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Remote in-bore laser cutting and welding tools for use in future nuclear fusion reactors

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ABSTRACT

The maintenance, replacement and decommissioning of future nuclear fusion reactors will require quick and reliable cutting and joining of in-vessel pipework. Initial design studies for nuclear fusion reactors for power generation have estimated cutting and welding could account for up to 60% of the maintenance duration using conventional in-situ processing techniques (dry-mechanical cutting and arc welding) and that new methods are required to expedite the process. Additionally, the expected radioactivity and limited access at the cutting and welding sites mean these processes cannot be done manually and robotic tools are required. To this end, remote in-bore laser cutting and welding tools have been developed for use in 90 mm internal diameter steel pipes. Here, we will present the designs of the remote in-bore laser cutting and welding tools, and how the tools fit within the overall remote maintenance strategy of a nuclear fusion reactor. Initial high-power laser trials were performed with prototype tools and successfully demonstrated their laser processing, thermal management and dust protection functionality. The tools described herein have been developed specifically for use within the fusion reactor environment, however the tool design and technology demonstrated here is readily transferable to many remote applications in challenging environments such as fission reactor maintenance, nuclear decommissioning and other in-accessible pipework.

INTRODUCTION

Components within a future fusion reactor will need to replaced every three to five years due to damage and degradation in performance incurred from the high neutron radiation, high temperatures, cyclic loads and erosion experienced during operation[1,2]. The planned overall maintenance strategy for a fusion reactor involves vertically removing the central blanket components through an upper access port at the top of the reactor and horizontally removing the lower divertor components through a lower access port at the bottom of the reactor, shown in Figure 1. Prior to removing these large components, the service pipes to them must first be disconnected. After the components have been replaced the service pipes must be reconnected. To perform the disconnection and reconnection of service pipes, remote in-bore cutting and welding tools have being developed.

