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The maintenance of nuclear reactors requires the rapid cutting and welding of thick-walled pipework, to which laser processing is highly suited for. However, the large size and stand-off of current laser heads precludes their use and incorporation into in-bore processing tools. To address this, novel miniaturised fibre-fed laser cutting and welding heads have been designed which are capable of being used within a 90 mm internal diameter pipe. Here we will present the optical design of the processing heads, their on-board gas systems and operating parameters. Prototype processing heads have been built and trailed at a high-power laser facility. Power transmission testing and beam profilometry confirmed the prototype heads produced suitable laser spots for processing. During the trials, the prototypes successfully produced full-depth cuts and full penetration welds in both 5 mm plates and 90 mm internal diameter, 5 mm wall pipes. Additionally, the trials demonstrated the gas cooling in the processing heads was able to provide good thermal management. Porosity and oxidation were found in the produced welds and further optimisation of the process parameters is required. However, the results presented here demonstrate the feasibility of in-bore laser cutting and welding using the novel miniaturised optics designs.

I. INTRODUCTION

The high processing speed, single pass penetration depth and reliability of laser cutting and welding[1] make them attractive candidate techniques for in-situ severing and joining of steel pipework in nuclear reactors and other applications. The specific application[2,3] that laser processing was being considered for was in-bore cutting and welding of 90 mm internal diameter (ID), 5 mm wall steel pipes. The processing site is located 6 metres down a vertical pipe with only in-bore access. The large size and stand-off working distance of the existing laser processing heads means they cannot be used in this application. To overcome this, a novel miniaturized laser processing head design with a short stand-off working distance has been developed and trialed.

II. PROCESSING HEAD DESIGN

Two processing heads have been designed: a laser cutting head and a laser welding head. Both heads have a similar optical design, but have different processing gas systems.

A. Optics Design

The optics and laser path in the processing head designs are shown in Figure 1 and consists of four optical components:

1. An optical fibre – to supply the laser to the processing head
2. A plano-convex lens – to focus to the laser beam emitted from the optical fibre

3. A mirror – to rotate the laser through 90˚ and direct it onto the pipe wall

4. A window – to provide dust protection for the optics from the process zone

The processing heads was designed with 1064 nm optics for use with a high power continuous wave fibre laser source. The tool head can be rotated around this axis to apply the cutting/welding process around the internal circumference of the pipe. The optical fibre and plano-convex lens are aligned with the central axis of the pipe to keep a consistent stand-off distance with the pipe wall as it rotates.

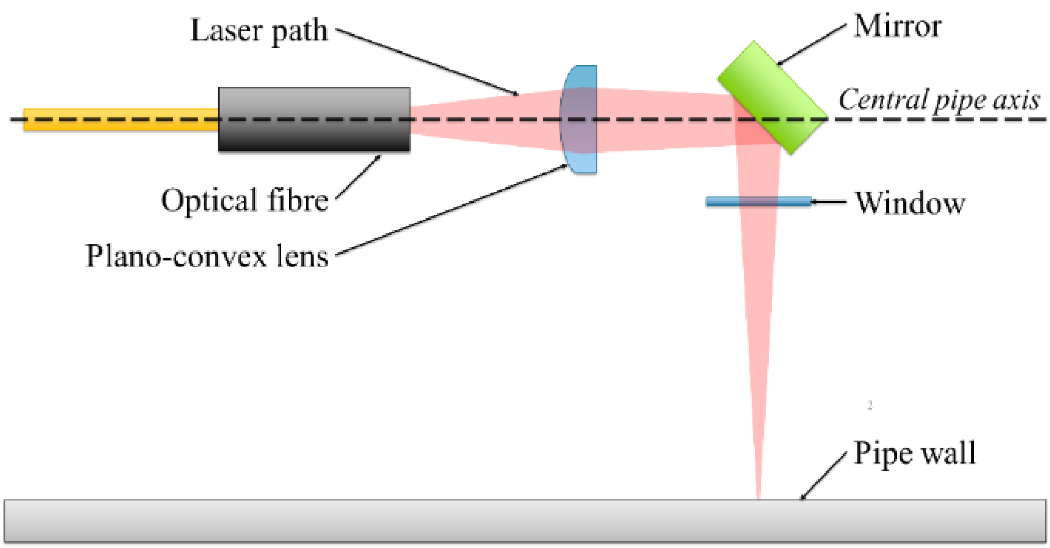

FIG. 1. Optical layout and laser path of the processing head design.

