UNDERWATER LASER CUTTING: AN APPLICATION TECHNOLOGY FOR DISMANTLING AND SIZE REDUCTION OF IRRADIATED NUCLEAR STRUCTURES

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ABSTRACT

In nuclear power plants, most Intermediate Level Waste (ILW) and High Level Waste (HLW) are stored underwater after service. Due to restrictions in storage space and increased risk of dose uptake during handling, the use of underwater cutting technology for dismantling or size reduction is often preferred. This paper describes the development of underwater laser cutting technology for size reduction of C-Mn and 304 stainless steels. A special cutting head was developed, to create a localised dry area between the cutting nozzle and the material being cut. A commercially available 5kW laser source, operating at 1 micron wavelength, was used to establish cutting performance. Compressed air, with a maximum pressure of 8 bars, was used as cutting gas, to identify the maximum underwater cutting speeds for a range of material thicknesses. It was possible to separate material up to 35mm in thickness with a moderate laser power of 5kW. Comparative results to cutting in-air, using the same optical equipment, are also presented and it shown that underwater cutting with a laser presents some benefits in terms of an increased amount of material remaining solidified at the base of the cut, after separation of the material.

1. Introduction

The desire and motivation for dismantling medium to high level nuclear waste underwater is to significantly reduce contaminants escaping into the atmosphere and eliminate the logistics of handling and transporting such waste from pond to processing area. There is an increasing interest in the nuclear sector, 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 in water 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 in a water sludge.
2. **Diamond Wire Sawing:** This technology is frequently used by oil and gas industries for dismantling of 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 removal 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, due to considerably large kerf, 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 optical fibre delivery of the beams, could offer a fourth choice to the nuclear industry. Various laser sources such as CO_2, Coil and YAG have been used to demonstrate their potential in underwater cutting applications [1, 2, 3 & 4]. A laser beam delivered via fibre optic offers considerable benefits in terms of flexibility of manipulation of a cutting head and depth of operation. It has been reported that the volume of sedimented dross produced in cutting using a fibre delivered pulsed YAG laser beam was much lower compared to cutting with a CO_2 laser source, and the dross particle size generated by the pulsed YAG laser was two to three times smaller [1]. In this case, the comparison was for underwater cutting with oxygen. However, underwater laser cutting using compressed air and continuous wave, rather than a pulsed laser beam, has shown to result in further reduction of sedimented dross at the bottom of the tank, [3]. Therefore, the use of the current generation of high power and high beam quality continuous wave fibre and disc laser sources, may provide further benefits in terms of both cutting capability and dross reduction when cutting metallic structures underwater.

This paper reports on underwater cutting using a fibre laser source [5], on S355JR+N mild steel, in terms of available cut depth and speed and compares these results to trials conducted in air. In addition, results of dross retention underneath the material for 6, 12 and 32mm thickness S275JR mild and 304 stainless steel, are also reported.

2. Experimental

To construct the underwater cutting head, the optics from a conventional laser cutting head were used to collimate and then focus the laser light emerging from the delivery optical fibre. Although the mounts for these optics are ‘O’ ring sealed against dust, their performance underwater is not known. As a result, for these experiments, it was decided to house the cutting head in a protective sealed shroud, as one might do when using a underwater camera, but in this case made from aluminium. This also offered an easy possibility of bringing the beam delivery fibre to the collimating optic without getting it wet. Further modifications included the addition of special nozzle on the end of the cutting head, which, by means of streams of compressed air, removed water from the region of the cutting point. A purpose built water tank with capacity of $1m^3$, with a suitable sample holder, was used for all underwater cutting trials. The cutting head, which was submerged in about 600mm of water, was made to traverse across a stationary workpiece using a 6-axis Kawasaki robot. A multi kilowatt Yb fibre laser, with 0.15mm core diameter delivery fibre was used in these trials. A 3mm thick fuse silica cover-slide was used to protect focusing optics from contamination.

