New developments in laser cutting for nuclear decommissioning

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ABSTRACT 14045

Time, cost and safety are key drivers for nuclear decommissioning. Laser cutting is a technology which has the potential to reduce time, because of the high cutting rates it offers, reduce cost, because the high value laser can be operated remote from the active environment and therefore be used for multiple cutting jobs and increase safety, because of its inherent flexibility for remote deployment by virtue of the delivery of the laser power via optical fibres. This paper will address two new aspects of laser cutting with direct applications in decommissioning and size reduction. These are laser cutting underwater and laser 'gouge' cutting, where, unlike conventional laser cutting, repeated passes, successively gouging a deep groove into the material being cut are used. For underwater cutting a 5kW laser has been used to deliver power via an optical fibre, to a purpose built underwater cutting head. The device relies on creating an air pocket, using compressed gas, between the laser beam and the material surface. 35mm thick steel immersed in water has been cut at a speed of 50mm/min with this system. For the gouge cutting trials, angled laser beams and additional side gas jets have been used to make gouges up to 6mm wide in CMn and stainless steel blocks. Using this technique, it has been possible to laser cut through 12mm of steel, bonded to a concrete base with hardly any damage to the underlying concrete.

INTRODUCTION

Decommissioning of a nuclear facility is a complex process that takes years. The cost of ecommissioning varies greatly, depending on the plant type and size, its location, the proximity and availability of waste disposal facilities, the intended future use of the site, and the condition of the plant and the site at the time of decommisioning. Each decommissioning task can be very different to the next, so an innovative and flexible approach to process deployment may be necessary. In the United States, the estimated average cost of decommissioning a nuclear facility is around US$500 million or approaximately 10-15% of the initial capital cost. In France, the estimated cost of decommissioning a nuclear facility has risen by 26% to €500 million, between 2001 and 2008 and it is likely to increase further [1]. In the United Kingdom, the Government's financial provision for decommissioning rose from an estimated £2 million in 1970 to £67.5 billion by 2013 [2]. It is clear that decommissioning can sometimes be much more expensive than originally budgeted [3].

Many nuclear facilities were construced for fuel processing in varios forms, which contain large amounts of equipment which needs decommissioning. Most of this reqires size reduction for long term storage. A key to reducing the volume of contaminated waste is to improve the efficiency of seperation of material during decommissioning. Future decommissioning of nuclear facilities will make increasing use of non-contact remote cutting techniques, some of which are currently in use and considered state-of-the-art. They can be grouped into, A) mechanical (sawing, shearing, milling, diamond wire sawing, etc). B) thermal (oxy-fuel, thermic-lance, plasma-arc, laser beam, etc), and C) hydraulic (water jet and abrasive water jet, shears) [4-8]. Some of these techniques are also applicable underwater. When applied underwater, generally radiation protection is improved, but visibility in the cutting area is reduced [9].

Each cutting techniques has its advantages and disadvantages. However, at present contractors mostly use mechanical techniques, because they have abundant knowldge and experience in using these tools. Neverlesess, as the complexity, urgency and cost of dealing with ever increasing challenges in decommissioning increases, organisations responsible for decommissioning operations are looking for more innovative techniques to deal with the problem. What is needed is a highly automated remote technology that can deliver a non contact smarter dismantling process, cut most materials, cut complicated structural geometries, produce minimum secondary emmissions, deliver high throughput at large operating distances, requires minimum deployment effort and maintanance and be flexible enough to be reused in many decommissioning processes.

Laser cutting is one such technology that meets many of these decommissioning requirements. In the past, various high power lasers have been used to demonstrate cutting of thick-section metallic materials for nuclear decommissioning applications, where constant power density and nozzle standoff distance to the substrate were usually maintained. These included CO_2, CO, COIL and Nd:YAG lasers [10]. Some of these lasers have also been researched for other decommissioning applications such as surface cleaning and concrete scabbling [11, 12]. All lasers offer unique capabilities, but the flexibility offered from solid-state lasers, employing optical fibre delivery of the laser power, reduces complexity and risks. Development of high power *disc* and *fibre* lasers, coupled with improvement in beam delivery, thermal management of the system and multiple channel output, have further enhanced decommissioning capability, by providing scalable power in the multi-kilowatt regime with significantly better beam quality. Furthermore, the high value asset, which is the laser itself, can be situated and maintained in a safe clean area, some 100s of meters away, thus allowing the system to be reused for several other decommissioning applications. However, commercially avialable laser technology has not yet mutured enough to cut extremely thick materials effectively, such as a reactor vessel, which require special considerations. Nevertheless, current laser technology, at modest powers, is well capable of cutting material in exccess of 50mm in thickness. Significant numbers of pressure vessels and dissolvers with wall thickness below 50mm and tube networks with wall thicknesses of 10mm and below and diameters up to 100mm exist.

One particularly interesting application is the size reduction of containers, previously used to store waste fuel. These particular containers were initially welded together from CMn (Carbon Manganese Steel) (in thicknesses from 6mm to 12mm) and subsequently painted with a layer of epoxy based paint. Empty irradiated containers are now taking up so much space in ponds, that there is a requirement to remove these, size reduce them and pack the resulting parts in a similar container, before returning everything to the pool for long term storage. Clearly it would be beneficial to get as many size reduced containers as possible into the receiving container. TWI has developed a laser cutting sequence to size reduce such a container, so that the parts from four containers may be placed comfortably in a single container. For both the tube, plate and the container cutting described above, the cutting heads were held in the arm of an articulated robot, which was programmed to follow a selected path. This is a convenient method in the laboratory, to demonstrate remote manipulation of a laser cutting head.

