

LaserSnake2: Remote High Powered Laser Cutting in Confined Hazardous Spaces – 16161

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ABSTRACT

LaserSnake2, a UK collaborative project, seeks to deliver remotely operated cutting techniques into high hazard nuclear environments. This paper describes the developments and results of combining proven robotic manipulators with high-powered laser cutting tools, to allow for selective dismantling within complex nuclear process cells.

Decommissioning old and poorly catalogued nuclear plant is a problem faced the world over. Designed with little consideration for decommissioning, or adapted significantly from the original drawings, legacy plant and infrastructure is full of spaces where it is undesirable or impossible to send people. Typically a process cell or cave will require modification to ensure suitability for human entry or deployment of heavy duty equipment to complete the decontamination processes. The process of widening access routes, or selectively moving sections of highly contaminated material, is ideally suited to remote handling technology.

The results of TWI's research into fibre-delivered laser cutting techniques, and integration with a dexterous snake-arm robot, are presented. Coupled with novel laser process head design and diffractive optical elements, the result is an integrated system capable of cutting up to 100mm thick C-Mn steel plate at significant stand-off distances, encompassing the range of infrastructure found in a typical nuclear plant.

Two options have been considered for deployment of the laser cutting tool. The first is focused on a fixed installation using a standard industrial robot. The second is a large, highly flexible snake-arm robot capable of entering cluttered cells through existing penetrations. Designed to operate through a standard 11" MSM port, the 4.5m snake-arm robot has the capacity to carry grippers, sensors or the laser cutting tool at the tip. The snake-arm is sealed and housed within a glove box for contamination control, allowing operation within a radioactive environment. Significant technical developments and material research are presented which have led to improved operational life, payload and bend.

This paper describes the series of inactive trials which have been conducted to demonstrate the LaserSnake2 system's capabilities. These include: horizontal and vertical deployment, underwater operation, object manipulation and laser cutting.

With global nuclear decommissioning costs running in to the \$trillions, safe and cost efficient tools such as the LaserSnake2 system are essential as part of the decommissioning toolbox. Remote handling can account for up to 20% of a decommissioning project's costs, however significant time and financial savings can be made by utilising this new technology to reduce operator exposure and reach previously inaccessible areas.

INTRODUCTION

Early generation nuclear power plants the world over are now in the process of being decommissioned. Often poorly catalogued or vastly modified from the original designs, they contain large numbers of process cells and spaces that are congested and difficult to access. In many cases limited access restricts human entry to these spaces or, when following the as low as reasonably practicable (ALARP) philosophy, it is no longer justifiable to send people where remote handling technologies and robotics can be successfully used.

Thousands of vessels and hundreds of kilometers of pipework are used to transport, store and process radiated material in a typical plant. Although decontamination and demolition of the buildings they are housed within is a relatively simple, the work to clear out these internal structures is a complex task. Equipment is placed close together leading to cluttered spaces that were not built with maintenance or decommissioning in mind, Figure 1. As human access is limited or undesired, remote methods for size reduction of infrastructure are required. Traditional manual cutting methods that require 'feel', such as circular saws or grinders, are hard to use remotely. Laser cutting provides a simpler, non-contact, method which can be applied to these challenges.



Figure 1 – Complex process cave (photo taken during commissioning)

LaserSnake2, a UK collaborative project, seeks to deliver remotely operated laser cutting techniques for the nuclear decommissioning sector. The project has focused on combining flexible snake-arm robot manipulators with high-powered laser cutting tools to selectively dismantle structures within complex and cluttered nuclear process cells. Additionally larger industrial robots have been used to develop a dedicated size reduction facility that also uses laser cutting.

