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In-bore Robotic Laser Cutting and Welding Tools for Nuclear Fusion Reactors

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The installation and decommissioning of components in nuclear fusion reactors will require quick, and reliable, cutting and welding of hundreds of thick-walled steel cooling pipes. To this end, laser cutting and welding techniques have been investigated and prototype in-bore robotic tools have been developed to apply these laser process within a pipe. The prototype laser tools include a novel miniaturised laser head design to fit within the confines of the pipe and apply the laser processes with a short standoff distance. The novel laser heads and prototype tools were manufactured and used for a series of demonstration trials at a high power laser facility. Here, we will present the design of the laser optics heads and prototype tools, results of the high power laser trials, analysis of the demonstration cuts and welds produced, and laser process issues discovered during the trials.

Keywords: Fibre laser, laser head, P91 alloy steel, 316L stainless steel, cooling pipes, nuclear fusion reactors, laser cutting, in-bore, robotics

1 BACKGROUND AND INTRODUCTION

Nuclear fusion is the process of reacting small nuclei together to form larger nuclei[1,2]. To create nuclear fusion the reactant nuclei, deuterium (^2H) and tritium (^3H), need to be heated to extreme temperatures of approximately 100 × 10^6 K [1, 2]. These conditions can be created in magnetic confinement fusion reactors, known Tokamaks [2].

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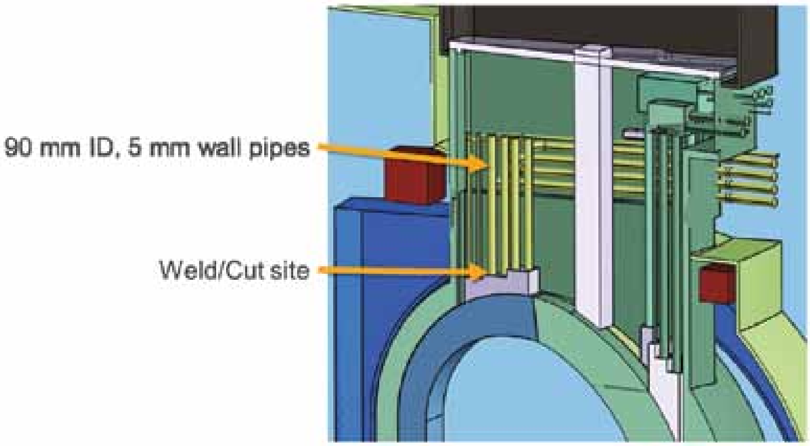


FIGURE 1
Schematic diagram showing pipe welding and cutting locations in a future nuclear fusion reactor.

Future fusion powerplants will generate electricity from nuclear fusion reactions [2, 3]; however, the components inside fusion reactors are subjected to high temperatures and large neutron fluxes so will need to be replaced every 3 to 5 years [4, 5]. The maintenance and replacement of reactor components will require the disconnection and reconnection of hundreds of thick-walled steel cooling pipes during each maintenance cycle [4, 5]. Due to the high levels of residual radiation, the pipe disconnection and reconnection need to be done remotely with robotic tools. The location of the pipe welding and cutting sites on the reactor components are expected to be 6 to 8 m vertically down a 90 mm inside diameter (ID) 5 mm wall pipe, as shown in Figure 1.

2 TOOL ARCHITECTURE

2.1 Tooling rationale

Prototype in-bore cutting and welding tools have been developed to perform the pipe disconnection and reconnection maintenance processes. Laser processing was chosen because of its small process area, low dust production, fast processing speed and ability to cut/weld thick steel sections in a single pass [6].