Conventional laser processing heads[1,4] typically use two lenses (a collimating lens and a focusing lens) to manipulate the laser beam into a processing spot. In the design described here, all the optical processing is achieved using a single plano-convex lens. Using a single lens reduces the size of the processing head and results number of components that need to be cooled. The focal length of the processing head can be adjusted by moving the plano-convex lens closer or further away from the end of the optical fibre. Additionally, conventional laser processing heads use optical components with long focal lengths and have large distances (of the order of 100mm) between components to reduce position sensitivity. In the design presented here, has tightly spaced short focal length optics in order to reduce the size of the processing heads.

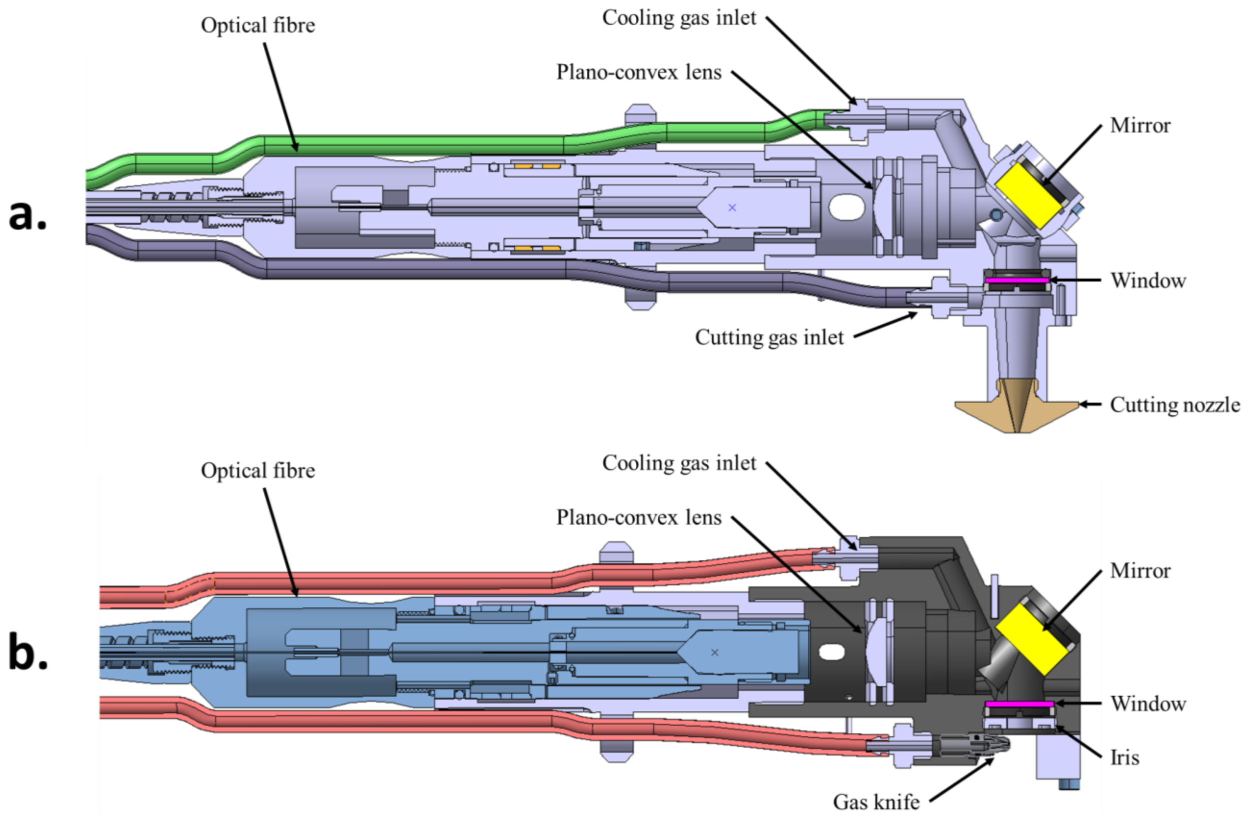

FIG. 2. Cut-aways showing the designs of the laser cutting (**a.**) and welding (**b.**) heads.