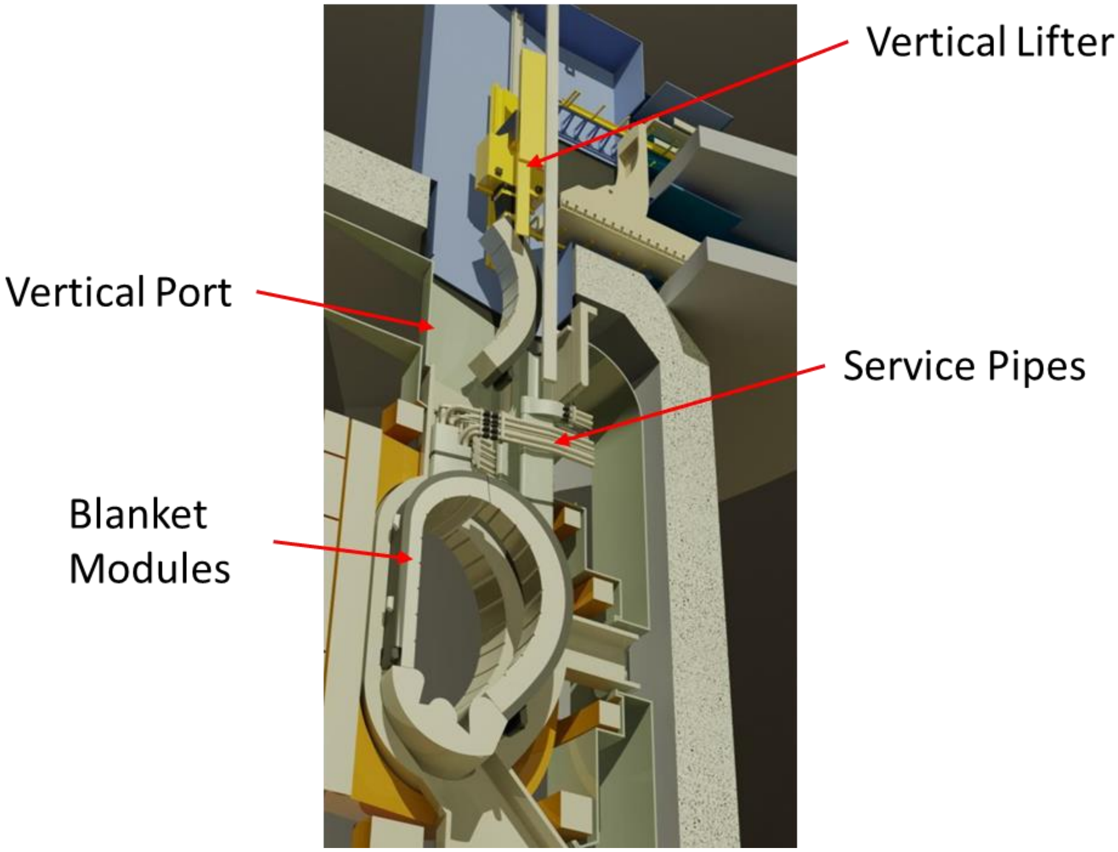

Fig. 1. Cross-section view of a nuclear fusion reactor showing the maintenance strategy for remote component replacement.

Process Site Location and Environment

As shown in Figure 2, from the nearest access point the cutting and welding sites are located:

A. 6 meters down vertical pipe through the upper access port
B. 12 meters through a horizontal pipe with a 1.5 metre radius corner through the lower access port

The cut/weld sites are only accessible from inside the pipes. The service pipes will carry high pressure water and helium coolants, and potentially liquid lithium-lead nuclear breading fluids[3]. The pipework is expected to be a combination of 75 mm internal diameter with 5 mm wall thickness and 200 mm internal diameter with 15 mm wall thickness sized pipe works. Based on current fusion reactor concepts[2], it is estimated that approximately 800 pipes will have to be disconnected and reconnected per reactor maintenance cycle.

20 – 200 Gy/hr of residual radiation (predominately Gamma radiation) caused by nuclear activation during operation is expected at the cutting and welding locations[4]. The radiation level and in-accessibility of the weld/cut site means manual intervention is unfeasible and robotic tooling is required.

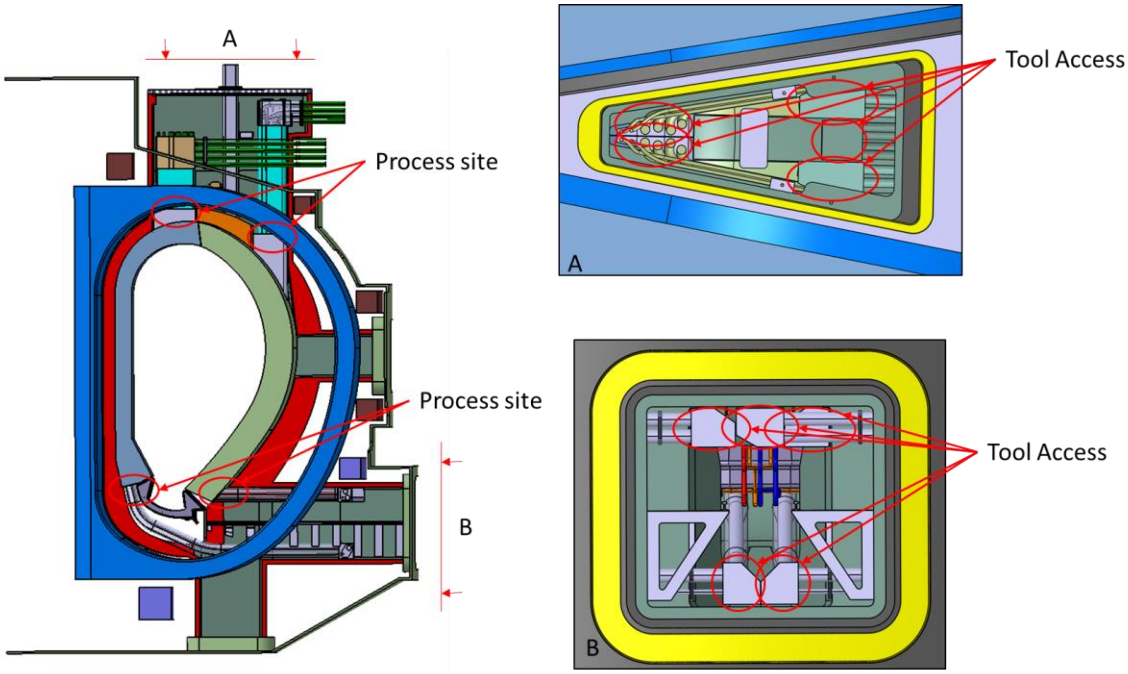

Fig. 2. Pipework cut and weld site locations within a fusion reactor: **a.** Blanket service pipe & **b.** Divertor service pipes.