2.2 Functions

The functions of the tools [7, 8] are to: (i) Deploy down the pipe; (ii) clamp into position; (iii) align with the cut/weld site; (iv) apply the laser cutting/

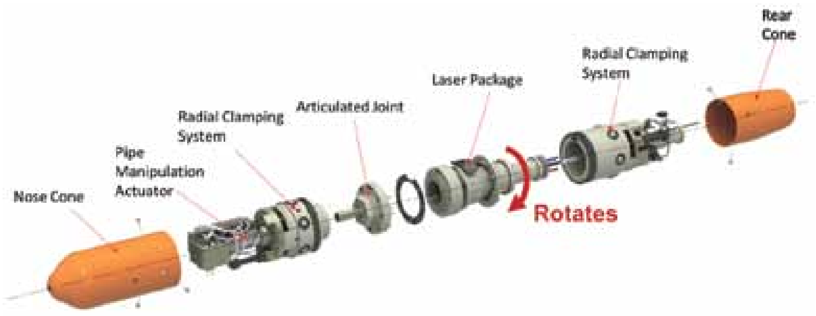


FIGURE 2
In-bore tool design showing its functional sub-systems including a central rotating laser package [7, 8].

welding process; (v) unclamp from the pipe; and (vi) withdraw from the pipe. These functions were included in the prototype tools and are shown in Figure 2. The prototype tool designs include an articulated joint to allow the tool to deploy through the pipe and round corners, two radial clamping system to clamp and align, and a central laser package which can be rotated by an on-board motor to apply the laser process around the pipe. Both the cutting and welding tools have the same design expect for the laser heads within the laser package which are modified to produce their respective laser processes.

2.3 Optics design

For the prototype tools are required to apply these processes inside a 90 mm ID pipe. This limited space envelope and short working distance meant existing cutting and welding heads were unsuitable for this application and bespoke miniaturised cutting and welding heads were designed. Figure 3 shows the miniaturized cutting and welding heads in which the laser source is supplied to the heads with a laser fibre, the beam is then focused by lenses and rotated 90° by a mirror. The optics are cooled by flowing gas through the optical cavity. The cutting head includes a cutting nozzle to create a jet of N_2 gas with the laser beam to create the cutting process. The welding head includes an argon cross-jet which protects the optics from dust produced during the process and also creates an inert environment in the pipe for the process.

3 HIGH POWER LASER TRIALS

3.1 Apparatus and procedures

The prototype in-bore cutting and welding tools were tested in two stages. First, just the laser heads mounted in a frame attached to a robotic arm to

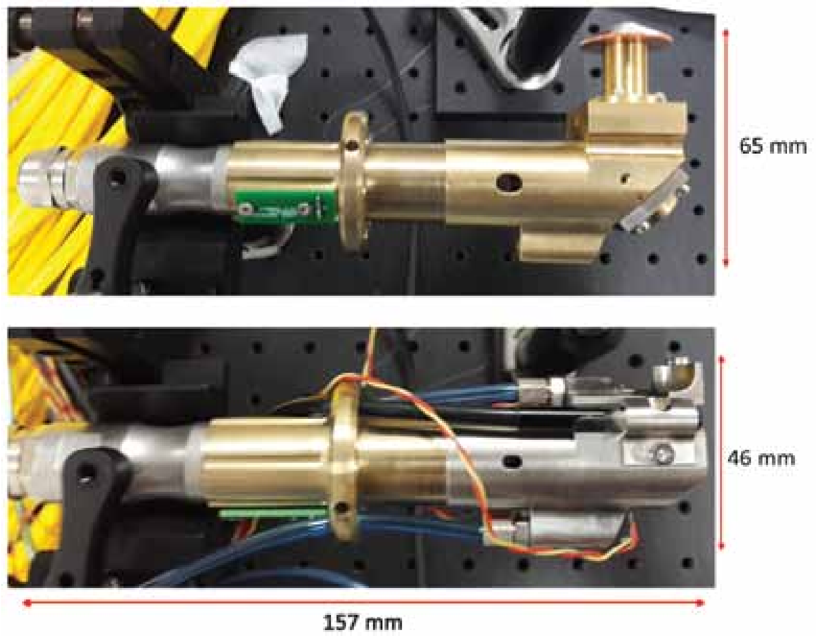


FIGURE 3
Photographs of the miniaturized bespoke laser cutting (top) and welding (bottom) heads developed for the in-bore tools [8].

provide rotation. Second, with the complete tools providing their own rotation. The high power laser trials were performed at the TWI Laser Facility in Cambridge, UK using a fibre laser source (YLS-5000; IPG Photonics Corporation) emitting a multimode beam at 1064 nm with 5.0 kW maximum power output. The materials investigated were P91 alloy steel and 316L stainless steel pipes of with wall thicknesses of 3 and 5 mm.