This paper will address two new aspects of laser cutting with direct applications in decommissioning and size reduction. These are laser cutting underwater and laser ‘gouge’ cutting, where, unlike conventional laser cutting, repeated passes, successively gouging a deep groove into the material being cut are used. For underwater cutting a 5kW laser has been used to deliver power via an optical fibre, to a purpose built underwater cutting head. The device relies on creating an air pocket, using compressed gas, between the laser beam and the material surface. 35mm thick steel immersed in water has been cut at a speed of 50mm/min with this system. For the gouge cutting trials, angled laser beams and additional side gas jets have been used to make gouges up to 6mm wide in CMn and stainless steel blocks. Using this technique, it has been possible to laser cut through 12mm of steel, bonded to a concrete base with hardly any damage to the underlying concrete.

The laser cutting technique is a thermal process which generates significant amounts of heat. For laser cutting to be used in nuclear decommissioning the safety case needs to be established. Two issues which are of primary concern are a) the heat generated and its potential to cause fires and b) how to protect against the effects of the laser beam energy which passes through the cut, and subsequently impinges on anything positioned below the component being cut, or indeed the walls of the cell in use. The safety case will not be mentioned again in this paper but work is currently on-going, to quantify and minimise these effects, as well as study the fume and aerosols generated during laser cutting. Useful data on fume generation from laser cutting can be found in ref [13].

LASER SOURCES AND EQUIPMENT USED

Industrial high power carbon dioxide lasers (CO_2) became available in 1970. One of the earliest in the UK was installed for the Thorp plant at Sellafield, in the UK, for a welding and cutting operation on product containers. Since this time, the CO_2 laser has become the workhorse for many industrial applications, notwithstanding its relatively low power conversion efficiency, size, high consumption of gases, and its use of complex rotating pumps and vacuum systems. The main reason for this is that until recently, there has been no viable alternative technology, particularly for powers greater than 3000W. More recently, however, compact high power lasers operating in the near infra-red, have become available, with the introduction of high power fibre and disc laser technology. In a fibre laser, the lasing medium is a small diameter optical fibre suitably doped, such that when pumped with diode laser power, lasing action is created in the optical fibre. The laser resonator is completed by machining diffraction gratings inside the fibre, to reflect laser light and pass some of this light out (through the same optical fibre) to form a usable beam. A typical laser module as previously described, would have a power of up to 800W. To increase the available power, multiples of the units are simply bundled together using fibre splicing techniques. Using this assembly method, lasers up to 50,000W in power are now commercially available. In a disc laser, the light is generated in a thin disc of material, suitably cooled and also pumped by laser diodes. A more conventional resonator then produces the laser beam which is focussed onto the end of the delivery fibre.

The fibre and disc laser technology has many advantages when compared to carbon dioxide laser technology. The efficiency in converting electrical power to optical power is of the order three times higher than carbon dioxide lasers. The new lasers contain no moving parts at all, use solid state technology and as a result, are robust and compact in size. As the beam is generated in an optical fibre, several fibres can be used to carry the beam to the workpiece, thereby increasing the flexibility of the system and providing an opportunity for remote processing. An indication of the reliability and efficiency of these types of laser source is their uptake in the German automotive industry for seam welding of car bodies, as alternatives to resistance spot welding. Another important factor in laser processing is the ‘beam quality’ of the laser. This is a measure of how small a spot size can be formed from a given lens. The fibre and disc lasers have the high beam quality necessary for laser cutting applications, which require high power densities. The technology is highly reliable and is considered to be the closest approach available to the concept of a laser simply as a black box power source equipped with a tap, which when turned on, performs the required process. In addition, all the technology required to switch the laser beam from one process head to another, down the flexible but armored optical fibres is well tested, commercially available and already in use in the highly demanding automotive manufacturing sector. The combination of high beam quality, available power and beam switching, therefore offers the capability of a single laser source to address more than one type of process application.

In the work described here a 5kW fibre laser, manufactured by IPG Photonics was used. This had a 30m 150 micron diameter optical fibre to deliver its power to a cutting head. The cutting heads used were of TWI design and employed either 250mm or 500mm focusing lenses. The lenses were protected by flat ‘coverslides’ coated (as were the lenses) to maximize transmission of 1 micron light.

UNDERWATER LASER CUTTING

Introduction

The desire and motivation for dismantling medium to high level nuclear waste underwater, is to significantly reduce contaminants escaping into the atmospheres and eliminate the logistics of handling and transporting such waste from the pond to the processing area. There is an increasing interest, particularly in the UK, to acquire an underwater cutting technology that could be versatile enough to both size reduce and decommission such waste. The primary benefits of dismantling nuclear waste underwater are to minimise production of secondary waste and reduce the complexity of remote operation. Currently, there are three underwater cutting technologies considered for dismantling structures in the nuclear industry:

1. Abrasive Water Jet: This technology is capable of cutting variety of materials, in varied depths and in thick-sections but it is inherently slow and produces significant secondary waste in the form of contaminated abrasive.