Technology Selection and Duration Estimation

Maintenance procedures in current fusion reactor use conventional TIG welding and non-lubricated cutting processes[5,6]. Initial design studies for powerplant scale nuclear fusion reactors estimated cutting and welding could account for up to 60% of the maintenance duration using conventional processing techniques[7]. Alternative techniques were investigated in order to reduce the overall maintenance duration. Laser processing identified as a suitable technique due it's fast processing speed, high reliability, non-contact, effects only a small area and can cut/weld large sections in a single pass[8].

The effect of using laser processing on the overall maintenance duration was assessed against conventional TIG welding and non-lubricated cutting using the Maintenance Duration Estimation tool developed by UKAEA[7]. The duration estimates considered processing time, tool deployment time and tool retraction times. Table 1 and Table 2 show the calculated duration estimates for cutting and welding per access port, respectively. A clear advantage can be seen in using laser processing compared with conventional processing, particularly for the cutting process. As an example, using conventional cutting processes on the large DEMO pipe diameters and thicknesses an estimated duration of cutting of ~1.5 hour per 200 mm pipe, compared to laser cutting of ~30 seconds. With this difference the total reactor maintenance cycles change from eight months with conventional technologies to five months using laser processing. Though the laser based processes are much faster the peripheral service joining activities: deployment, inspection, and post weld heat treatment remain the same, preventing major savings in welding duration.

TABLE 1. Duration estimates comparing cutting operations per port

	Mechanical Cutting	**Laser Cutting**
Total cutting operation	488 hours	5 hours
Total port clearance operation	700 hours	217 hours

TABLE 2. Duration estimates comparing welding operations per port

	TIG Welding	Laser Welding
Total welding operation	148 hours	121 hours
Total port assembly operation	330 hours	312 hours

CONCEPT TOOL DESIGN

Concept designs have been produced for an in-bore remote laser cutting tool and an in-bore remote laser welding tool. The two tools have a similar overall design due to the common functionality of alignment, clamping and laser processing. The two tools differ by have different laser processing heads and focusing gas systems to create their respective laser welding and laser cutting conditions. In order for the tools to fit into the pipe, bespoke miniaturised laser processing heads have been designed.

The concept operation for both tools are:

I. Insertion of the tool into the pipe via the access point
II. Tool travel along the pipe to the cut/weld site
III. The tool clamps into the pipe and aligns with the cut/weld site
IV. The tool laser cuts/welds the pipe
V. The tool unclamps and is extracted through the access point

The overall design of the remote in-bore laser tools is shown in Figure 3. The tools include a central motorised rotating laser processing head, a pneumatic radial clamping mechanism, articulation joint and pipe alignment mechanism. The design utilises commercially available components (pneumatics, high power fibre connectors, optics lens and high torque motors) and resulted in the tool design being capable of fitting inside a standard DN 90 Sch 40 pipe (90 mm ID, 5 mm wall thickness).