The project has three main areas of research:

1. Development of an 'in-situ' cutting tool – LaserSnake2 – combining a snake-arm robot with a fibre delivered laser process head to create a mobile tool for cluttered spaces with complex geometries within a plant.
2. Integration of an industrial robot and laser process head at an 'ex-situ' size reduction facility, where items (flasks, vessels etc.) are brought to be remotely size reduced.
3. Design of laser process heads suitable for use within nuclear facilities, the advancement of cutting techniques through trials and the development of novel diffractive optical elements (DOE) to adjust the laser beam characteristics.

The project partners have worked closely with Sellafield Ltd to identify representative demonstration tasks for remote laser cutting. A related need for manipulator capability for pick and place tasks in cells and fuel storage ponds has also been identified. The technologies will address the key business drivers of safety, cost, reliability, throughput and the minimization of secondary waste generation.

DESCRIPTION

LaserSnake2 - In-situ Laser Cutting of Nuclear Infrastructure

During operation, the radioactive material and other chemicals processed within plants are done so in sealed areas. Thick concrete walls and windows protect workers from radiation and other hazards, and intervention is undertaken via remote handling. Historically, tools such as master slave manipulators (MSMs) and overhead cranes were used to interact and maintain the facilities. In order to minimize plant modification when decommissioning active inventory, it is desirable to use these existing access routes where possible.

Snake-arm robots have been proven, within the nuclear industry, for navigating confined and hazardous spaces for inspection and maintenance. In 2011, along with TWI Ltd, OC Robotics integrated an off-the-shelf snake-arm robot with a high-powered laser process tool typically used for the automotive industry, Figure 2. This small feasibility study proved the principle of combining these technologies for nuclear decommissioning applications.



Figure 2 – Feasibility study mock-up trials of a standard snake-arm robot with a 5kw high-powered laser.

In 2013, the project set out to enhance the capabilities of the technology, building a longer reach system and refining the laser process head design to create a deployable product. A snake-arm robot system has been designed with the following capabilities:

- 4.5m of articulated length (an increase of 100% on the previous longest snake-arm robot)
- 180degrees of curvature
- Integrated laser cutting head and inspection camera tool
- Laser control and safety systems for the robot and laser integrated
- Gripper tool
- Compact introduction axis options
- Modular base extension options
- Integrated glovebox enclosure for introduction axis
- 5 axis local orientation and translation control, plus cutting path control for laser cutting
- Submerged deployment capability down to 5m

LaserSnake2 is a spatial snake-arm robot, able to navigate around complex 3D environments. Made up of a rigid links, each connected with a 2 degree-of-freedom joint, the arm is controlled using wire ropes that are actuated from the base of the arm. A new design has changed the configuration of the holes which guide the ropes (originally built as a single piece) into individual inserts positioned outside the link. This allows them to be easily exchanged and replaced as they wear, reducing through life costs and allowing materials with different friction or wear properties to be used. These advances have resulted in significant steps forward in snake-arm

robot length and payload capabilities.

Improvements to the control software have increase the systems robustness to long term use by operators at nuclear sites. This includes clear and simple recovery techniques that were highlighted as a requirement during the development of the safety case. Given the undefined nature of objects to be size reduced, focus has been given to control of the laser process head to facilitate reliable cutting. Five axis local orientation and translation control, plus cutting path for laser cutting can be undertaken using predefined paths or man-in-the-loop control. At all stages the software has been developed to reduce complexity and the burden on the operator.

Ex-situ Size Reduction Facility

Larger contaminated items dismantled and removed from site need to be further sized reduced and packaged into containers ready for further processing. Packing these containers as full as possible is essential with the cost of processing a container of intermediate level waste (ILW) running to over \$100,000. Within the project, National Nuclear Laboratory (NNL) has undertaken the development of size reduction facility in the Windscale Laboratory, Figure 3. Combining an industrial manipulator with the same high-powered laser cutting technology used on the LaserSnake2, a remotely operated cutting station has been designed.