2. Diamond Wire Sawing: This technology is frequently used by oil and gas industries for dismantling of extremely large structures and can be used at extreme depths. However, such machines are large, heavy and contain complicated mechanisms for traversing the wire. The cost of deployment, running and final decommissioning of such cutting systems in nuclear decommissioning operations restricts the use of this technology in this sector.

3. Plasma Arc: This technology has proven itself to be cheap and reliable in cutting metallic materials, but mostly on planner geometries and it is used by the nuclear industry as well as the oil and gas sector. However, its use is inherently limited by standoff distance and electrically conductive and flat material geometries. Furthermore, the process produces a high level of secondary waste, and requires frequent nozzle changes, increasing operational time and costs.

Laser technology, especially with recent development in fibre delivered beams, could offer a fourth choice to the nuclear industry. Because of the attenuation of fibre delivered laser light in (dirty) water, the approach taken in the work described below was to design a cutting nozzle that would create a ‘dry’ zone in the immediate area of the interaction of the laser beam with the material being cut.

System Design and Testing

Figure 1 shows a schematic of the underwater ‘nozzle’. This system was designed to add to an existing 250mm focal length cutting head. The housing was designed so that the position of the nozzle tip of the cutting head could be moved up and down with respect to the external housing. This facility allowed changes to be made to the cutting nozzle tip to workpiece stand-off distance, without changing the position of the focusing laser beam. In this way, the beam focus position, with respect to the surface of the material, remained constant as the stand-off distance varied. The external metal housing, which separated the water from the air space, could be replaced using a Perspex sleeve, so that it was possible to see the effect of the various air streams applied to sections inside the housing. The purpose of these air steams was to pressurise the inside of the housing removing the water inside and maintaining a dry zone, both at the cutting point and for the laser beam emerging from the cutting nozzle tip. The system provided:

1. A primary high pressure gas jet which flowed in the central of the system, co-axial with the laser beam (as found in conventional cutting heads).
2. A secondary annular gas nozzle surrounding the central cutting nozzle tip. This was designed to provide a first dry zone and minimise dynamic instabilities in the primary central high pressure cutting gas jet.

3 A tertiary static gas pressure chamber (the housing itself), to promote a much larger dry zone, provide an equilibrium pressure gradient between the primary and secondary gas jets, and in addition, prevent nozzle tips (and optics) from water and contamination.

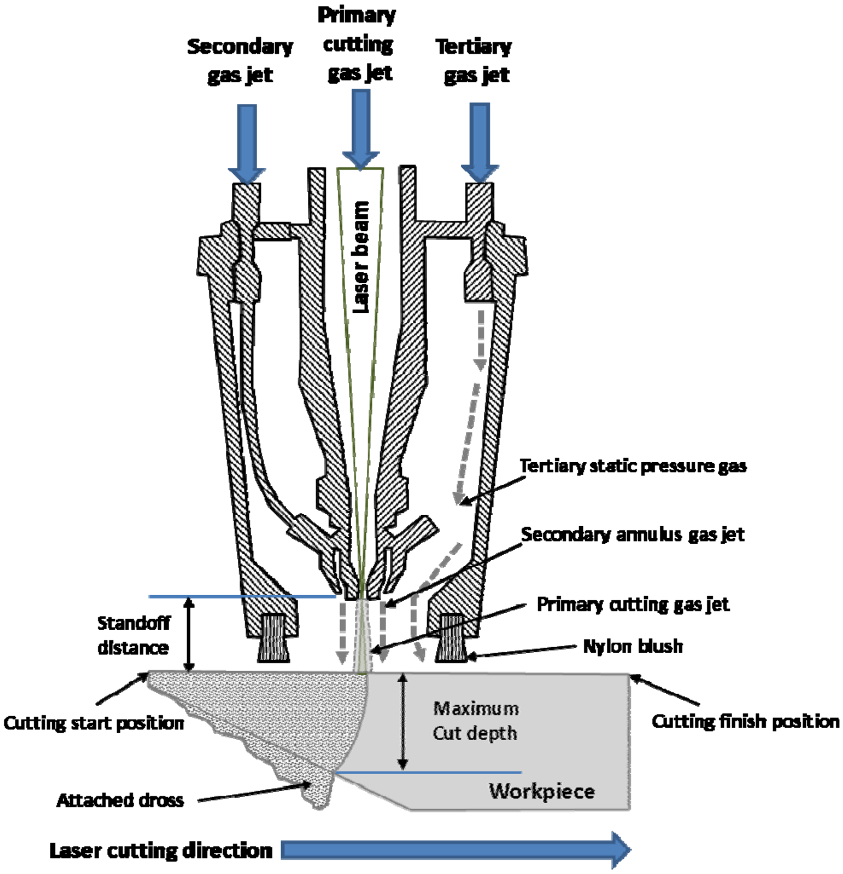


Figure 1 Underwater laser cutting process schematic.

The unit was tested with various different gas pressures in the three delivery systems. Compressed air was used for these trials and for all the cutting trials reported subsequently. In use the unit was used inside a 1m^3 water tank with glass sides and the cutting head was manipulated via a robot arm.