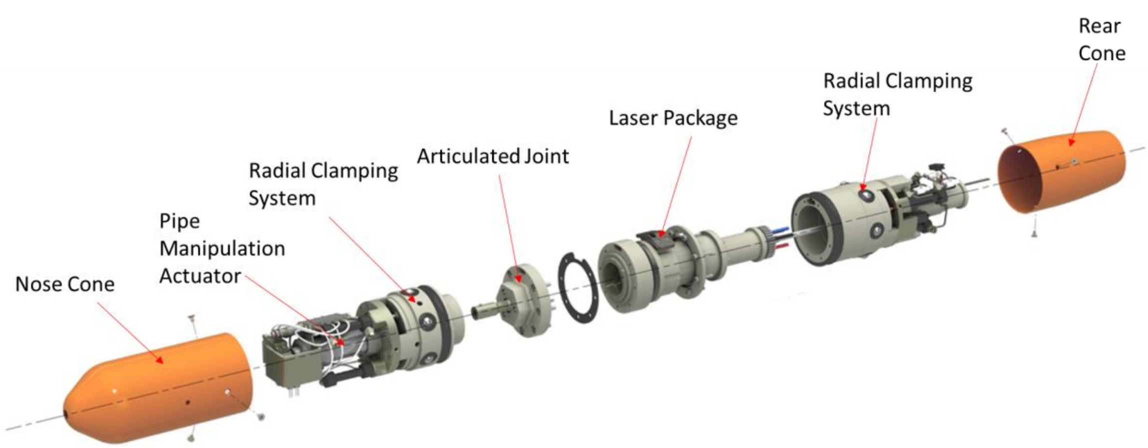

Fig. 3. Exploded view of the in-bore laser tool design showing the constitutive functional components.

Radial Clamping System

The tools include two radial clamping systems either side of the laser head. The clamping system consists of a pneumatically driven tapered ring that deploys 6 ball bearings into a mating datum feature in the pipe. When the clamp is released the ball bearings are loose and act as wheels, allowing the tool to roll through the pipe during deployment. The clamp pushes out radially so the mechanism also acts to centre to tool in the pipe. The clamping also acts a reaction force to locally draw the pipes together, by using the central cylinder needed for pipe alignment.

Articulation Joint

The articulated assembly in the centre of the tool uses a balled hex design. This geometric shape prevents rotation of the tool axially but allows the tool to pitch in any direction up to 10°. This allows the tool to travel around a pipe bend of 1.5 m radius. This combined with the ball bearings of the clamping system allows the tool to travel through the service pipes.

Laser Package

The laser package contains the laser processing head. It is held in a set of bearings to allow it to rotate around the pipe. It is rotated by an electrical motor housed in the upper clamp section. The laser package focuses the laser delivered through a high-power fibre, creating the required spot for processing of 0.2–0.6 mm[8] through a bespoke optics setup. Two attached endoscope cameras allow visibility of the pipe fit-up and laser processing.

The laser packages also concentrate the gas systems. The optics within the processing heads in both tools are gas cooled. The cutting tool has a focused nozzle to create a parallel cutting gas jet at the laser spot. The welding tool includes a gas system to flood the local pipe area with inert gas to create the necessary environment for welding. The welding head also includes a gas knife over the optics to protect them debris created in the process.

Pipe Manipulation

The tool design also a large pneumatic actuator in the lower section. Once the tool is clamped to the pipe the actuator allows it to pull them together or apart, during welding and cutting, respectively. During welding, this to ensure the pipes faces are aligned and as a gap of 0.1 mm or less is needed between the pipes to ensure a good weld[8]. During cutting, the tool can apply a tension to the pipes during processing to ensure separation of the pipes and prevent molten waste re-joining the pipes.

HIGH POWER LASER TRIALS

As part of developing the in-bore remote laser tools, a series of high power laser trials were performed using the miniaturised laser processing heads.

Experimental Method

The performance of the miniaturised laser processing heads, shown in Figure 4, developed for the in-bore tools designs were tested at the TWI high power laser facility in Cambridge, UK. The processing heads were connected to an IPG YLS-5000 laser system (1064 nm continuous wave beam) via the optical fibre. The trials used beam powers up to 1.2kW. The processing heads were attached to a robotic arm to provide movement and rotation, shown in Figure 5. A traversing speed 1.0 m/min we used in the trials, resulting in the processing heads operation for 17 seconds at a time. The purpose of these trials were to test performance of:

- The optical system to produce the correct spot size for laser processing
- Gas systems to cool the optics
- Dust protection systems to stop the build up of dust on the optics

The high power laser trials involved:

1. ***Laser power testing -*** to measure the power loss through the processing head
2. ***Beam profile -*** to confirm the laser spot size produced by the processing head
3. ***Plate & pipe welding -*** to confirm the thermal management and penetration depth of the processing head

Laser processing heads were instrumented with thermocouples to record the temperature rise during operation. Welding trials were performed on both P91 and 316L steel samples, the materials being considered for use for the fusion reactor pipework.