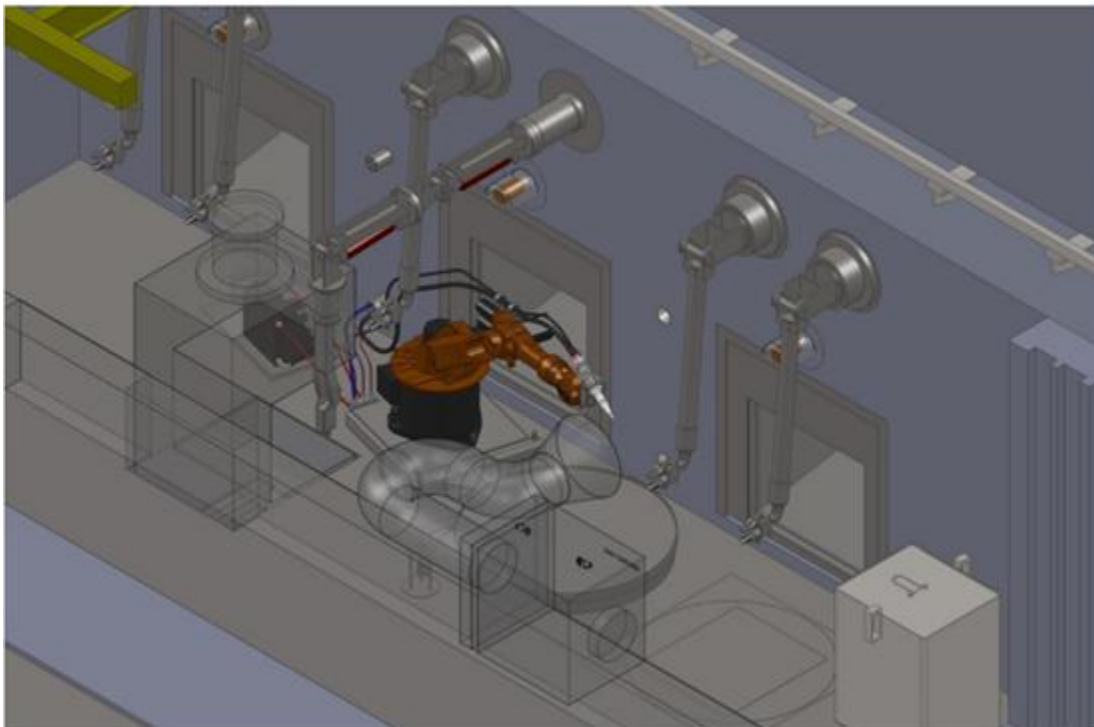


Figure 3 – Ex-situ laser cutting facility scheme design [2]

Along with the development of a robust, easy to use user interface, a key focus for the program has been writing a safety case for radiological deployment of high powered lasers by robotics systems onsite at Sellafield. With regular use planned,

and irregular objects to size reduce, large volumes of cuts and fume are expected. During the project, management of fume and control of the release fraction has been a high priority for the safety case. To address this issue, detailed local extract design, with CFD tools used to optimize air flow, and extensive fume characterisation trials have been undertaken.

Laser Cutting Research and Development

Lasers are used extensively in other industries to perform precise cutting of relatively thin, and well constrained materials. In contrast, the support structures and vessels found in nuclear plant can be very thick, and are often in unexpected positions. As a result the implementation of laser cutting technology needs to be very versatile and able to deal with a range of materials, thicknesses and orientations.

Bespoke laser process heads have been designed to be tailored for nuclear environments with easy to clean surfaces and features for simple maintenance by remote tools or within glove boxes, Figure 4.



Figure 4 – Laser process head developed for the LaserSnake2 project

Along with standard optics, DOEs have been designed to provide an extended depth of focus for the cutting beam. This allows the laser head to cut thicker metals and have a greater tolerance to stand off from the surface of the item to be cut.