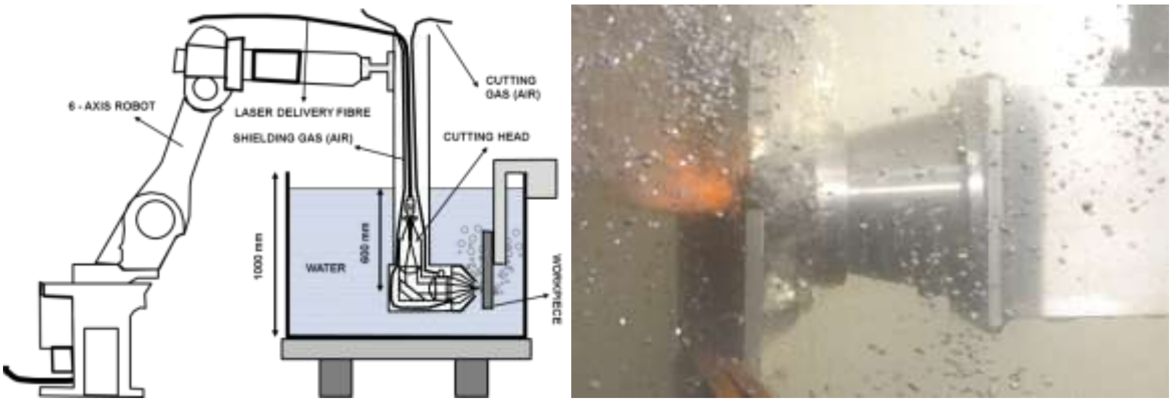

Fig.1. Schematic of the setup for underwater cutting trials (left), and an image of underwater laser cutting of a 12mm thick stainless steel plate.

Two compressed air supplies were used during cutting. The first was concentric to the focussing laser beam and exited through a cutting nozzle tip of diameter 3.5mm. The primary purpose of this gas stream (henceforth referred to as the cutting gas) was to blow away molten material from the cut kerf. A secondary stream of compressed air was provided on the outside of the cutting nozzle, which exited via an annulus between the cutting nozzle tip and a circular wire brush seal. The primary purpose of this secondary gas jet was to support the formation of a local 'dry' zone in the region of the cut. A schematic of this experimental set up is shown in Fig. 1, which also includes an image of the head during cutting of 12mm thickness 304 stainless steel.

Materials considered for underwater laser cutting trials were S355JR+N, S275JR mild steel and 304 stainless steel. These materials are representative of those that may be found inside nuclear waste storage ponds. Usually vessels, canisters and high active waste storage containers are constructed using 300 series and duplex stainless steels. Components such as racks, shelves and support structures for stacking waste containers or storing canisters, are constructed using mild steels. These mild steel components are normally painted to protect surface from rusting.

The laser cutting experiments were performed in two stages. Stage 1 trials were carried out on a 60 x 120 x 350mm thickness S355JR+N mild steel block, which was machined on one edge to form a 45^o wedge with respect to the material thickness. The sample was securely located inside the tank and using a constant laser power of 5kW, a series of linear cuts with speeds ranging from 50 to 1000mm/min were performed, by moving the cutting head from the apex of the wedge (material thin) to the point where the full thickness was achieved. Each set of linear cuts were carried out with cutting gas pressures of 2, 4 and 8 bars. The standoff distance (distance between the end of the cutting nozzle tip and the sample surface) was varied between 15mm and 30mm in four increments. The laser beam focus position was always kept 15mm above the surface of the material being cut. The distance between the end of the wire brush seal and the sample surface was less than 5mm.

Stage 2 trials involved performing series of underwater laser cuts, at selected parameters based on the Stage 1 results, on 6, 12 and 32mm thickness S275JR mild and 304 stainless steel flat plates, with particular emphasis on a measurement of the dross which remained adhered to the base of the material after cutting and its dependence, primarily on laser power, cutting gas pressure and position of the beam focus (at the material surface and 15mm above the material surface). Table 1 summarises the experimental parameters used in Stage 1 and Stage 2 trials.

Parameters	Stage 1 cutting trials		Stage 2 cutting trials	
	Underwater	In Air	Underwater	In Air
Laser power (kW)	5	5	2 - 5	--
Optical fibre (mm)	0.2	0.2	0.2	--
Lens focal length (mm)	250	250	250	--
Focal position, FP (mm)	15 above	15 above	Surface & 15 above	--
Standoff, SD (mm)	15-30	15	15	--
Cutting speed (mm/min)	50 - 1000	50 - 1000	50 - 2500	--
Cutting gas pressure (bar)	2 - 8	2 - 8	2 - 8	--
Shielding gas pressure (bar)	6	--	6	--

Tab.1: Laser cutting parameters for underwater and in air conditions

3. Results and discussion

Typical examples (5kW laser power and two cutting gas pressures) of the series of underwater laser cuts produced on the 45^o wedge shaped steel samples are shown in Fig.2. The cuts with the largest depth (and most dross attached at the kerf exit) were achieved with the slowest cutting speed of 50mm/min. As the cutting speed was incrementally increased to 1000mm/min, the depth of cut as well as the dross attachment reduced progressively.