3.2 Cutting and welding head trials

During the initial trials the laser heads were attached to a robotic arm and had power supplied to them *via* a high power fibre optic cable, as shown in Figure 4. The laser heads were instrumented with thermocouples to monitor the temperature and detect when failure occurred. Beam profiling confirmed the cutting head and welding head both produced beam diameters of 0.7 mm at the working distance. The laser heads were power tested by gradually increasing the laser power to establish the upper operating limit of the design. The power tests found the laser head failed at 3.4 kW at which point the mirror overheated, fractured and was melted. At 2.2 kW the laser heads were found to operation continuously without incurring any damage. Having established the operating limits, the laser heads were then trialled to cut and weld pipes, shown in Figure 5. The cutting head was operated using N_2 cutting gas at 1.2

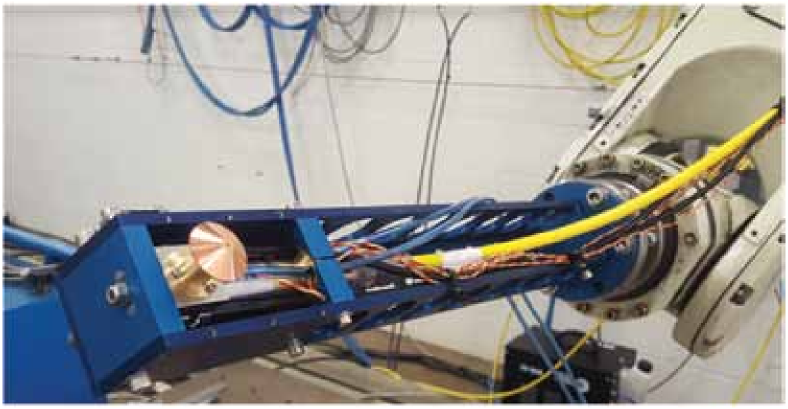
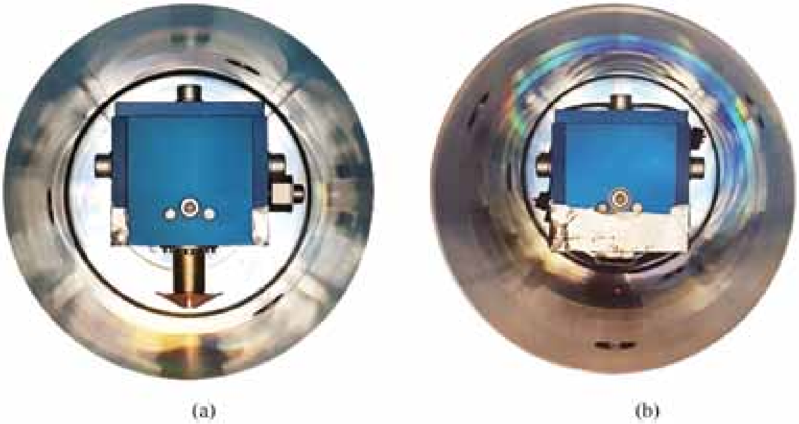


FIGURE 4
Photograph of the laser cutting head mounted on a robotic arm during the cutting and welding head trials.



(a) (b)

FIGURE 5
Photographs of (a) the laser cutting head and (b) the welding head inside the pipe rig during the trials.

kW at 0.5 m/min traversing speed at the internal pipe surface and was able to cut through 5 mm wall thickness P91 alloy steel and 316L stainless steel pipes. The welding head was operated at 2.2 kW at 0.5 m/min traversing speed at the internal pipe surface and was able to weld through 3 mm wall thickness P91 alloy steel and 316L stainless steel pipes. The welding head was unable to weld through 5 mm wall thickness steel pipe.