High powered laser heads require cooling of the optics and the fibre couplings. Typically this is achieved using a water cooling circuit and refrigeration unit. As water is a moderator it is undesirable in a radioactive environment. In addition, water entering and leaving a cell risks transmission of contamination and radioactive material out of the contained environment. To remove this risk the

project has developed and trialed an air cooled process head, using the purge gas normally used to blow molten material out of a cut, to cool the optics.

Finally, underwater laser cutting has been researched, targeting the ponds which are typically used on nuclear sites to store spent fuel and other contaminated objects.

DISCUSSION

Snake-arm Robots Developments

To access confined environments in nuclear sites, including the cells proposed for trials at Sellafield, OC Robotics has had to increase the size, and capabilities of its snake-arm robots. Targeting 4.5m of horizontal reach, 10kg payload, and higher curvature has required detailed FEA, assessing higher loads than have previously been seen. To make this size of arm possible, low friction, low wear materials for the link inserts that guide the wire ropes within the arm had to be identified.

Coated aluminum, brass, bronze and ceramics were all extensively tested on rigs to determine the co-efficient of friction and wear rates at different operating loads. A soft self-lubricating bearing material was chosen as the optimum balance between frictional properties and wear rates. This material was installed into a new design of arm that allows for easy and quick exchange of both the inserts and the ropes. To qualify test rig work, and prove suitability of this material for the larger snake-arms being built (and higher loading), an extended test sequence was run.

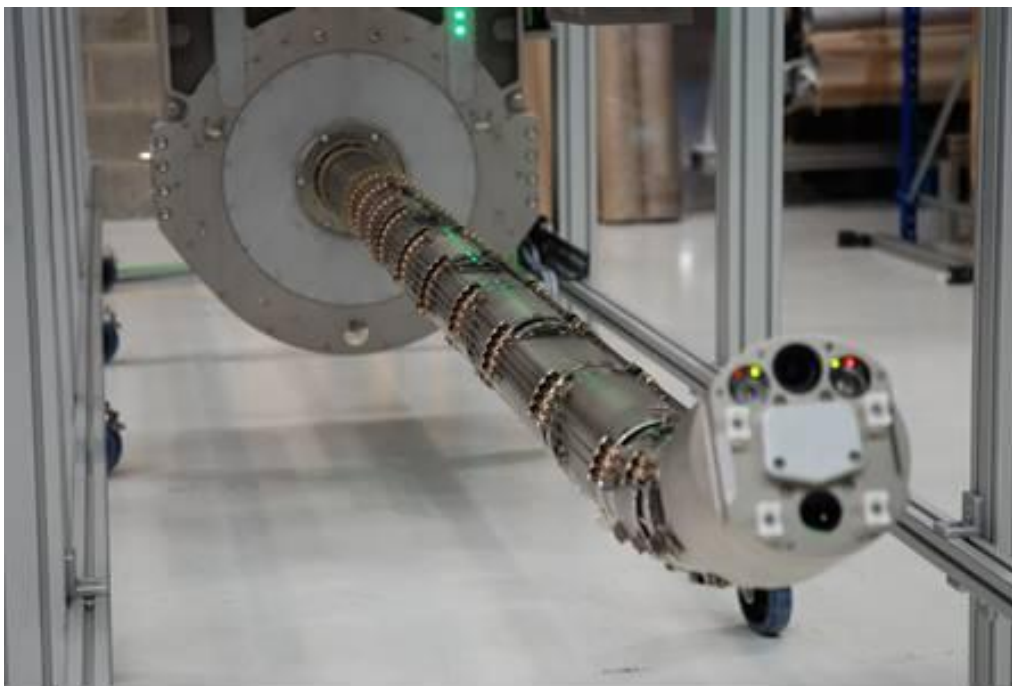


Figure 5 – Extended life testing of snake-arm robot

A variety of paths and tip motions, representing deployment and laser cutting

motions were repeated over a 4 week period. Over 1500 deployments and 250 hours of continuous use were undertaken. Subsequently ropes and flutes were inspected and the arm was found to be less than 5% through its potential usable life, thus proving the selected material was appropriate.