In order to minimise the number of initial cutting trials, a 60mm thickness S355J2+N C-Mn steel plate was flame cut into a 45^o wedge. Simple linear cuts across the wedge shaped section, made with the laser beam axis pointing vertically downwards, were performed to assess the maximum cut depth attainable for cutting speeds ranging from 50 to 1000mm/min. For each cutting speed, the secondary and the tertiary gas supply was maintained at constant pressure, whilst the primary central gas pressure (from now on referred to as the assist gas pressure) was varied between 2 and 8bar. In addition, for each combination of cutting speed and assist gas pressure, 4 stand-off distances (cutting nozzle tip to plate surface distance) were tested, ranging from 15 to 30mm. The standoff distance described here was the distance between the tip of the primary gas jet and the workpiece. The standoff distance between end of the nylon brush and the workpiece was kept constant (~2mm) for the initial cutting trials. The emphasis in these experiments was to assess the effectiveness of the assist gas jet underwater. A constraint in the underwater cutting head design was the fixed laser focal position of 15mm above the material surface. For the 250mm focal length lens in use, this equates to a calculated laser beam diameter of 1.1mm on the material surface. In all the laser cutting trials, a constant laser power of 4.8kW was used and all cuts were performed with the samples at a water depth of 200mm.

The underwater cutting procedure consisted of first charging the secondary and tertiary parts of the cutting head with compressed, when the nozzle assembly was located outside the tank. This procedure was seen to maintain the dry zone and also kept all optical surfaces from splashing with water. The robot was first programmed to index the nozzle and the cutting head to the start position relative to the workpiece, ensuring the chosen distance between the brush seal and the workpiece was always maintained by pre-programming the robot movement and performing a simulated cut without the laser and the assist gas jet. Just before commencing the cutting process, the laser beam and the assist gas jet were activated. This procedure was repeated for each set of parameters. For each parameter set, kerf width and maximum cut depth were measured, and the data recorded.

Following these trials, further plate materials were cut immersed in water, at selected process parameters. For comparison to performance cutting in air, the underwater housing was removed and the same materials were re-cut in air at the same process parameters.

Results

Figure 2 shows a comparison of the maximum cutting depth achieved for the underwater cutting processes for primary (co-axial) cutting assist gas pressures of 2 and 8bar as a function of cutting speed. The figure also includes the same data for in air cutting.

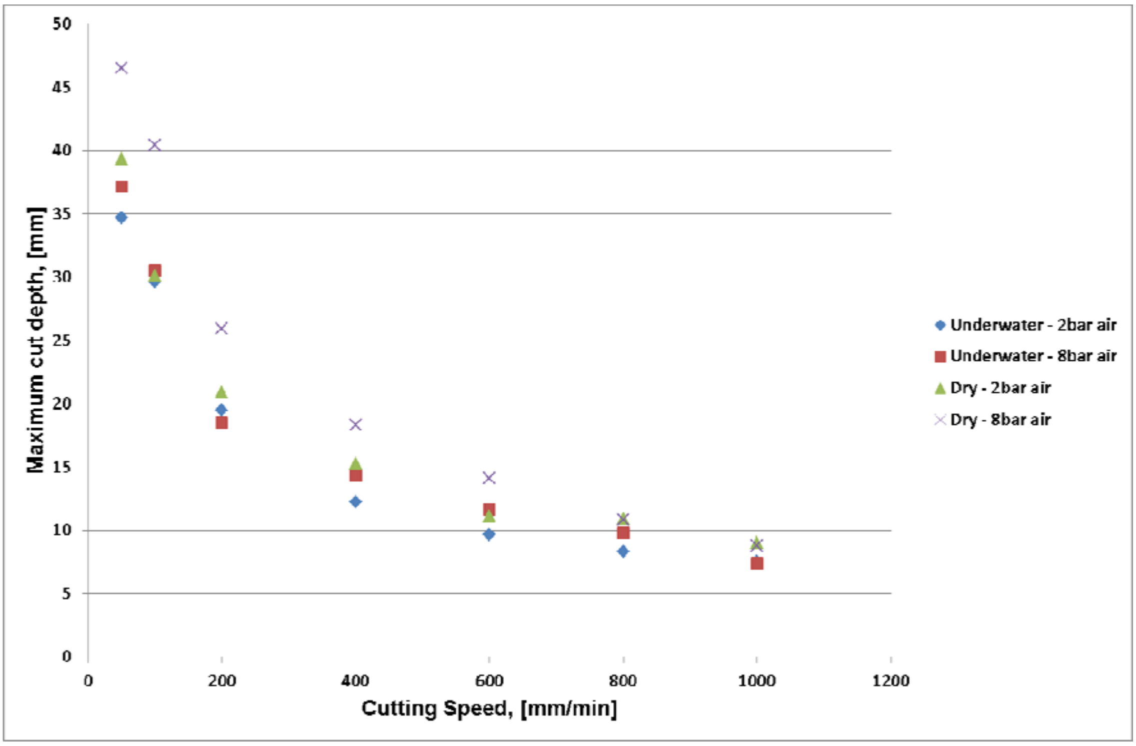


Figure 2. Maximum cut depths achieved for the underwater and in-air cutting processes as a function of cutting speed using 2 and 8bar coaxial assist gas pressures, using 4.8kW of laser power with a standoff distance of 15mm.

This figure shows that at low cutting speeds, the in-air performance is better than the underwater performance, but the difference gets smaller as the cutting speed increases.

