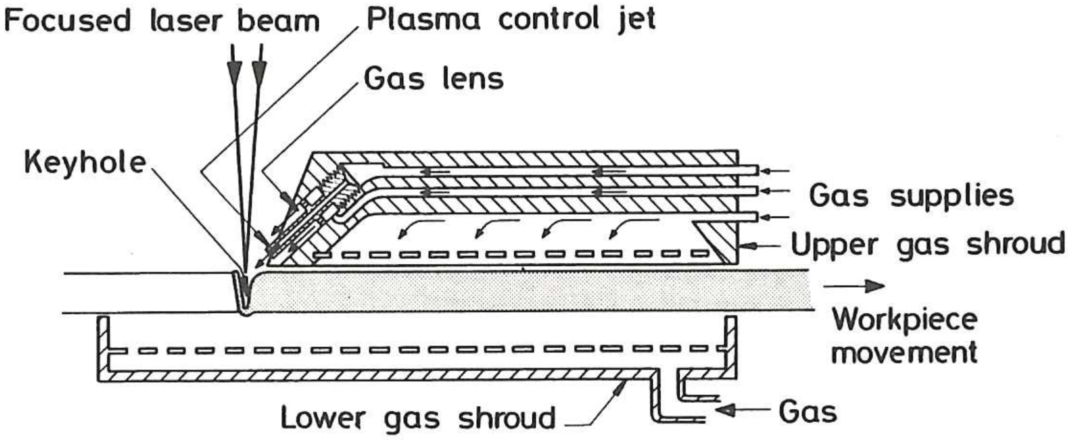


Fig. 2. Plasma control and gas shielding arrangement.

During the course of laser welding process development, part of which has been directed towards nuclear components, the authors have designed and developed an effective plasma control and gas shielding arrangement. A longitudinal section view of this device is shown in Figure 2. A plasma control jet of ≈2mm bore is directed at the laser beam/workpiece interaction point at an angle of 45^0 to the direction of movement. A gas lens, shown here coaxial with the jet, increases the extent of inert gas coverage and prevents entrainment of air around the jet; laminar flow in the lens is arranged by 6 equi-spaced 1mm diameter holes. Uniform gas distribution and laminar flow in the upper and lower shrouds is arranged by finely perforated plates as shown, or by gauze sheets.

This gas control arrangement has been used successfully on a variety of flat and cylindrical components, for both external and internal welds, with Culham's multi-kilowatt lasers CL5 and CL10 operating in the power range <1.0 to >10kW. Welding speeds varying from <5 to >200mms^{-1} have been used in thicknesses from <1.0 to >20mm. The shroud integrity may be judged from its ability to produce welds in reactive metals such as titanium and zirconium without any trace of oxide discolouration. Typical helium flow rates depend on the laser power, welding speed and material thickness, and for the jet, lens and each trailing shroud are 5-25, 20-50 and 50-100 $slmin^{-1}$ respectively. Argon, at flow rates <20$slmin^{-1}$, may be substituted for helium in each shroud.

A second equipment development relevant to nuclear applications

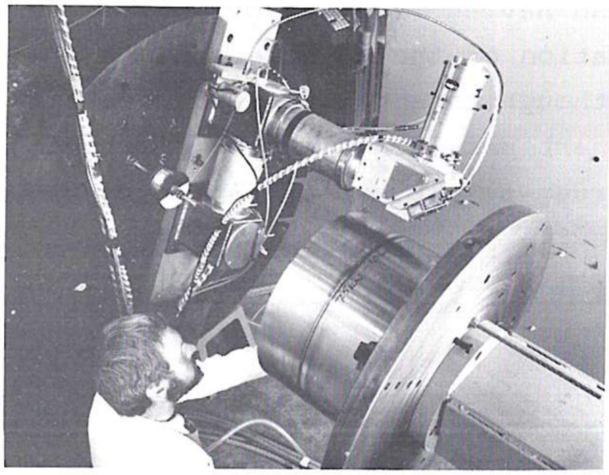


Fig. 3. Moving optics facility for horizontal pipe welding.

studies is shown in Figure 3. It consists of a lathe-mounted focusing head, with appropriate moving optical path, which permits studies at powers up to 10kW of the girth welding of fixed pipe samples having horizontal axes. Thus effects such as gravity on the weld pool stability can be investigated in a configuration appropriate to process plant fabrication.