Fig. 2. Series of linear underwater fibre laser cuts across a 45^o wedge in a 60mm thickness S355JR+N mild steel block.

Fig. 3 shows plots of the maximum underwater cut depth measured as a function of cutting speed, for cutting gas pressures of 2, 4 and 8bar and at standoff distances of 15mm (a) and 30mm (b). Both sets of results were achieved with the beam focus 15mm above the surface of the material being cut.

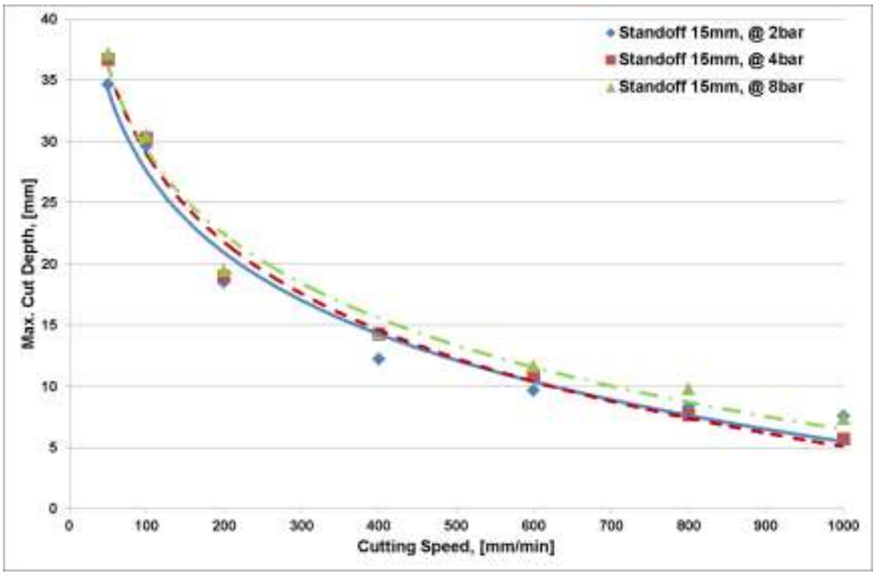

Fig. 3 (a). Maximum underwater cut depth as a function of cutting speed, for cutting gas pressures of 2, 4 and 8 bar, with the laser beam focus 15mm above the surface of the material and a standoff distance of 15mm.

The results in Fig. 3 indicate that at the smaller standoff distance between the nozzle tip and the workpiece surface, cutting gas pressure has very little effect on the cutting performance in terms of cut depth, but a slight increase in the maximum cut depth was seen when using higher cutting gas pressure. However, the effect of increasing the standoff distance appears to have a more significant influence. The longer standoff distance produced lower cut depths at equivalent laser power and cutting speed. The laser power density on the material surface is the same for both standoff distances, so this reduction in performance at the larger standoff can be attributed to the effectiveness of the gas stream in removing material from the laser cut kerf. Hence, at this standoff, the higher cutting gas pressure of 8bar produces deeper cuts.

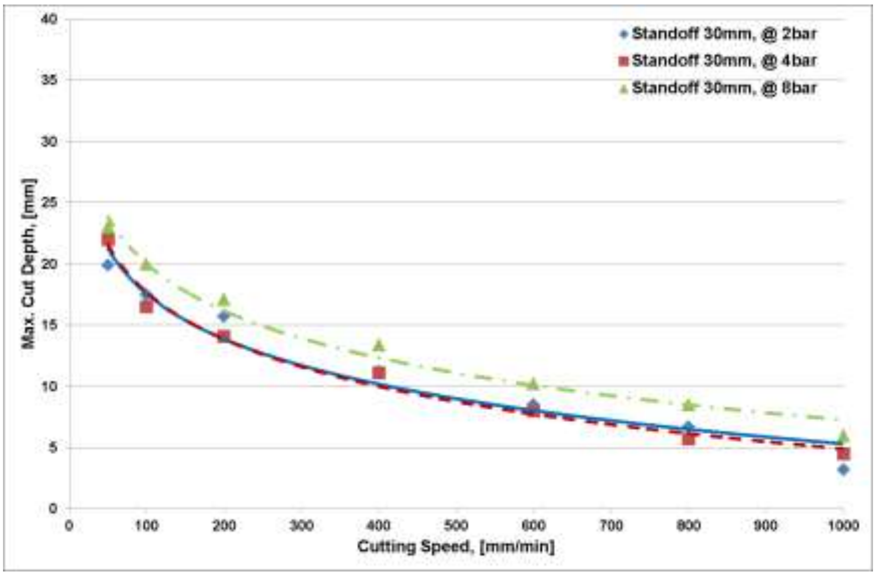

Fig. 3 (b). Maximum underwater cut depth as a function of cutting speed, for cutting gas pressures of 2, 4 and 8 bar with the laser beam focus 15mm above the surface of the material and a standoff distance of 30mm.