Since this test, this style of arm has logged over 4000 hours of operation. Proving the integrity of hardware and software through these tests has been essential for the LaserSnake2 safety case, with certainty of operation and recovery being essential for deployment within a hazardous nuclear environment.

Prior to the start of the project, the longest snake-arm robot developed was 2.2m with a payload of 5kg. In order to understand the implications of longer arm design and the associated loading empirically, an intermediate 3.1m was developed, Figure 6. Motor currents were logged across a defined set of motions and different payloads. These were compared with equivalent data from the 2.2m arm and used to inform the design of the 4.5m arm. Integration of the laser process head with an existing snake-arm robot laid the platform to develop improved motion modes for positioning the laser, Figure 6.

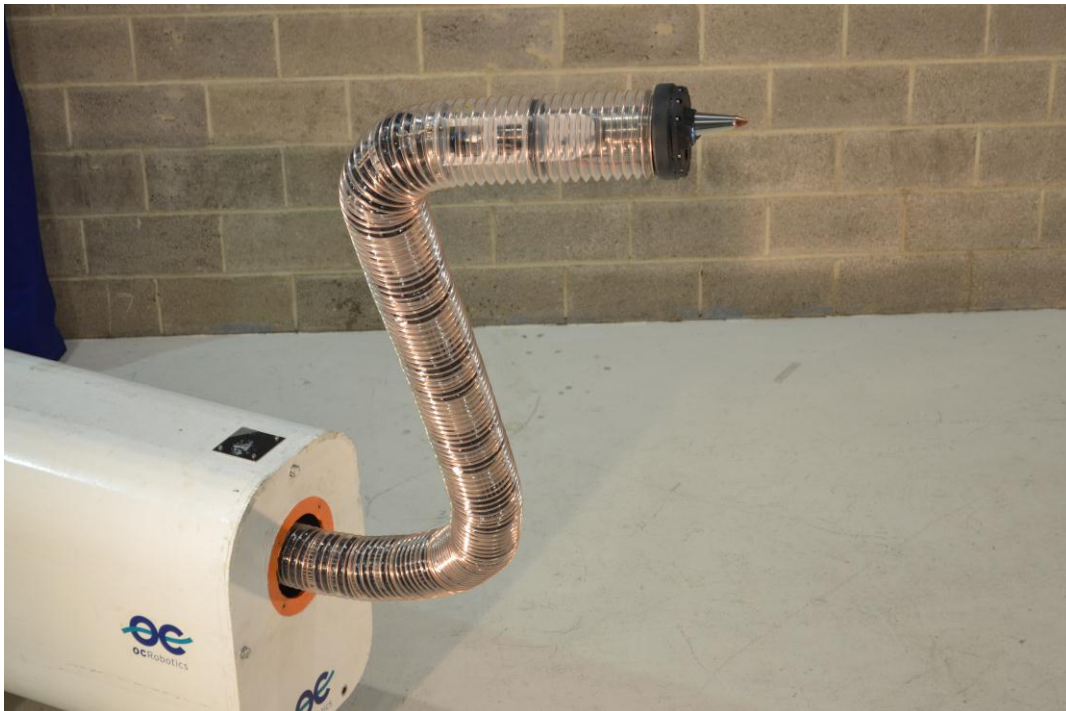


Figure 6 – Laser process head integrated with a Series II snake-arm robot

NNL industrial robot

The NNL has already produced a range of innovative solutions. These include a solution to enable an operator to easily specify, simulate and execute a robot cutting path, which avoids obstacles, yet satisfies demanding cutting parameters. A ventilation solution to remove fume and dross from the cutting, which required design, CFD analysis and testing, has been successfully developed. Integrated

testing and further development enhancements will be performed using a dedicated test rig at NNL Workington, before final deployment and commissioning in the Windscale Laboratory during 2016.