Using the lens equations[5], the relation between the spacing of the optical components and the focal length of the lens is given by:

$$y = \frac{xf}{x-f} - z, \qquad (1)$$

where x is the distance between the focal point of the optical fibre and the lens, y is the distance between the lens and the mirror, z is the distance between the mirror and the focal point of the optics, and f is the focal length of the lens. As the optics are focused at the pipe wall, z is equal to the inner radius of the pipe.

The convergence angle at the focal point is given by

$$\alpha = \left(\frac{x}{y+z}\right)\theta, \qquad (2)$$

where α is the convergence angle at the focal point and θ is the divergence angle of the optical fibre.

The optical design used ½ inch diameter fused silica optics. The plano-convex lens had a focal length of f = 20.3 mm which resulted in an effective focusing distance of 79 mm between the lens and the focal point on the pipe wall. The optical fibre used in the design had a divergent angle of $\theta = 0.3$ rad which resulted in a convergent angle of $\alpha = 0.1$ rad at the focal point on the pipe wall. The design used a 1 mm thick window and had a stand-off of 32 mm between the window and the pipe wall. The same optical layout was used in both the cutting and welding head designs.

B. Gas & protection systems

The cutting and welding heads include built-in gas systems, shown in Figure 2, to protect the optics and create the processing conditions.

The welding head is gas cooled via a gas inlet at near the top of the mirror. The gas flows over the mirror, around the lens and exits the optical cavity near the end of the optical fibre. The retaining rings holding the lenses include flow channels to allow the cooling gas to pass around the lens. Argon was used as the cooling gas as upon exiting the cavity the argon gas can flood the process area to create an inert welding environment, but also because it has the same refractive index as air[6]. The welding head also includes an orifice, front plate and argon cross-jet which protect the optics from the dust plume produced during the welding process.

The cutting head is gas cooled in the same manner as the welding head. Argon was used as the cooling gas for consistency between the heads, although other gases could be used as the inert environment is not needed for laser cutting. The cutting head includes a gas nozzle with a 1.4 mm exit hole to create co-axial gas jet with the laser beam for the laser cutting process[1]. The cutting head used Nitrogen cutting gas was used as required for cutting steel[1,7].

Thermocouples were included in the processing heads for temperature monitoring during the cutting and welding trials. The thermocouple locations are shown in Figure 3.

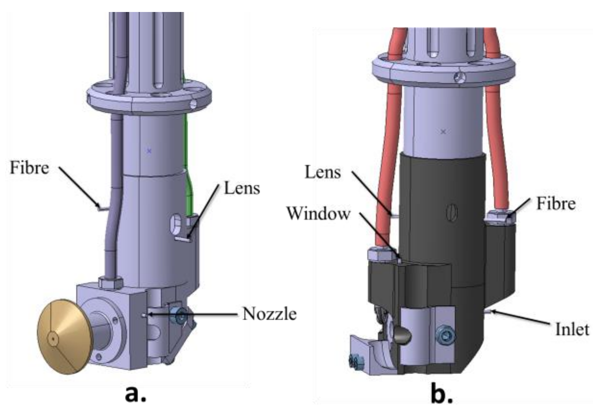

FIG. 3. Thermocouple locations on the cutting (**a.**) and welding (**b.**) heads.

III. HIGH POWER LASER TRIALS

The performance of the processing head designs were assessed through a series of high power laser trials. These trials were performed at the TWI laser facility, Cambridge UK. The processing heads used a 200 µm diameter optical fibre and were powered by an IPG YLS-5000 fibre laser source (1064 nm, 5 kW maximum power output). The processing heads were held in a tool mount attached to an articulated arm, that provided motion and rotation during the trials, shown in Figure 4.