A comparison between underwater and in-air laser cutting was performed by simply repeating a set of laser cutting trials outside the water tank, using the same equipment. This was carried out for a standoff distance of 15mm and with the laser beam focus 15mm above the material surface and using cutting gas pressures of 2 and 8bar. Maximum cut depth was measured for each cutting speed and compared with the underwater laser cutting results. Fig. 4 shows plots of both maximum cut depth for in-air as well as underwater cutting and the difference between the two, as a function of cutting speed.

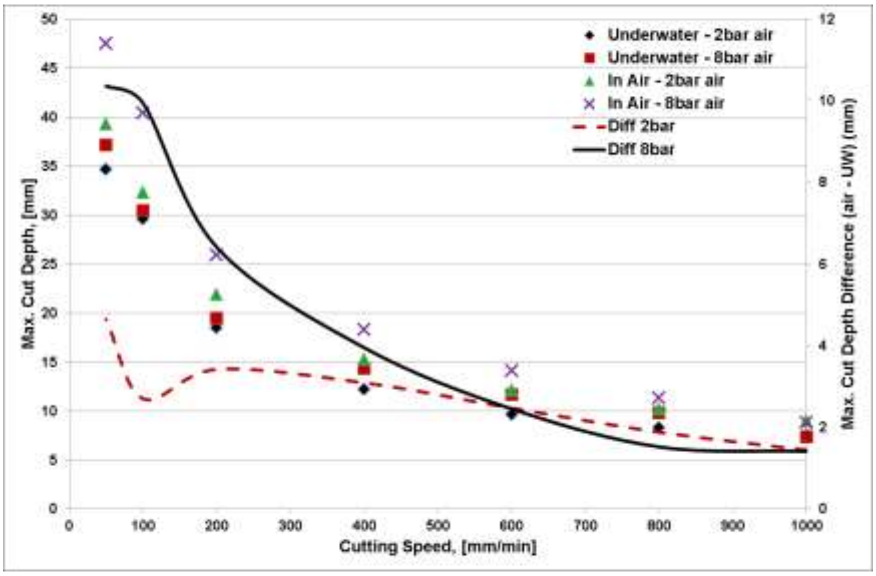

Fig. 4. Comparison between underwater and in-air laser cutting as a function of cutting speed at a constant laser power of 5kW, for cutting gas pressures of 2 and 8bar.

Generally, higher cut depths are produced in-air compared to underwater laser cutting trials on S355JR+N mild steel. This is believed due to a higher cutting gas jet momentum transfer inside the laser cut kerf and reduced laser beam scattering, in the absence of air bubbles during in-air cutting trials. The heat sink produced by the mass of water round the material being cut might also have an effect. In Fig. 4 the difference in the maximum cut depth achieved between in-air and underwater laser cutting is shown (solid lines) for the two different cutting gas pressures. The results clearly indicate that for speeds above

450mm/min, there is little difference between the two gas pressures. At the lower speeds this difference is much higher, particularly at the highest gas pressure used. The implication of this is that if a mild steel plate less than 10mm in thickness is being cut, then the gas pressure has very little impact on performance (when comparing laser cutting in-air and underwater).

In nuclear decommissioning the laser cut edge quality is not important, but minimum production and release of secondary waste is. Other cutting techniques such as abrasive water jet, plasma arc and diamond wire, produce significantly higher secondary waste compared with laser cutting technology [3]. Management of secondary waste emission during size reduction of irradiated material is an important factor. If, during laser cutting, as much of the molten material removed from the kerf can be induced to remain attached to the lower sides of the cut, the less material will end up on the floor as dross. This aspect has been evaluated in the Stage 2 underwater trials on two different materials. Fig.5 shows examples of kerfs (seen from the underside) produced in the Stage 2 underwater laser cutting trials on 12mm thickness S275JR mild and 304 stainless steels.