WELDING APPLICATIONS

Zircaloy

Zircaloy 2 is widely used as a fuel-cladding material in water-cooled reactors, and is conventionally welded by TIG or eb methods. An investigation was carried out to assess the possibilities of laser fabrication of this material in 4mm thick flat plate. Other earlier work(10) concerned laser welding in thicknesses predominantly below 1mm. In the present study, attention was directed to the following aspects:- (a) Fusion zone geometry, including underside reinforcement and topside undercutting, and the target specification is shown in Figure 4. (b) Spatter, since adherent material could survive post-weld cleaning but become dislodged in service. (c) Microporosity, which can be prevalent in beam welding of this material, and which may be related to: alloying additions (the vaporisation temperature of the tin in Zircaloy is a little over half that of the zirconium); the different solubilities of gases (O_2,H_2) in α and β phases; possibility of oxides and hydrides being present on incorrectly prepared joints. The target specification was the absence of any pores >0.4mm diameter, and that any weld cross-section should exhibit no more than one micropore.

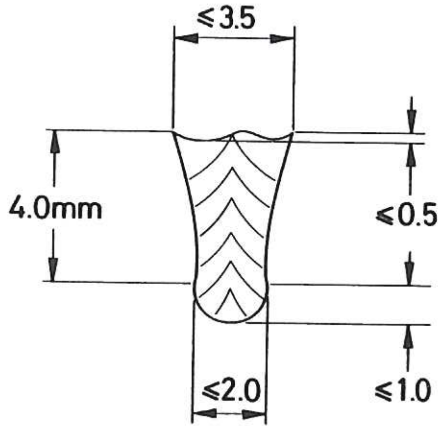


Fig. 4. Specified bead profile for Zircaloy plate welds.

A parametric study to establish optimum laser welding conditions was performed by making a series of melt runs (bead-on-plate welds) using three different focal length ZnSe lenses and a gas control arrangement as described above. The work was carried out on Culham's 5kW CO_2 laser CL5 and a range of welding speeds and powers at the workpiece were investigated. Three workpiece-to-lens distances (FD) were used for each lens, the middle one in each case being that which gave full penetration at maximum speed. Welding conditions are plotted in the graphs shown in Figure 5. Unacceptable levels of spatter and lack of penetration were established by visual examination of the underside of each plate. A more sensitive indication of spatter was achieved by viewing the underside of the plates through a window in the under shroud during welding. Weld bead widths and the incidence of any underbead undercutting were found by sectioning. Radiography of the complete plates could resolve pores >0.08mm diameter whilst metallography could resolve those >0.01mm.

It was found that acceptable weld profiles were achieved with both the f/6.4 and f/9 lenses, but those made with f/3.6 were generally too narrow. Those made at powers >3kW gave high spatter levels and those made at >50mms^{-1} showed considerable underbead undercutting. Spatter levels were reduced by minimising the plasma control jet helium flow rate. Macro-sections of welds made under optimum conditions are shown in Figure 6. Porosity levels were minimised by careful handling and cleaning of the plates. However, whilst spatter is minimised if the keyhole does not break through, incidence of porosity is then increased due to reduced venting of vapour. Thus, operation below 2.5kW gave lower spatter but greater porosity, whilst the converse was true at 3kW. Further work is required to understand more fully and control these phenomena.