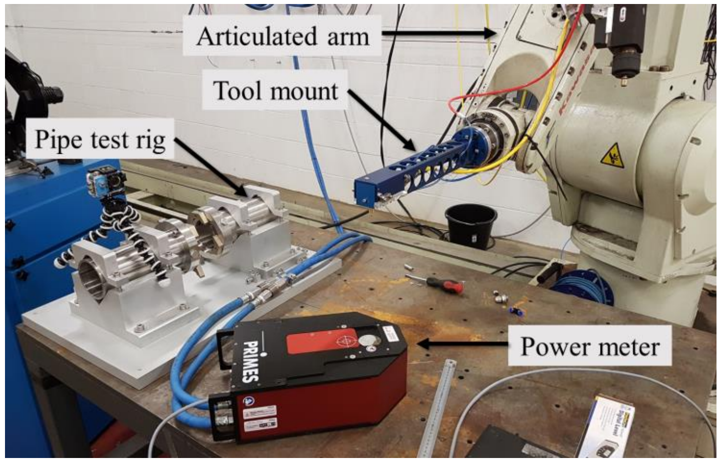

FIG. 4. High power laser trials setup.

Using the processing heads, trial cuts and welds were performed on in 5 mm plate samples and 90 mm ID, 5 mm wall pipe samples. The trials were performed on two nuclear-relevant steels: P91 chromium-molybdenum steel and 316L stainless steel. Figure 5 shows the processing heads inside the pipe. The robotic arm was used to rotate the heads to apply the cutting/welding process around the pipe. A standard welding jig was used to hold the plate samples and provide a backing gas during welding trials. The test rig used to hold the pipe samples during the cutting and welding trials is shown in Figure 4. The pipe test rig includes a backing-cuff around the outside of the pipe to provide backing gas during welding and to contain ejecta during cutting. The axis of the pipes were horizontal for all the tests.

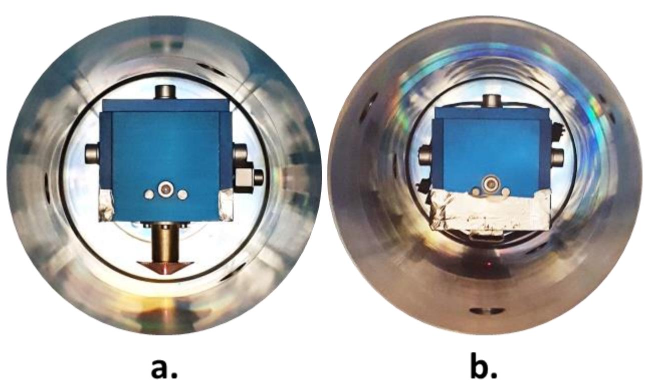

FIG. 5. Cutting (**a.**) and welding (**b.**) heads shown inside 90 mm ID pipes.

A. Beam characterisation

Prior to cutting and welding trials, power transmission tests were performed using a PRIMES PM-48 power meter to assess the laser power losses in the processing heads. Additionally, beam profilometry was performed using a Promotec UFF100 unit to verify the spot size and focal distance produced by the processing heads.

B. Process parameters

1. Welding head

The process parameters for the welding head were:

- Laser Power 2.4 kW
- Spot Size: 0.7 mm
- Traversing Speed: 0.5 m/min
- Rotation Speed (pipe operation only): 1.8 rpm
- Cooling Gas: Argon 32 L/min

The 1.8 rpm rotation speed for the pipe welds was chosen as it produces a 0.5 m/min linear traversing speed at the inside surface of the 90 mm ID pipe. Prior to welding, the samples were tacked using the welding head. The plate samples were tacked at three points: the start, middle and end of the weld. The pipe samples were tacked at eight points spaced equally around the circumference. The pipe welds started at the bottom of the pipe and rotated through 405° at a constant speed, giving an overlap region of 45°.