For a comparison of edge quality between in-air and underwater cutting of a 15mm thickness C-Mn steel plate, a cutting speed 360mm/min was used. Sections of the 15mm steel cut using this speed with 4.8kW of laser power, at standoff distance of 15mm and gas pressure of 8bar were used. Figure 3 shows the cut edge comparison between the two processes. As can be seen the underwater sample has a very large amount of dross attached to the bottom of the kerf, and the striation patterns are very different to what one would see cutting in air.

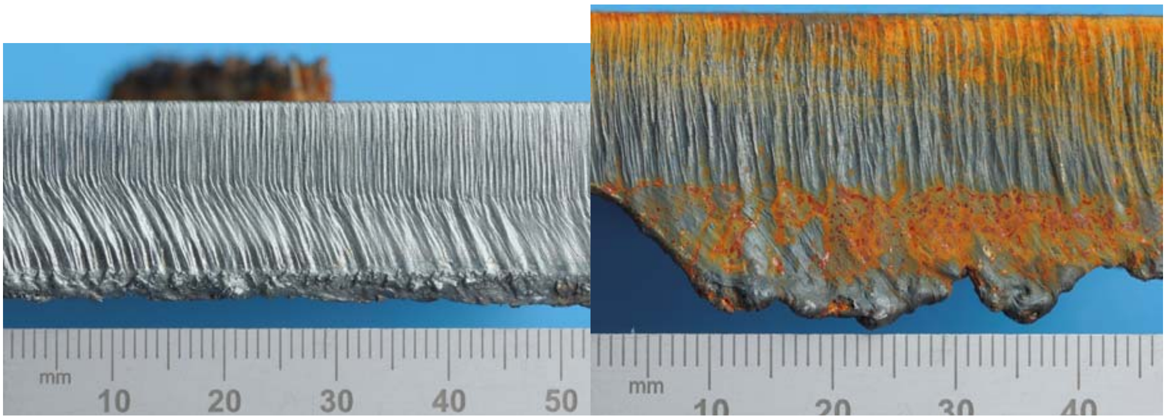


Figure 3 Shows the edges of 15mm S355 C-Mn steel plate cut underwater (right) and in-air (left) at the parameters described in the text.

Figure 4 shows the cut edges of 3 plate samples, all cut underwater using 4.8kW of laser power.

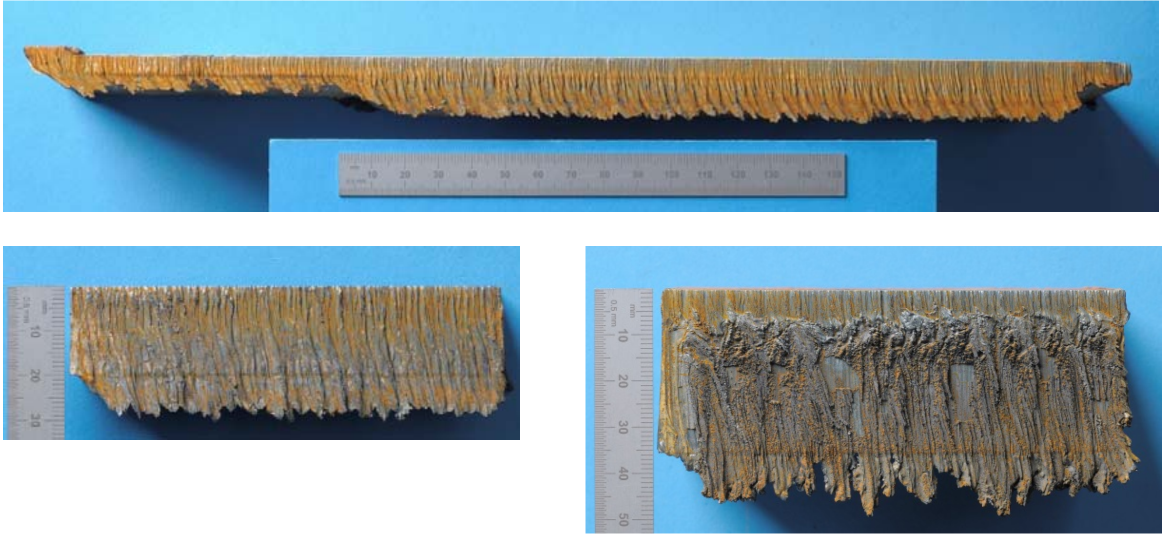


Figure 4 Sections of underwater laser cut samples:
Top: Variable thickness (6 to 12mm) S275JR C-Mn steel plate cut at 500mm/min;
Lower left: 20mm thickness S355J2+N C-Mn steel plate cut at 200mm/min;
Lower right: 35mm thickness S355J2+N C-Mn steel plate cut at 50mm/min.

Figure 5 shows the underwater cutting head in operation in the tank, cutting 12mm thick stainless steel plate. The image was photographed through the glass wall of the tank.