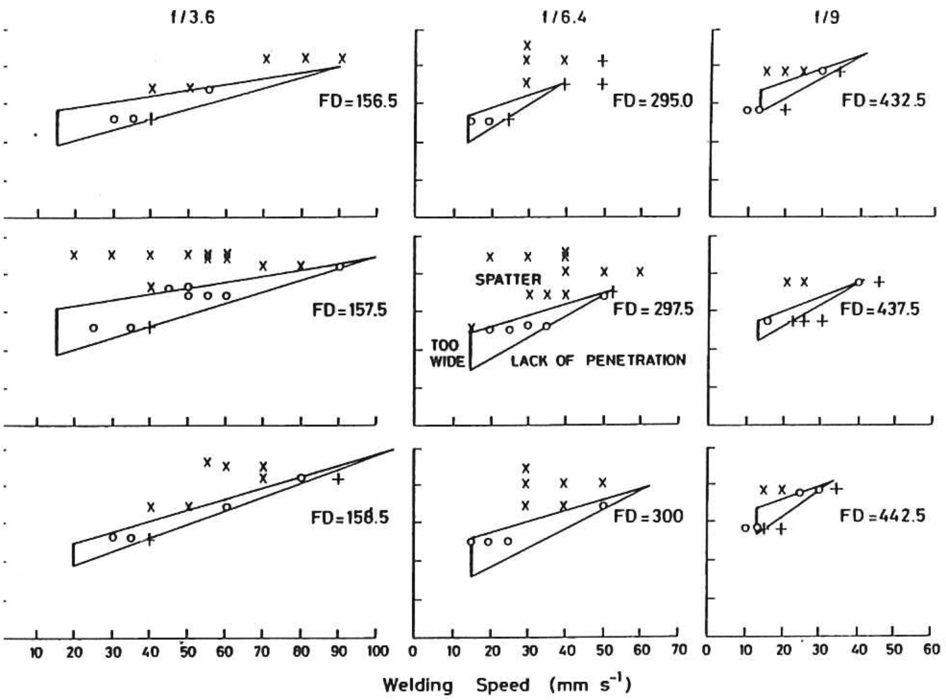
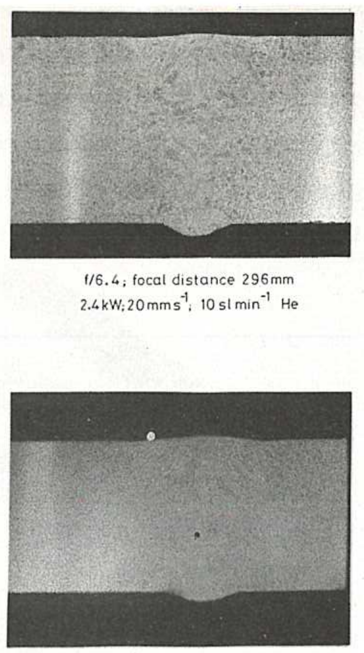


Fig. 5. Laser power vs. welding speed in 4mm Zircaloy: (o) acceptable spatter & penetration; (x) unacceptable spatter; (+) lack of penetration.



f/6.4; focal distance 296mm 2.4kW; 20mms^{-1}; 10 sl min^{-1} He

f/9; focal distance 437.5mm 2.4kW; 13mms^{-1}; 10 sl min^{-1} He

Fig. 6. Optimum melt run profiles in 4mm Zircaloy.

Dissolver Plant

The reprocessing of spent nuclear fuel includes dissolution of the fuel to separate it from its canning. Hot nitric acid is normally used and is contained within a dissolver vessel which may be of materials such as austentic stainless steel, Inconel 690 or zirconium. Typically, the vessels are large and of complex shape so that a joining technique such as laser welding is attractive because it creates minimum distortion and shrinkage. Additionally, the limitation of thermal disturbance is also important; in stainless steel, carbide formation and therefore risk of intergranular attack should be minimised. Although significant effort will be required to develop appropriate beam delivery systems in order to permit laser fabrication of complete plant, some related trials have commenced.