2. Cutting head

The process parameters for the cutting head were:

- Laser Power 1.2 kW
- Spot Size: 0.7 mm
- Traversing Speed: 0.5 m /min
- Rotation Speed (pipe operation only): 1.8 rpm
- Cooling Gas: Argon 32 L/min
- Cutting Nozzle: 1.4 mm exit diameter, 7 bar Nitrogen

The cutting process included a one second dwell prior to starting movement to allow the creation of the initial cut hole. Similarly to the pipe welding, the pipe cuts started at the bottom of the pipe and rotated through 371° at a constant speed, giving an overlap region of 11° to ensure a complete cut was achieved.

IV. RESULTS

A. Beam characterisation

Power transmission testing on the cutting and welding heads at 1.2 kW and 2.4 kW, respectively, showed there were power losses of less than 50 W (below the resolution of the power meter used) in both heads. The very low power losses indicated the laser beams are passing along the optical paths in the processing heads without being impeded or absorbed. Figure 6 shows the measured beam profiles for the processing heads. The spot diameters that were measured, were not nominal. The expected spot diameter at 45 mm from the central axis was 0.4 mm, but what was measured was closer to 0.7 mm. Although the spot was larger than expected it was still suitable for processing and was used in the trials. Both the cutting and welding optics created similar beam profiles.

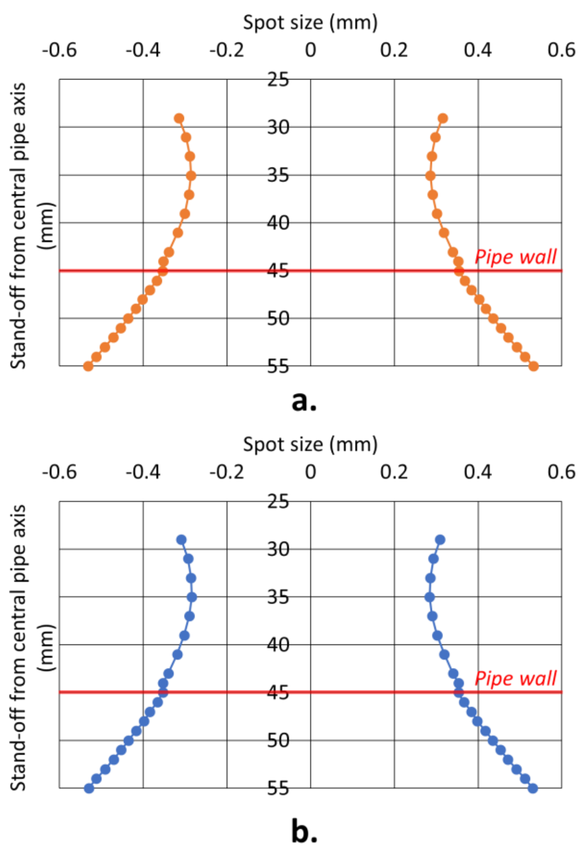

FIG. 6. Beam profile for the (**a.**) cutting head and (**b.**) welding head. The stand-off distance of the pipe wall (shown in red) has been added for reference.

B. Thermal management

The thermocouples attached to the processing heads recorded the temperature rise during operation. Figure 7 shows the temperature profiles for processing heads. The heating during operation and cooling curve after the operation can be clearly seen. Additionally, the temperature profiles show the processing heads do not reach a steady state thermal equilibrium during the 34 second operation sequences. The maximum temperature rises in the cutting and welding trials were 5 °C and 16 °C, respectively. The thermocouples were attached to the metal bodies of the processing heads so, assuming the heating is caused by laser absorption[1], the temperature rise on the optics will be higher than the values recorded on the thermocouples. The highest temperatures were consistently recorded at the thermocouple near the nozzle in the cutting head and near the inlet in the welding head.

Higher temperature rises were observed in the pipe cutting and welding trials compared with the plate cutting and welding trials; this was attributed heat from the processes being contained in the confined space of the pipe during the in-bore testing.