Laser Cutting Trials

Several areas of research have been undertaken to improve the laser cutting process and its application within nuclear decommissioning. The following results have been achieved using conventional off-the-shelf optics, bespoke process heads, novel diffractive optical elements, and a mixture of air and water cooled optical fibres.

Restriction of cutting power (<5kW) may be required where heat transfer from the process head is limited. In this case it is necessary to facilitate cutting of thicker materials using techniques such as gouge cutting, where a groove is progressively deepened in a material by successive passes of the laser beam. Optimisation of parameters including cutting speed, cutting jet pressure, and the addition of a side jet and varying angles, has led to significantly deeper cuts being achieved than in a single pass, Figure 7. Similarly, cutting bonded materials without piercing or inducing too much damage to the lower layer have been proven to be good use cases for this cutting technique.

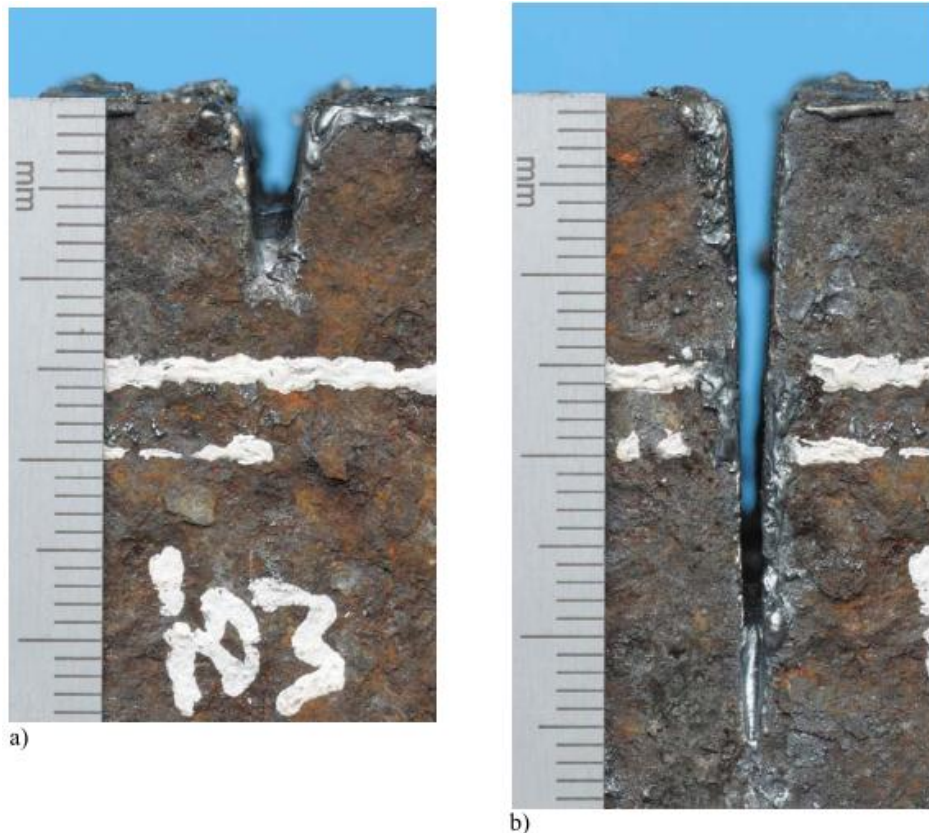


Figure 7 – Gouge cutting results, showing a) single pass, and b) multiple passes [1]

In order to support the safety case for use of high powered lasers on site at

Sellafield, the project has conducted a set of experiments to explore the impact on materials that are not being directly cut. During the time the beam is released, before a cut has taken place, the laser beam will diverge beyond the focal point, reducing in power density with increasing distance. Work has been conducted to measure the effects of these 'stray' beams on materials that may typically be found in a nuclear cell. Steel plates, graphite plate, concrete, fibreboard, fire retardant materials, PVC polymers, and electrical cables, have all been exposed to calibrated 'stray' beams to determine the effects.