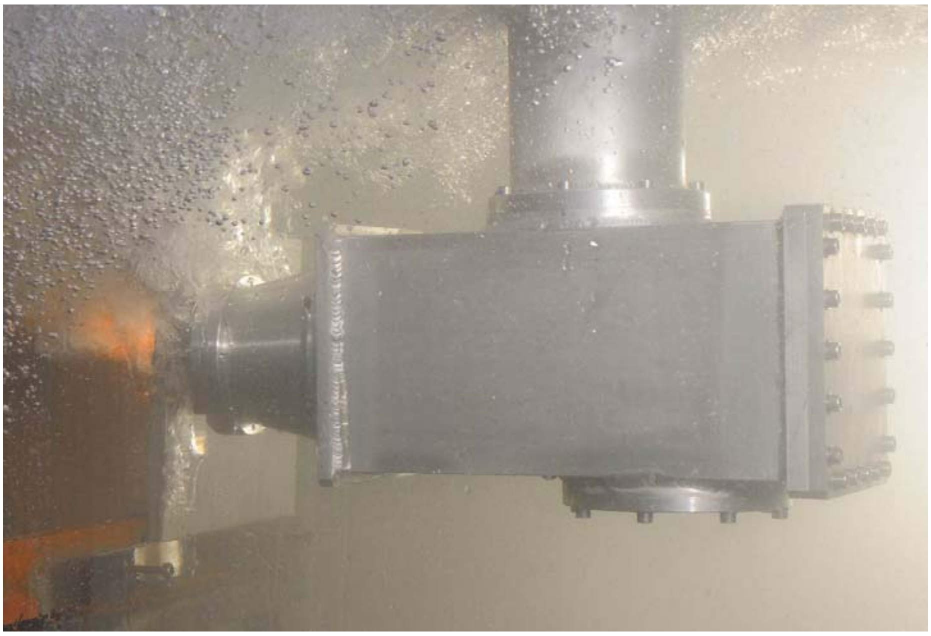


Figure 5 The underwater laser cutting unit in operation

Discussion

It is encouraging to note that this ‘underwater’ laser cutting process works very well. Cutting speeds are lower than for in-air cutting (at low cutting speeds ie higher plate thickness) presumably due to the heat sinking effect of the surrounding water. However, at the higher speeds (lower thickness materials) there is little difference in cutting speed, at least at the modest laser power of 4.8kW used here.

The most significant result is the dross attachment, which is high in the case of the underwater work. This is quite significant for decommissioning as for size reduction it is better that the material removed from the cut kerf is left attached to the parts after separation, rather than this being blown into the water to condense and solidify, eventually to accumulate at the base of the pond. Further work is on-going to quantify what proportion of the material removed from the kerf re-solidifies at the base of the cut. It is clear already that the amount of dross attached at the kerf exit with the underwater process increases with material thickness and when using a lower cutting gas pressure.

In this work, generally higher assist gas pressure produced a smaller kerf width and the largest kerf width was produced at the highest stand-off distance used, of 30mm. This may indicate a variation in the laser beam diameter (laser power intensity) on the material surface due to possible variations in the refractive index of a mixed phase (water vapour (steam) and air) medium inside the kerf width.

‘GOUGE’ LASER CUTTING

Introduction

In conventional laser cutting, the laser beam incident on a plate surface has sufficient energy density to produce a molten capillary of material extending the through thickness of the plate. An assist gas-jet, applied co-axially with the incident laser beam, blows the molten material out of the base of the cut, in order to separate the material. Using carbon dioxide lasers, conventional commercial laser cutting of steel can address thicknesses of the order 20-25mm, with good edge quality. Using fibre or disc lasers, this

maximum thickness is currently lower, mainly because one micron laser sources have great difficulty in producing the cut quality that can be achieved by carbon dioxide lasers, when cutting thicker sections. These figures above are typical of those produced by lasers in the power range between 5 and 7kW.
For decommissioning applications, it might be necessary to address the cutting of thicker materials using modest (say 5kW) laser powers. One way to do this is to use the laser beam to cut a groove in the material to be severed and then increase the depth of this groove by successive passes of the laser beam, until complete penetration of the material is achieved. This technique has been given the term ‘gouge’ cutting and this report details preliminary trials, made using a 5kW fibre laser source and TWI designed cutting heads, in order to achieve this particular type of laser cutting. In this work, ‘gouge’ cutting is achieved using an additional ‘side’ gas jet to blow away molten material from the top of the plate being cut.

Experimental arrangements

The arrangement of the cutting head with its two gas jets can be seen in action in Figure 7.

Figure 7 The lower end of the gouge cutting head, showing the conventional co-axial assist gas/beam delivery nozzle and the side gas jet. In this case the side gas is delivered through a narrow stainless steel tube so that, as successive cuts are made, the end of this nozzle can descend into the cutting groove.

With this arrangement there are a great number of experimental variables to investigate. These are summarised in Table 1 below. During the experiments however the following additional parameters were fixed: Laser power at 4.8kW, cutting gas was compressed air. The diameter of the co-axial gas nozzle tip was 6mm, the beam was focussed with a 500mm fl lens and the position between the laser beam focus and the co-axial nozzle tip was 15mm.