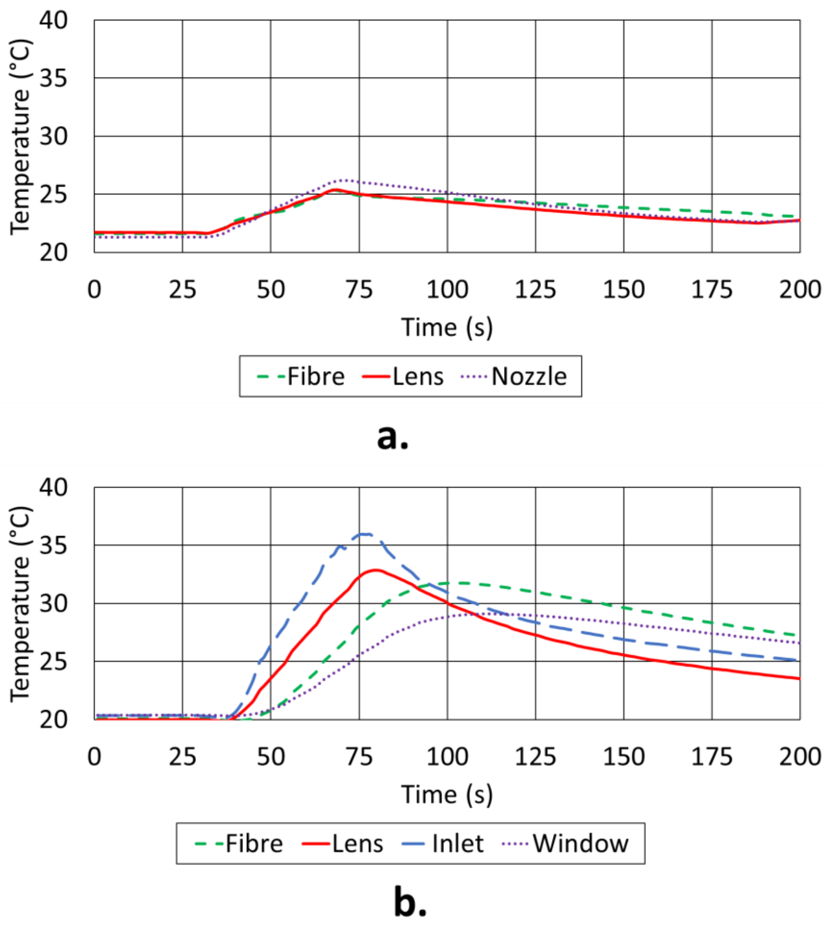

FIG. 7. Temperature profiles recorded at different locations in the cutting (**a.**) and welding (**b.**) heads during use.

C. Material analysis

1. Cutting

The high-power laser trials with the cutting head successfully produced full-depth continuous cuts in the plate and pipe samples, in both 316L and P91 steels. Figure 8 shows a typical cut pipe from the trials. The surface colouration indicates oxidation has occurred[8], however this is acceptable for the nuclear decommissioning application the cutting head is being developed for. The material removed during the cutting process can be seen to have deposited as dross on the outside pipe.