3.3 Cutting and welding tool trials

Having established the operating parameters and limits of laser heads in laser trials, the complete prototype tools were trialled. Figure 6 and Fig-

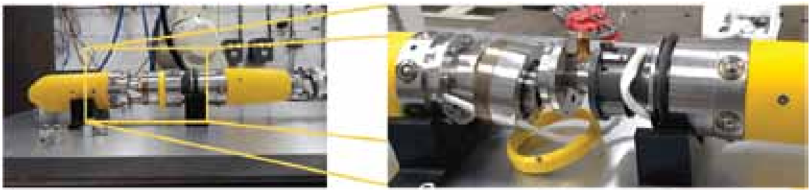


FIGURE 6
Photographs of the in-bore laser cutting tool showing the cutting head buried within the tool.

FIGURE 7
Photograph of the in-bore laser welding tool.

ure 7 show the in-bore cutting tool and in-bore welding tool, respectively, with the laser heads buried within the tools. For the trials the tools were attached to the end of a rod and deployed down a 1.5 m pipe to the cut/weld side where P91 alloy steel and 316L stainless steel samples, as shown in Figure 8. The services for the tools (optical fibre, gas supply,

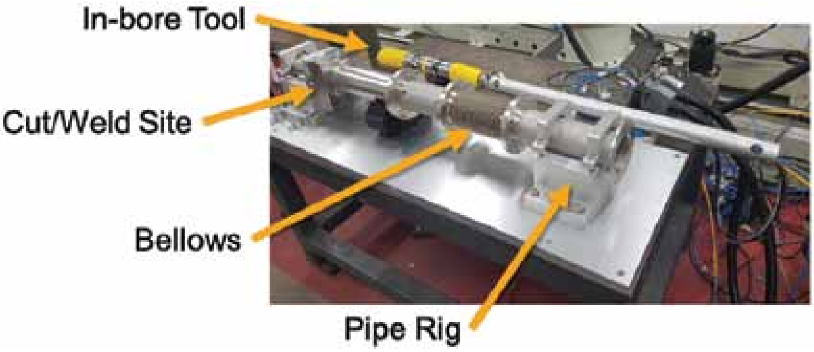


FIGURE 8
Photograph of the pipe rig and in-bore tool deployment used during the cutting and welding tool trials.

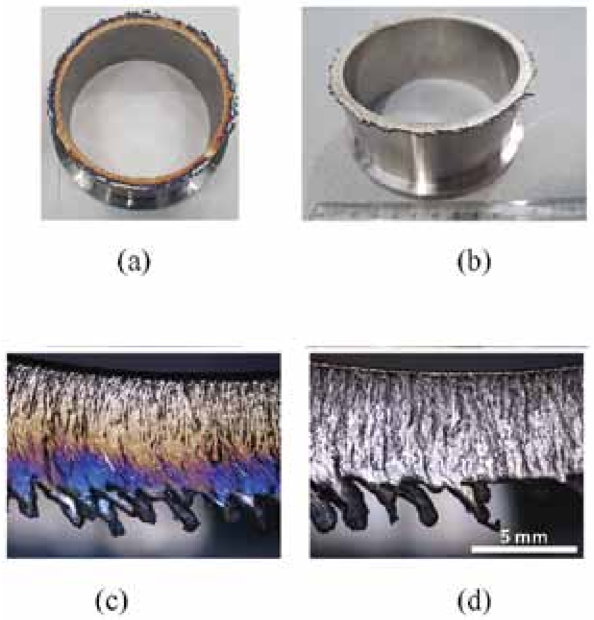


FIGURE 9
Photographs and micrographs of the surfaces of (a) and (c) P91 alloy steel cut pipe samples, and (b) and (d) 316L stainless steel cut pipes.

pneumatic lines and electrical motor supply) were provided along the rod to the rear of the tool.