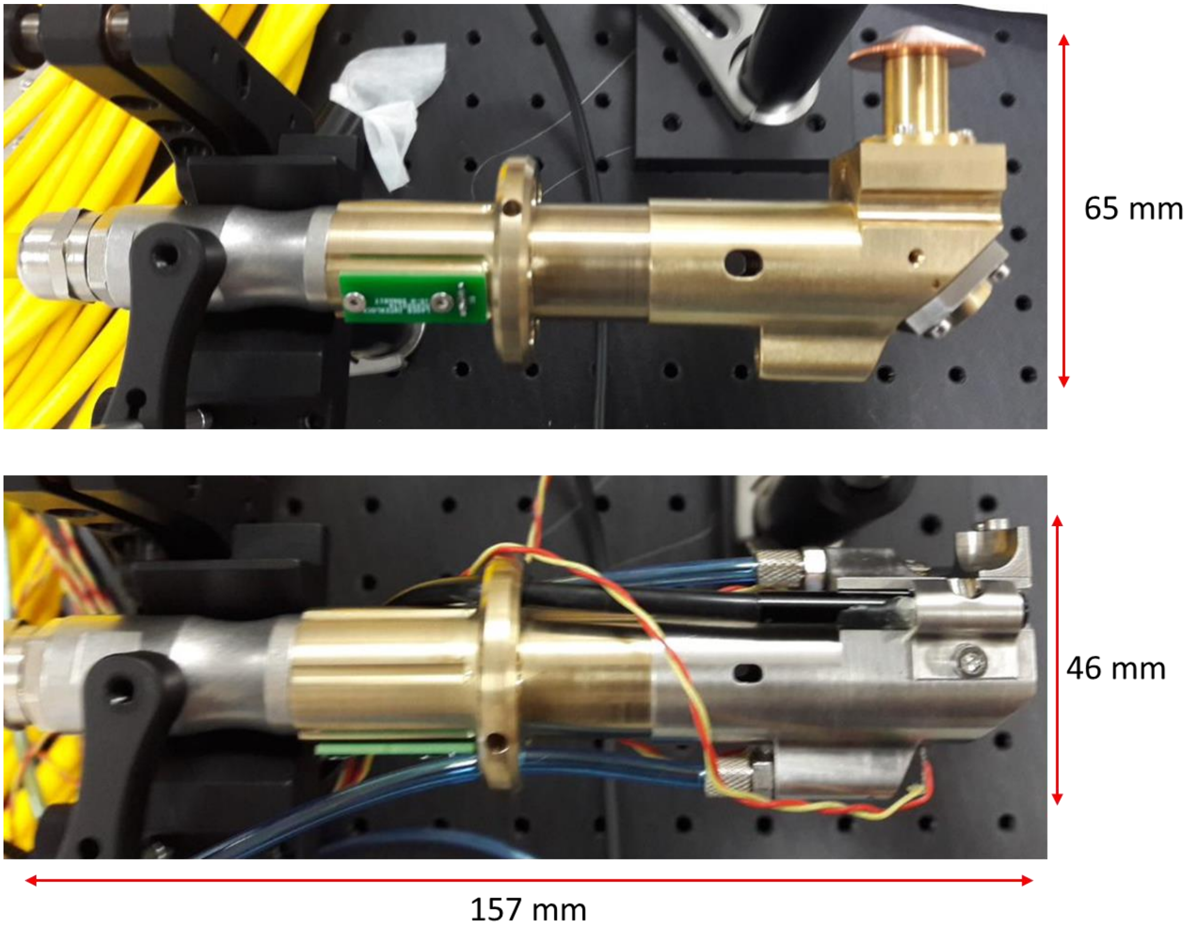

Fig. 4. Miniaturised cutting and welding processing heads used in the high power laser trials.