Although lower than some hot cutting methods, fume levels produced during laser cutting need to be characterized to understand the size distribution and the potential for blinding ventilation filters, as well as the possible release fraction from the material. The project has undertaken a series of fume trials to determine the mass loss and fume produced from sample materials. Datasets collected include: cutting speed, gas pressure, particle size data, mass loss from test coupon, dross mass, and mass of gathered fume. Analysis of results showed that the key variable to minimise fume release and the impact on the ventilation system, was the process cutting speed.

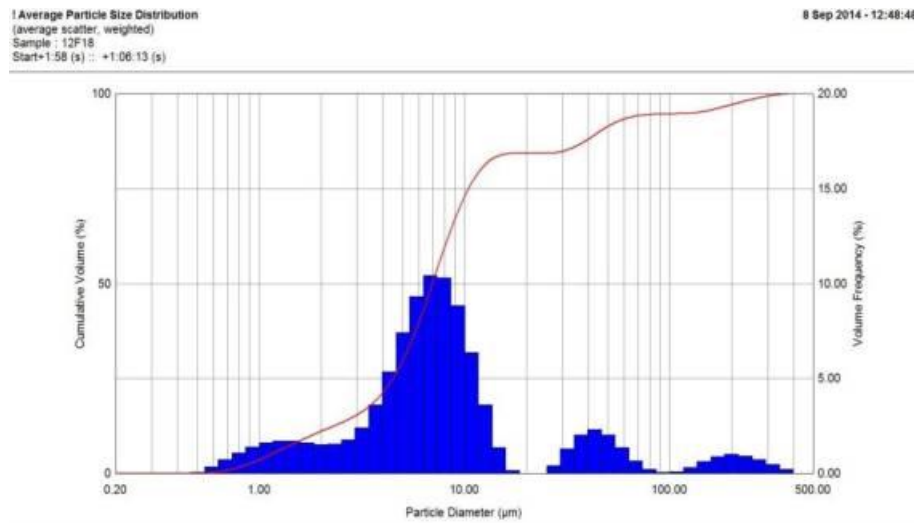


Figure 8 – An example of the particle size distribution recorded from the fume cutting trials.

The final significant area of testing has been multi-skinned cutting. NNL identified a range of containers, lids, vessel walls and sleeves/jackets that are examples of typical multi-skinned components that need size reduction. Using conventional focusing optics TWI established suitable process variables to successfully cut plates of differing thickness and separations, Figure 9.