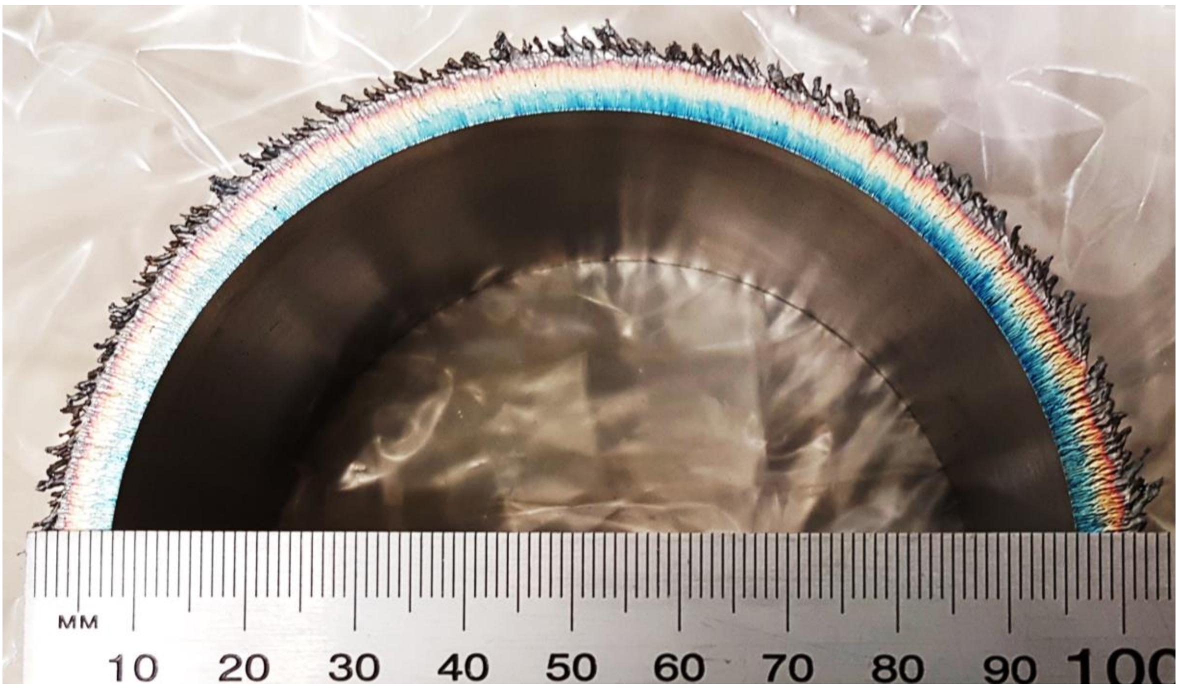

FIG. 8. Cut 316L pipe sample

No damage or material build up was seen on the cutting nozzle during the trials. The same optics were used in all pipe and plate cutting trials. Upon completion of the trials the optics were inspected, and no dirt or damage was found on any of the optical components.

2. Welding

The high-power laser trials with the welding head successfully produced fully-penetrated welds in the plate and pipe samples, in both 316L and P91 steels. Figure 9 shows a typical welded pipe from the trials. The welds had a positive root and cap profile. The weld was consistent around the entire circumference of the pipe. The root (on the outside of the pipe) showed no oxidization meaning there was good inert environment around the outside of the pipe[8]. The cap of the weld (inside the pipe) was oxidized indicating a poor inert environment was present during welding. Additionally, radiography showed unacceptable levels porosity present in the plate and pipe welds, in both 316L and P91 steels.