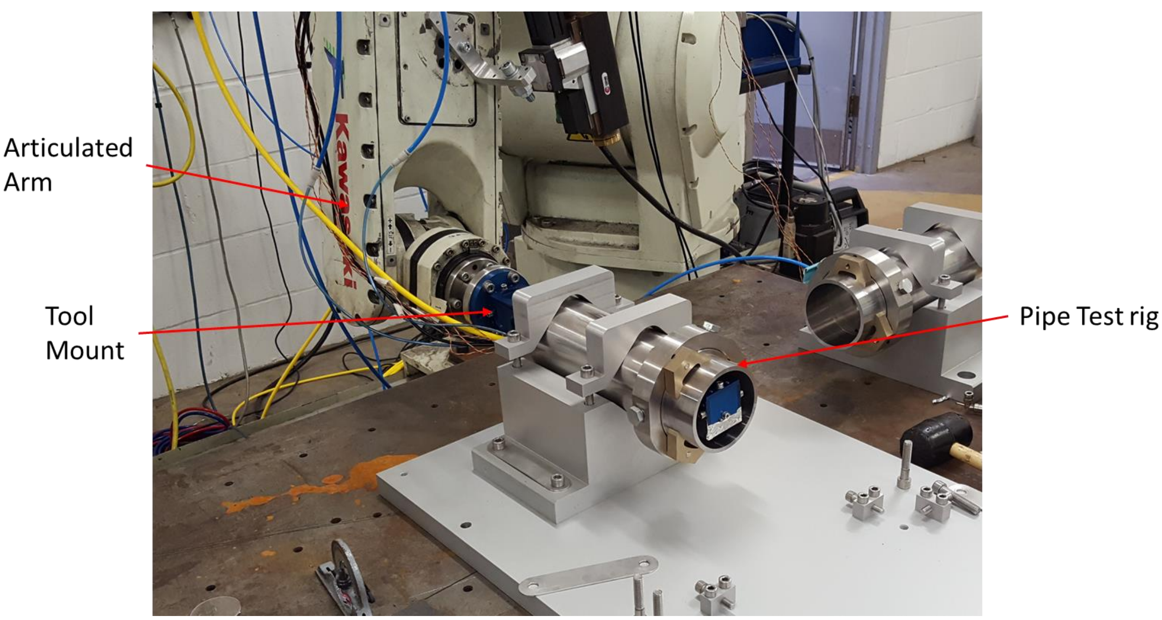

Fig. 5. TWI high power laser facility used in the trials.

Results

The high power laser trials found the laser power loss through the processing heads was less than 1% (the precision of the power meter used). The low power loss was expected due to the low reflectivity of the high power optics used, the small number of optical components used and short travel distance in the processing head.

The measured beam profile, shown in Figure 6, showed the optics in the processing head produced a focused laser spot of 0.38 mm at the correct standoff distance which is suitable for cutting and welding. The spot had a low divergence and was still less than 0.45 mm diameter ±3 mm of nominal focus point.

The thermocouple readings showed a peak temperature rise of 5°C during pipe welding at 1.2kW which returned to room temperature after 30 seconds of active gas cooling. The optics were visually inspected and no thermal damage was caused to the optics, although only a small number of high power laser operations were performed.

The welding processing head successfully produced a fully penetrated weld in 1.2 mm carbon steel plate and partially penetrated welds in 5 mm thick plate and pipe samples using 316L and P91 material. Cross-sections of the welds, shown in Figure 7, showed penetration depths of 2.5 mm and 2.8 mm in 316L and P91 pipes, respectively.