The parameters used for the prototype in-bore cutting tool were the same as those in the cutting head trials: N_2 cutting gas, 1.2 kW laser power and 0.5 m/min traversing speed at the internal pipe surface. The cutting tool was able to successfully cut through 5 mm wall thickness P91 alloy steel and 316L stainless steel samples, as is evident from Figure 9. The cut samples can be seen to have rough surface finishes and have significant dross on the outside of the pipe. The P91 alloy steel pipe also has oxidation on the surface; however, this is acceptable for the application as the welding step will be done on new pipework.

The parameters used for the prototype in-bore welding tool, similarly, were the same as those in the welding head trials: 2.2 kW laser power and 0.5 m/min traversing speed at the internal pipe surface. The welding tool was able to successfully weld through 3 mm wall thickness P91 alloy steel and 316L stainless steel pipes. Figure 10 shows the weld cross-sections from the trials where the tool was able to produce fully penetrated welds in both materials. Radiography showed there was no porosity in the welds, except at the stop/start point of the welds. A constant rotation speed was used for the welding so modification of the speed profile would be needed to improve the stop/start region.

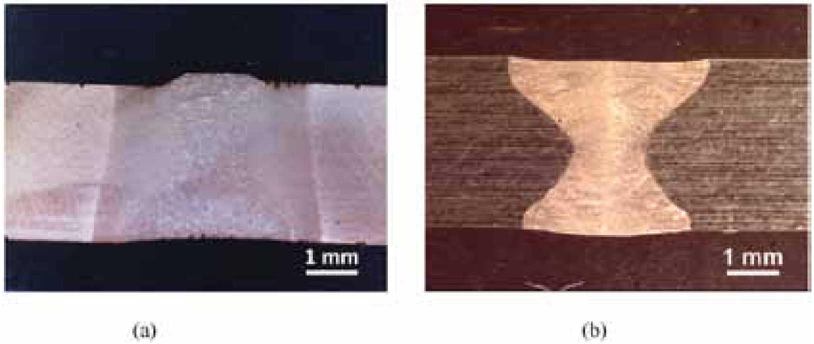


FIGURE 10
Optical micrographs showing welded pipe cross-sections produced from the laser welding tool trials on (a) 3 mm wall thickness P91 alloy steel and (b) 3 mm wall thickness 316L stainless steel.

As the welding prototype is an in-bore tool, the welding tool is trapped inside the pipe with fumes and debris produced during the welding process. The trials showed a steady build-up of damage and material on the front face of the welding tool. Figure 11 shows the damaged front face of the welding tool after 15 pipe welds. After several pipe welds the material builds up so much that it can encroach into the orifice that it blocks the edge of the laser beam and interferes with the welding process. For the final application of the weld tool, it will need to be inspected between uses to ensure the laser orifice remains clear.

FIGURE 11
Photograph showing built up damage to the front face of the laser welding tools from successive operation.

4 CONCLUSIONS

The maintenance of future fusion reactors requires remote tools to rapidly disconnect and reconnect pipes. To address this need prototype laser cutting and welding tools have been developed which include miniaturised cutting and welding heads. Initial laser trials on just the laser heads mounted on a robotic arm showed the gas cooled optical design were capable of operating for the process period safely at 2.2 kW laser power after which it fails by damaging the mirror. The initial trials also found the heads could cut and weld steel pipes from the inside.

Having identified the performance capabilities of the laser heads, the complete prototype tools were then trialled on pipe samples. The cutting tool was able to successfully cut 5 mm wall thickness pipes in both P91 alloy steel and 316L stainless steel. The cuts had rough surface finish and dross, but it is acceptable for this application. The welding tool was able to produce fully penetrated welds in P91 alloy steel and 316L stainless steel 3 mm wall pipes with radiography showing no porosity. There were issues in the start/stop region of the welds and to solve this further work would be needed to optimise the speed profile of the tools. The final application requires welding of 5 mm wall thickness pipes which would require higher laser power than the current optics design can handle so either higher laser power capable optics would be needed, or the optical design would need to be modified to reduce the power density on the optics.

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