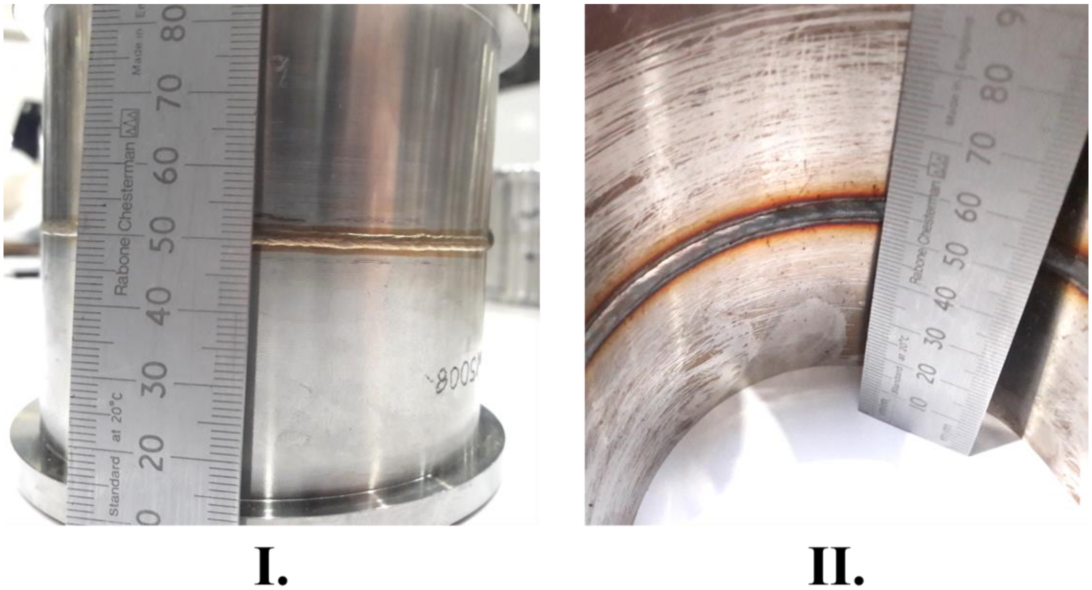

FIG. 9. External (I.) and internal (II.) surfaces of a welded 316L pipe.

The weld samples were sectioned, polished and etched to produce cross-sections, shown in Figure 10. The different regions of the weld[1,9] (weldment, heat affected zone and parent material) can be seen. The welds are fully penetrated, have positive root and a small amount of undercut at the cap.

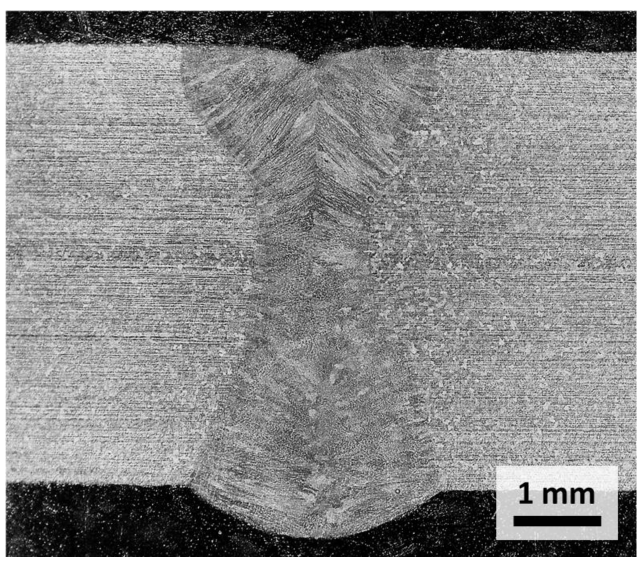

FIG. 10. Cross-section of a 316L plate weld.

V. CONCLUSIONS

Maintenance in nuclear reactors requires rapid cutting and welding of thick-walled pipework[1], to which laser processing is highly suited for. However the large size and stand-off of current laser heads, precludes their use and incorporated into in-bore remote tooling. In order to address this miniaturised fibre-fed processing head prototypes using ½ inch optics were developed and trailed using a high-power laser facility. The processing heads were small enough to fit within 90 mm ID pipe with the welding head operating at a stand-off of 32 mm.

Power transmission testing confirmed that no beam power loss through the processing heads was measured. Beam profilometry confirmed the processing heads were producing suitable laser spot sizes. The prototype cutting head successfully produced full-depth cuts in 5 mm plate and 90 mm ID, 5 mm wall pipes. The cuts produced minimal dust with most of the removed material remaining as dross on the back of the cut. An oxide layer formed on the cut surfaces, but this is acceptable for use in nuclear decommissioning application.

The prototype welding head successfully produced fully penetrated welds in 5 mm plate and 90 mm ID, 5 mm wall pipes. Visual inspection, radiography and cross-sectioning of the welds found oxidation on the weld cap and significant porosity inside the welds. The oxidation of the welds was caused by a poor inert environment inside the pipe. This issue could be solved by modifying the gas systems on the welding head and pipe seals to achieve the good inert conditions[1,8]. As the porosity issue was seen in both materials and in both pipe and plate welds it was likely caused by instabilities in the keyhole weld pool. This issue can typically be solved by reducing the spot size, and increasing the speed and laser power[1].

Future work is required to optimize operation of the welding head to solve the oxidation and porosity issues and produce nuclear standard compliant welds. However, the work presented here demonstrate the feasibility of laser cutting and welding using this novel miniaturised optics design. The processing head designs described here were developed for remote maintenance in nuclear reactors, but could be adopted for other applications maintaining pipework or confined-space processing.

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