Designator	Definition
Angle alpha	Angle between the surface of the material and the axis of the laser beam, degrees
Angle beta	Angle between surface of material and axis of side gas-jet, degrees
Z	Adjustment of side-jet with respect to cutting nozzle, mm
d1	Nozzle tip (laser) to material being cut distance, mm
d2	Nozzle tip to material surface distance, (side-jet), mm
NP	Cutting nozzle gas pressure, bar
SP	Side-jet nozzle gas pressure, bar
V	Cutting speed, m/min

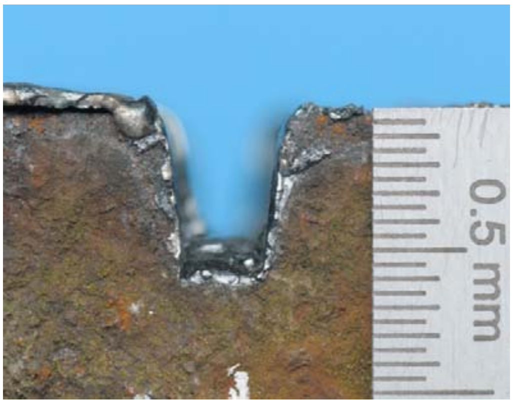
Table 1 Experimental variables for the gouge cutting trials

Cuts were made across the width (50mm) of a series of carbon manganese steel blocks, as can be seen in Figure 7. Parameters were first varied with the objective of achieving a clean gouge with a profile as close to 'U' shaped as possible. After finding the best set of conditions, attempts were made to increase the depth of the gouge, by repeated passes of the laser beam and moving the cutting head down into the cut in given increments. For cutting with the side gas-jets, most work was conducted with the direction of motion of the cutting head in line with the pointing direction of the side-jet. A few cuts were attempted with the cutting direction against the direction of the side-jet.

Following this work, trails took place on a 12mm thick CMn steel plate bonded to a block of concrete, with the objective of gouge cutting through the steel, without significantly damaging the underlying concrete.

Results

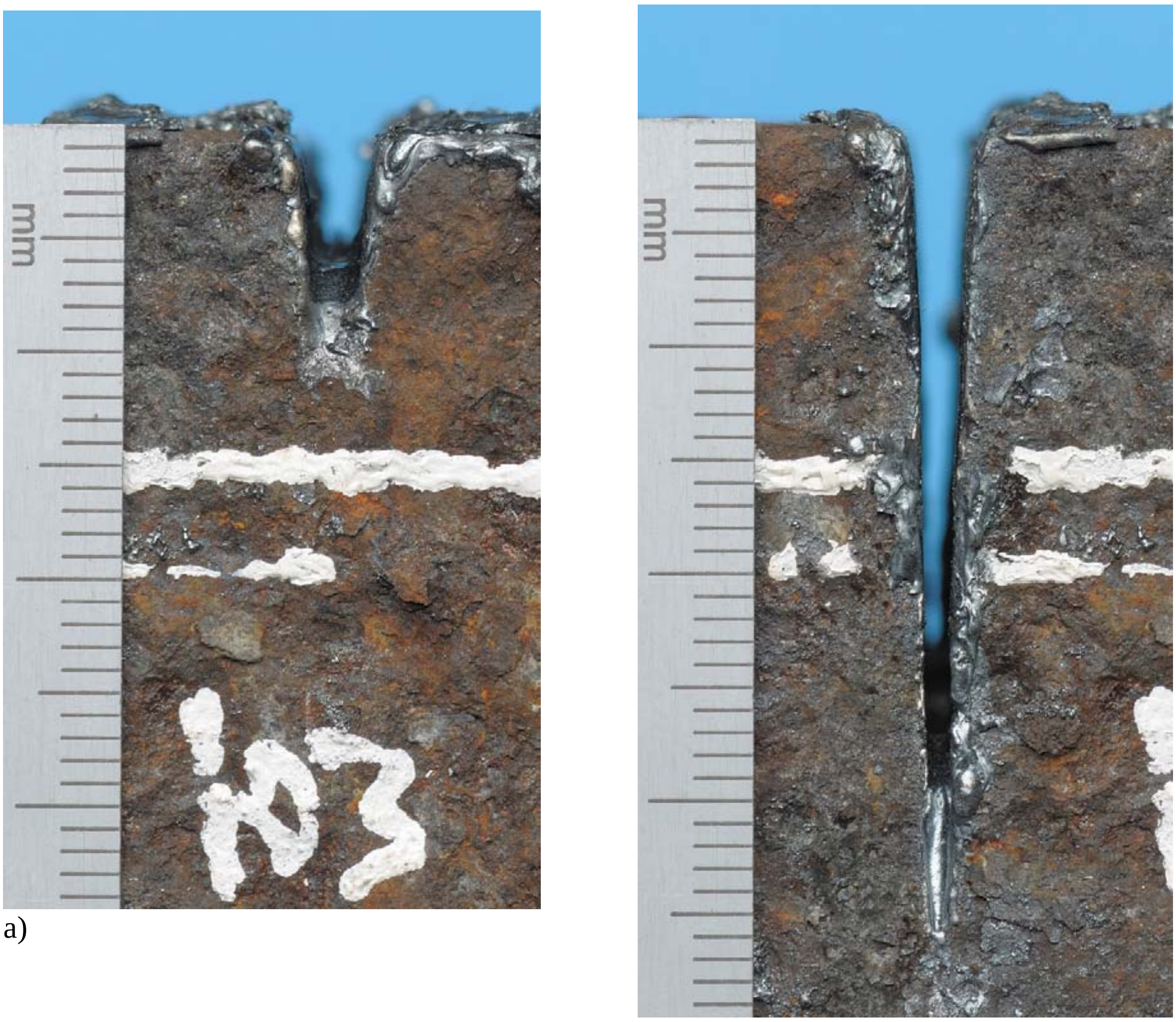
Figure 8 shows a side view of one of the best single-pass gouge cuts, obtained with angle alpha at 67 degrees. The experimental conditions associated with this cut are provided by the side of the photo. The resulting groove was approximately 4.5mm wide at the top and 6mm deep. The travel speed was 0.8m/min. The photograph indicates the desired 'U' shape at the base of the groove. Significant amounts of molten material from the cut could be seen deposited on the top of the cut but only on one side. Examination of the top of other cuts from this series indicated that, on many instances the molten material from the groove had re-solidified in the groove, almost like a 'wave' adhering to one side of the cut. Relative changes in gas pressures and cutting speed had little effect on the cut.