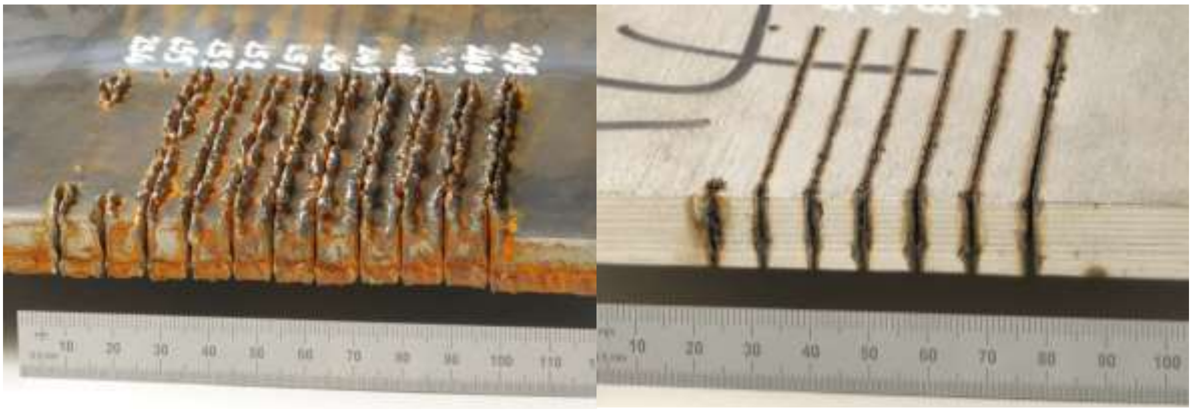

Fig. 5. A view of underwater laser cut kerf exits in a 12mm thickness S275JR mild steel (left) and 304 stainless steel (right).

For both sets of cuts, similar experimental parameters were used. It can be clearly seen that dross adhesion at the bottom of the underwater laser cut S275JR mild steel plate is significantly larger than that produced when cutting 304 stainless steel. For each cut produced in these trials, a Mitutoya dial gauge was used to record the dross height relative to the plate surface. An average dross height was measured by taking 10 random readings along a length of cut for a corresponding cutting speed. The results are plotted in Figs. 6 and 7 for two material types as a function of cutting speed, at laser powers of 2 and 5kW. In this work, the standoff distance and the cutting gas pressure were kept constant at 15mm and 8bar respectively, and the laser beam focus was positioned either at the surface of the material or 15mm above the surface of the material.

Fig. 6 a) and b) show the average dross height variation on the kerf exits on 6, 12 and 32mm thickness S275JR mild steel plates, with respect to cutting speed. Fig. 6 a) is for a laser power of 2kW and Fig. 6 b) for a laser power of 5kW. The general trend of the results is that the level of adhering dross produced is inversely proportional to the cutting speed, and directly proportional to the material thickness. Interestingly, the results in Fig. 6 suggest that when cutting 6mm thickness or less S275JR mild steel, a laser power of 2kW with a laser beam focus 15mm above the material surface could be used to maximise dross adhesion. For higher plate thickness (up to the limit in this work), 5kW of laser will be required. Nevertheless, cutting with a slow speed and a beam focus position above the material surface is still likely to result in maximised dross attachment.

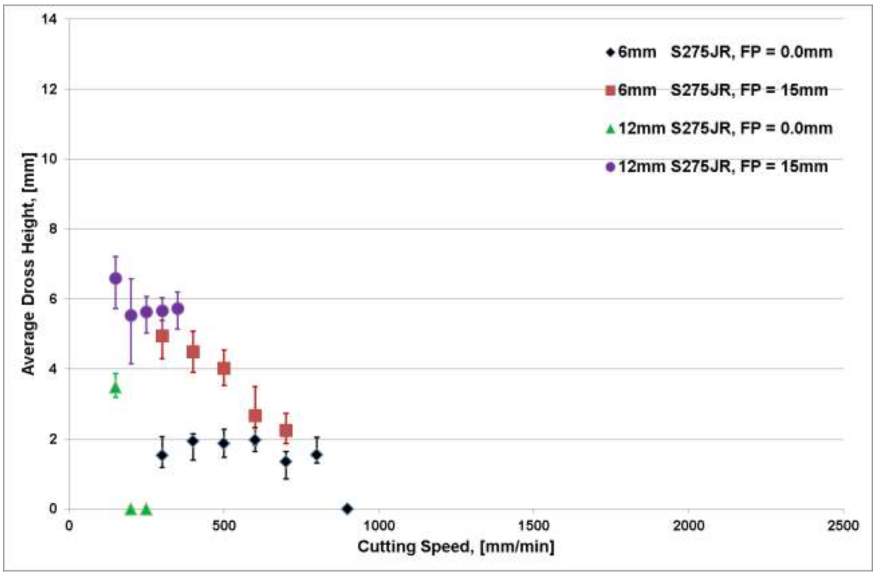

Fig. 6 a) Measured average dross height at the underwater laser cut kerf exit produced in S275JR mild steel plates at a laser power of 2kW, for laser beam focus positions at the surface of the material (0mm) and 15mm above the surface of the material (15mm).