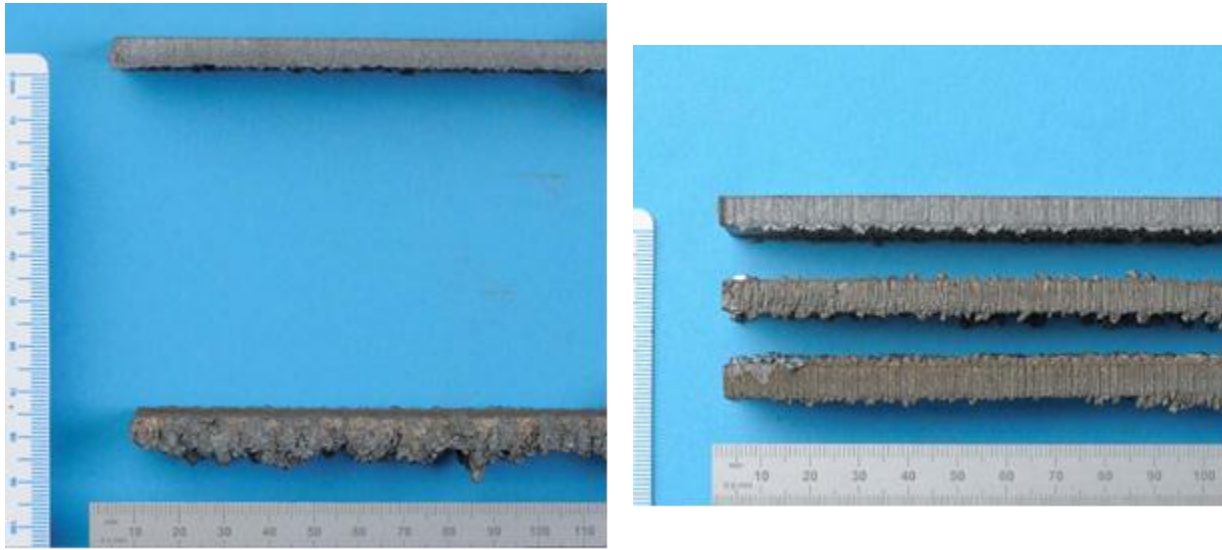


Figure 9 – Samples of double skinned cuts (6mm 304SS, 75mm separation), left, and tripe skinned cuts (6mm 304SS 10mm separation), right [3]

Large scale demonstrations scheduled

Large scale trials are being undertaken during 2016 to demonstrate the advances in the robots and laser cutting during the project. The project has worked closely with Sellafield to find suitable facilities that contain current or near future decommissioning challenges.

Submerged snake-arm robot demonstration

Trials of the 4.5m snake-arm robot in an inactive storage pond will take place in January 2016. The purpose is to demonstrate and further understand the underwater capability of the snake-arm robot to conduct inspection and retrieval operations within a congested underwater environment.



Figure 10 – Vertical deployment of LaserSnake2 system in preparation for submerged trial

LaserSnake2 active laser cutting trials

The snake-arm robot, integrated with the laser process head, will be trialed at TWI Cambridge in Q1 2016, before being installed at the First Generation Reprocessing Plant (FGRP) at Sellafield. Accessing a cell through a 5ft wall and a standard 11" penetration, the system will be used to size reduce a process vessel and support structure, aiming to simplify the removal of waste infrastructure by producing small, easy to transport pieces.

The cell will not be specifically prepared for laser cutting and investigation will be carried out, after the trial, to determine any effects to the surrounding building structure.

CONCLUSIONS

This paper presents the work done to demonstrate the versatility of high powered, fibre delivered laser cutting to dismantle process vessels, pipework and infrastructure within nuclear plants. Two platforms have been configured and developed to deploy this cutting process, both in a dedicated size reduction cell, and on equipment 'in-situ', within the typical process cells found in nuclear sites.

Laser cutting trials have been conducted to develop procedures to achieve extended depth of focus (cutting thick materials), low fume production, and minimized release fraction. Using a 10kW laser, sections of steel up to 100mm have been size reduced. In addition an air cooled fibre and process head have been trialed with the robots for use in situations where water cooling is impractical or undesirable.

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Significant improvements in snake-arm robot design have been achieved throughout the project, yielding increased length (up to 4.5m), bend capability (up to 270degs), payload (up to 10kg), and improved maintainability. These improvements have been demonstrated on a number of systems, providing data on reliability and long term operation to support the safety case for use on nuclear sites.

2016 will see major trials and demonstrations of the technology, including deployment of the LaserSnake2 system at Sellafield within the FGRP, to conduct remote, confined space laser cutting on a stainless steel dissolver.

REFERENCES

- [1] P. Hilton and A. Khan, "New developments in laser cutting for nuclear decommissioning," in *WM2014*, Phoenix, 2014.
- [2] NNL, "www.nnl.co.uk," [Online]. Available: <http://www.nnl.co.uk/media/1593/nnl-tech-conference-presentation-jim-harken-teleoperation-autonomy-may-14.pdf>. [Accessed Jan 2016].
- [3] TWI Ltd, "Development of Multi-Skin Cutting Techniques Phase 1: Preliminary Study," 2013.

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