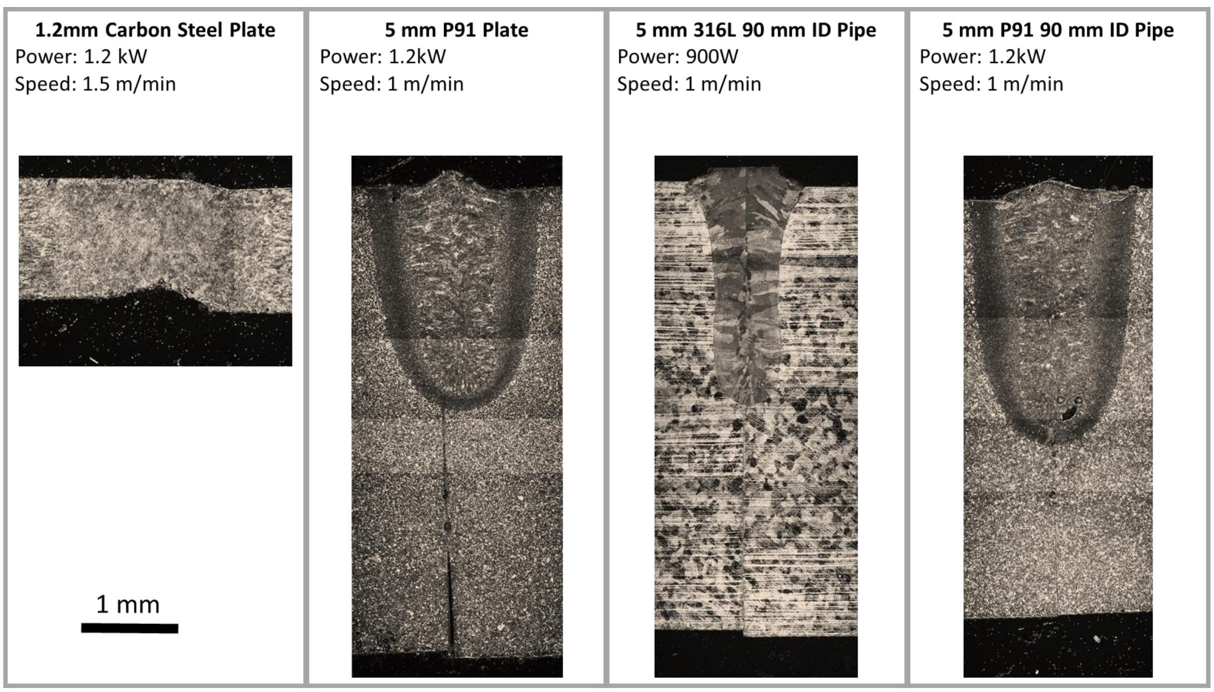

Fig. 6. Cross-sections of welds produced by the miniaturised laser welding head. The notes above each cross-section lists the process conditions and material sample.

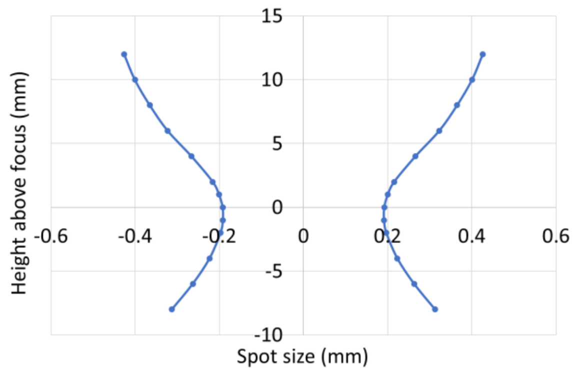

Fig. 7. Laser divergence profile produced by the processing head.

CONCLUSIONS

The maintenance and decommissioning of future fusion reactors require remote cutting and welding of pipes. To achieve this, remote in-bore laser cutting and welding tools have been developed. Laser processing was selected for it's high processing speed and was calculated to have a significant benefit by reduce the overall maintenance cycle for fusion reactor from 8 months to 5 months compared with using conventional techniques.

Concept designs for remote in-bore laser cutting and welding tools have been produced using commercially available components, fits within a 90 mm pipe and includes miniaturized bespoke laser processing heads. The tools are capable of clamping into the pipe, aligning with the cut/weld site and applying the laser process around the inside of the pipe.

The miniaturised laser processing heads were tested at a high power laser facility. The trials demonstrated the laser processing heads produced the correct spot size for processing, the gas cooling was sufficient and the air-knife in the welding head sufficiently protected the optics from dust. The laser welding tool was also able to partially weld pipe samples, penetrating 2.8 mm.

Further work planned will involve high power laser trials with the cutting head, mechanical testing of the clamping, alignment and rotation mechanisms, and full demonstrations of remote laser cutting and welding using prototype tools. The tools described herein have been developed specifically for use within the fusion reactor environment, however the tool designs and technology demonstrated here is readily transferable to other applications such as fission reactor maintenance, nuclear decommissioning and size reduction in waste management.

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