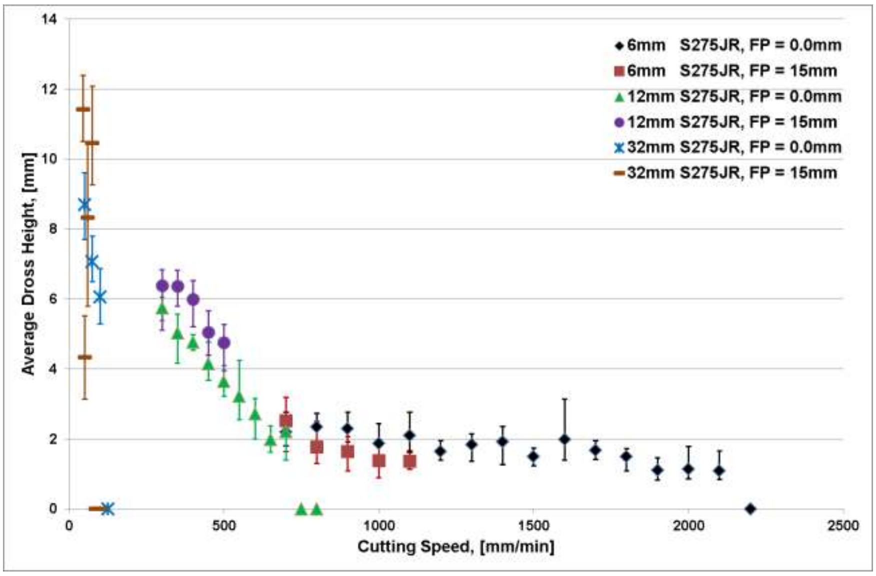

Fig. 6 b) Measured average dross height at the underwater laser cut kerf exit produced in S275JR mild steel plates at a laser power of 5kW, for laser beam focus positions at the surface of the material (0mm) and 15mm above the surface of the material (15mm).

Using a higher laser power also provides a larger operating window: higher laser power will be especially useful if the irradiated structures have variable thicknesses. The results indicate that a cutting speed of 500mm/min or below, is beneficial if high dross adhesion to the the material being cut is required. This also appears to hold true for size reducing 304 stainless steel material, as shown in Fig. 7. Overall dross adhesion in 304 stainless steel is considerably less than S275JR mild steel, but the concept of underwater laser cutting using a beam focus position above the material surface to achieve increased dross adhesion, still holds true for 304 stainless steel.

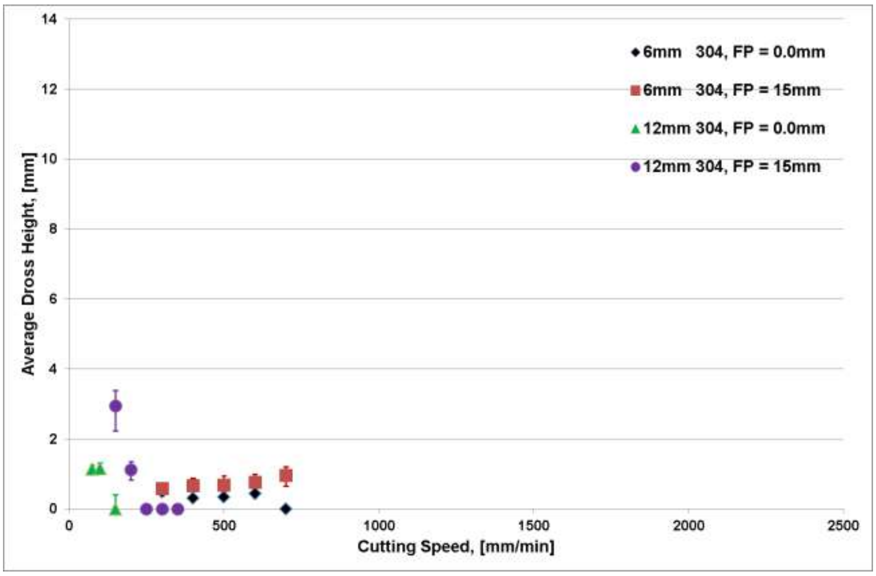

Fig. 7 a) Measured average dross height at the underwater laser cut kerf exit produced in 304 stailess steel plates at a laser power of 2kW, for laser beam focus positions at the surface of the material (0mm) and 15mm above the surface of the material (15mm).