Alpha	67 degrees
Beta	30 degrees
d1	100mm
d2	25mm
Z	0
NP	5 bar
SP	8.6 bar
P	4800W
V	0.8m/min

Figure 7 Profile of a single-pass gouge cut at a speed of 0.8mm/min

Based on parameters similar to those above, it was decide to attempt deeper cutting using multiple cuts. Figure 8 shows a side view of a single gouge made using the stainless steel side-jet nozzle and by its side, the result of several passes over a gouge made using the same parameters but successively dropping the height of the whole cutting head assembly.



a)

b)

Figure 8 Comparison of cutting using the stainless steel side-jet:
a) Single gouge;
b) Multiple gouges.

As can be seen, a depth of close to 30mm was achieved, using eight passes, each time dropping the cutting head by 5mm. After eight passes the cutting was stopped as the side nozzle was in danger of fouling on the sides of the cut. In addition, it became clear that the process appeared to self-limit, as the number of passes increased.

Figure 9 shows the results of gouge cutting a 12mm thick CMn steel plate attached to a concrete block using a set of parameters which produced a maximum gouge 14mm deep in a single pass.

The cutting speed was varied until the condition was found where a single pass of the cutting head, separated the steel plate, with little damage to the underlying concrete. Figure 10 shows a view of the steel on top of the concrete for this condition, with one half of the steel removed. Figure 11, shows the effect on the concrete with both pieces of steel removed.

Figure 11 Gouge cutting of 12mm thick CMn steel on top of concrete, with minimum damage to the concrete surface.

Figure 12 Effect on the concrete surface after removal of the steel.

Discussion

It is clear that using a side gas-jet as well as a co-axial gas-jet during cutting can result in a clean removal of material in order to produce a gouge in high thickness material. In the trials completed, cutting a single, one pass gouge was significantly easier than multiple pass cutting. The latter was affected by a), the width of the cut as the cutting depth increased and b), an apparent reduction in efficiency, in terms of the amount of material removed, again as the depth of the cut increased.

Some of this work was conducted with the laser beam axis perpendicular to the samples being cut. This would probably be the most convenient orientation to maintain in any practical cutting application and would also provide the opportunity to simply rotate the cutting head after one cut and return cutting in the opposite direction. In this orientation, grooves, however, were decidedly ‘V’ shaped. This is most likely due to the distribution of energy in the incident laser beam, (fairly Gaussian at the point of interaction with the material). However, it would appear that the best single gouge, in terms of producing a consistent width down the kerf, was when the head was at an angle of 67 degrees to the horizontal. At reduced angles, the incident laser beam profile as seen by the material will be elliptical in shape, with part of the beam falling on the leading edge of the melt front keeping it molten and viscous, which might promote a more efficient melt removal.

In these trials, no attempt was made to produce a very systematic approach to parameter changing, rather than to try initially to obtain a more general feel for this new cutting technique. One effect of this is that it is difficult, from the existing data, to draw significant conclusions as to which of the experimental variables has a significant effect on the cutting process. Nozzle gas relative pressures and nozzle orientations as well as cutting speed, would seem to be the important variables.

Although in this phase of the work, it was not possible to cut any deeper than about 30mm using a repeated gouge technique, a clean gouge could be made up to 14mm deep in a single-pass. This opens up the opportunity for the cutting of steel plates attached to concrete surfaces, with the possibility of achieving this with minimal damage to the underlying concrete.

CONCLUSIONS

Underwater Laser Cutting

- Laser cutting of material up to 38mm thick immersed in water has been demonstrated using a laser power of 4.8kW. The travel speed was 50mm/min.
- This was achieved using compressed air to create a local ‘dry-zone’ in the region of the cut.
- When the available underwater cutting speeds for various thicknesses of material are compared with those available in–air at the same power, at low speeds in-air cutting is approximately 22% faster but by a speed of 800mm/min, this difference has fallen to 10% (at 8 bars assist gas pressure).

Gouge Cutting

- Using a combination of side gas-jet and co-axial gas-jet, it was possible to produce a clean laser cut ‘gouge’ with a cross sectional area of 26mm,^{2} on a block of CMn steel, at a travel speed of 0.8m/min and using a laser power of 4.8kW.
- At perpendicular laser beam incidence, the resulting groove is more ‘V’ shaped than with the beam angled at 67 degrees to the surface of the material being cut, where the groove profile is more ‘U’ shaped.

- Decreasing the travel speed increases the depth of the groove.
- Multi-pass cutting in this work was limited to 30mm, felt due to a combination of narrowing of the groove with cutting depth and less efficiency of material removal with cutting depth.
- Using this technique it was possible to laser cut a 12mm CMn steel plate attached to a concrete block, without significant damage to the underlying concrete surface.

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