Preliminary work features the creation of test laser welds in coupons of candidate materials. These coupons are currently undergoing long term corrosion tests which will be reported elsewhere. However, the indications are that the weld region behaves at least as well as the parent plate.

Work using the 5kW laser CL5 was carried out on pipe of 100mm outer diameter x 6mm wall. Specimens of 25Cr/20Ni Nitric Acid Grade (NAG) stainless steel were successfully welded with 4.5kW at the work and at 25mms^{-1}. The welding conditions were then repeated on joints between pieces of similar size pipe and cold-formed T-sections made from Sandvic Type 2RE10 stainless steel. An internal diameter mismatch of ≈1mm presented no problems. Very smooth, continuous inner beads were achieved, as shown in the longitudinal sections in Figure 7. The laser welds were much narrower than the TIG welds incorporated in the same test piece (Figure 7) and, in contrast, did not require internal dressing of the underbead.

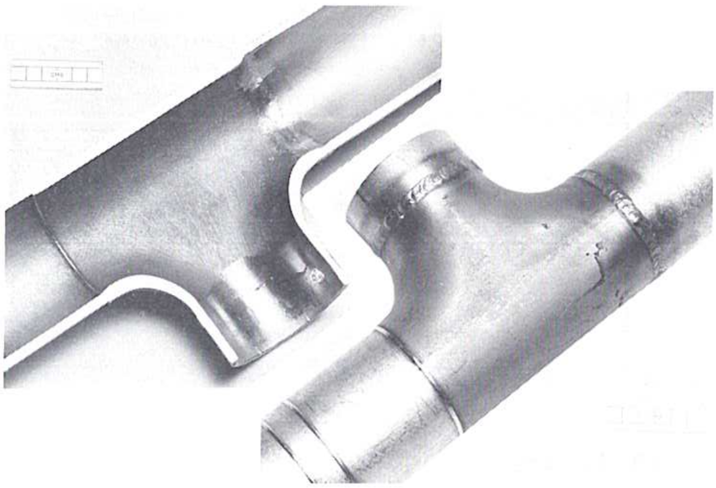
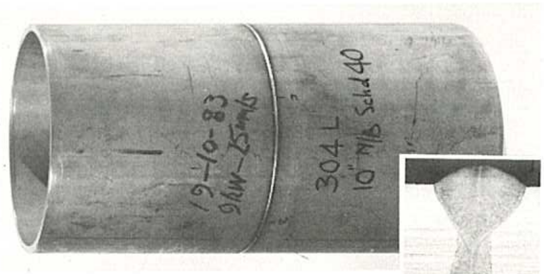


Fig. 7. Comparison between laser and TIG welds in 6mm stainless steel.

Work on the 10kW laser CL10 featured butt welding of Type 304L stainless steel pipe, ≈250mm O.D. x 10mm wall. These specimens were welded at 25mms^{-1} with 9kW using the lathe-mounted moving optics facility. Narrow, parallel sided welds were produced, but with some underbead undercutting and the occasional pore, as shown in Fig. 8. Very even penetration was achieved around the entire circumference. A short section of this material, containing one laser weld has been incorporated in the Prototype Batch Dissolver[11] at Harwell. This weld is situated near the proposed liquid/vapour interface, but has not yet been tested with nitric acid.



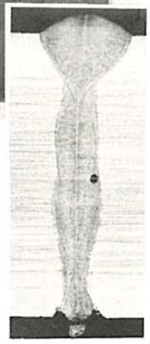


Fig. 8. Laser welds in a horizontal stainless steel pipe, made with moving optics.

CONCLUSIONS

We have described equipment developments of gas shielding and beam manipulation which significantly facilitate and extend the scope for laser welding investigations. Two welding studies which utilise these developments have also been described. These have demonstrated that high integrity welds can be produced using higher speeds and lower heat inputs than those found in conventional processes. The studies identify a need for further work in the areas of beam manipulation and microporosity control, but their results confirm that laser welding offers necessary and special capabilities which make it of significant interest to the nuclear industry.

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