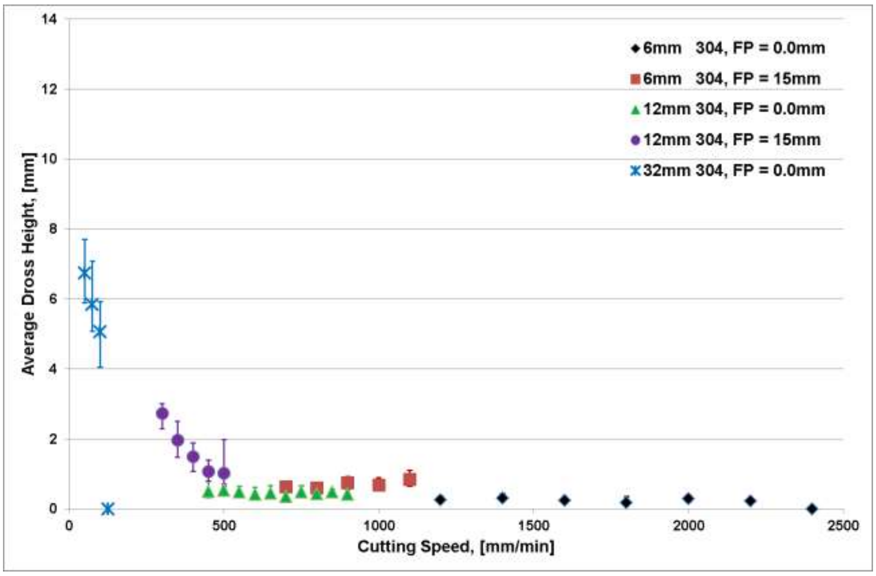

Fig. 7 b) Measured average dross height at the underwater laser cut kerf exit produced in 304 stailess steel plates at a laser power of 5kW, for laser beam focus positions at the surface of the material (0mm) and 15mm above the surface of the material (15mm).

Compared to underwater cutting of S275JR mild steel, generally higher laser power is necessary to underwater laser cut 304 stainless steel plates of the same thickness. Higher laser powers also apear to produce slight increase in dross adhesion in 304 stainless.

The influence of cutting gas pressure was assessed on material thicknesses of 6 and 12mm, for both materials at a constant laser power of 5kW, at the same two beam focus positions used above. For cutting with the beam focus at the material surface, cutting speeds of 600 and 2000 mm/min were used for material thicknesses of 12 and 6mm respectively. When cutting with the laser beam focus 15mm above the material surface, the cutting speed for both material thicknesses was reduced to 400 and 800mm/min respectively. The average dross height measured is shown in Fig. 8, as a function of cutting gas pressure for the two materials used.

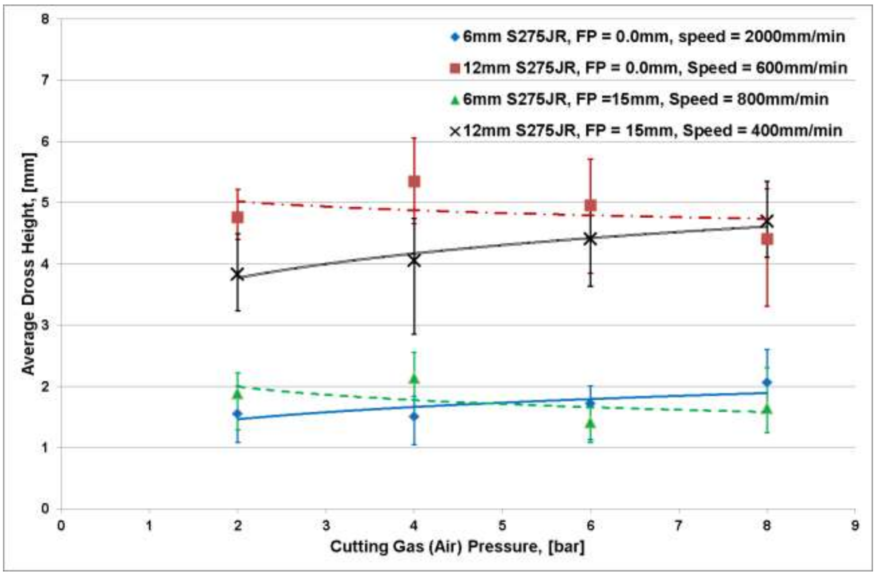

Fig. 8 a) Measured average dross height produced during underwater cutting of 6 and 12mm thickness S275JR mild steel using constant laser power of 5kW, for laser beam focus positions at the surface of the material (0mm) and 15mm above the surface of the material (15mm).

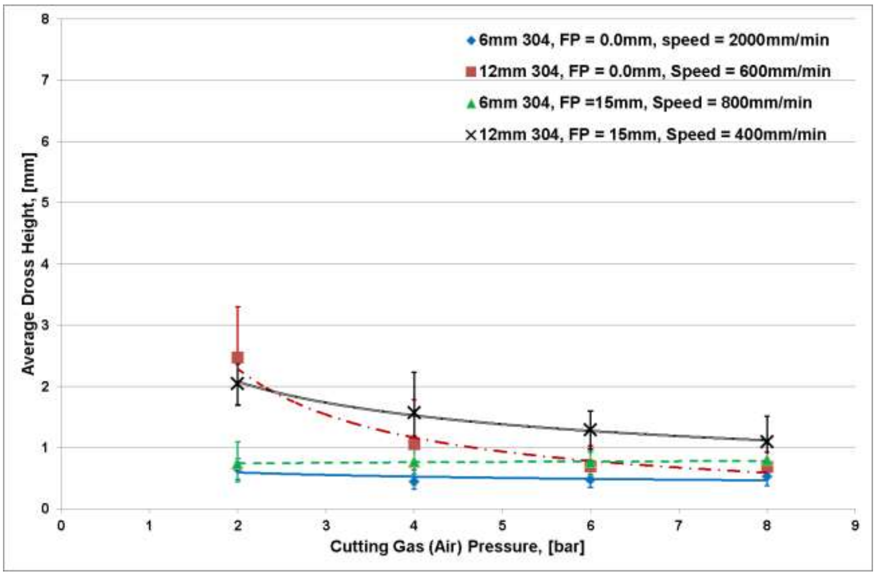

Fig. 8 b) Measured average dross height produced during underwater cutting of 6 and 12mm thickness 304 stainless steel using constant laser power of 5kW, for laser beam focus positions at the surface of the material (0mm) and 15mm above the surface of the material (15mm).

Fig. 8a indicates that variations in the cutting gas pressure when underwater laser cutting S275JR mild steel have only a marginal influence on dross adhesion. The combination of higher cutting gas pressure, a beam focus position 15mm above the material surface and a material thickness of 12mm tends to result in a slight increase in dross adhesion. Similarly, a combination of higher cutting gas pressure, a beam focus position on the surface of the material and a material thickness of 6mm, also tends to result in slight increases in the dross adhesion. This may be due to the dynamics of cutting gas and melt ejection from the laser cut kerf exit, which influences the dross adhesion mechanism. This dynamic ejection process can be directly dependent on the underwater laser cut kerf geometry, often determined by focal position of the laser. Fig 8b indicates that variations in the cutting gas pressure for underwater laser cutting 304 stainless steel plates have very little influence on dross adhesion in the lower material thickness, but may have some influence with increasing material thickness. The average dross adhesion in 12mm thickness 304 stainless steel in fact reduces with increase in the cutting gas pressure.

4. Conclusions

This work, using a 5kW laser source and the optical focussing system described, has allowed the following conclusions to be drawn:

- Comparison between in-air and underwater laser cutting of S355JR+N mild steel, indicates (parameters being equal) that deeper cuts are produced when laser cutting in-air. However, any significant difference in performance was limited to cutting speeds below 450mm/min.
- In underwater cutting of S355JR+N mild steel, for a constant laser power and position of the beam focus, the standoff distance between the nozzle tip and the material surface was the most significant variable. Variation in the cutting gas pressure did not show any significant influence, except at the largest standoff distance, where higher cutting gas pressure provided better cutting performance.
- Adhering dross measurements on S255JR mild steel and 304 stainless steel, indicated that significantly higher dross adhesion underneath the cut was measured in S275JR mild steel plates. The average height of this retained dross increased with material thickness and with a decrease in the cutting speed. Generally, positioning the laser beam focus above the material produced increased dross adhesion.
- Operating at the highest laser power available provided a larger operating window and slight increase in the dross adhesion. However, cutting speed was the most influencing factor in dross adhesion.
- Variations in the cutting gas pressure did not show any significant influence on dross adhesion in S275JR mild steel, but an increase in dross adhesion, particularly in higher material thicknesses, was noticed at low cutting gas pressures.

It is advantageous to the nuclear industry to use a size reduction technology that retains as much dross as possible attached to the irradiated structures. This would mean a minimal spread of contamination and a minimal post clean-up operation. These factors normally lead to reduction in the decommissioning cost. It is believed underwater cutting, particularly of mild steel structures, would be a good candidate for maximising dross adhesion.

5. References

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