OPTIMISATION OF UNDERWATER LASER CUTTING FOR DECOMMISSIONING PURPOSES

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Abstract

In both the nuclear and offshore sectors, there are many potential applications for underwater cutting. Although underwater cutting using lasers was demonstrated many years ago, the limitations imposed at that time by the 10 micron laser beam wavelength available, meant that practical realisation of underwater laser cutting was almost impossible. With the advent of fibre delivered laser power this situation has changed. This paper will describe recent work using a 5kW Yb fibre laser source, equipped with a specially designed process head for underwater laser cutting. Results will be presented for cutting both 304 stainless and C-Mn (S275JR) steel, at thicknesses of up to 32mm. The paper will also describe the various parameters thought to be important in underwater cutting and their effects on the cut achieved. It will be shown that for different applications, different sets of parameters can be used to achieve different results. As an example of this, in the application of nuclear decommissioning, choice of parameters for maximising dross height on the parts being cut will be described. In nuclear decommissioning, maximising the dross adhesion is important, as it means less radioactive material from the kerf is released into the water and therefore more remains on the parts being size reduced for future long term storage.

Introduction

The term “decommissioning” refers to the safe end-of-life management of many different types of nuclear and offshore facilities. The decision to decommission any facility is often based both on safety and on economics. The major costs of decommissioning a facility are associated with dealing with the safe removal, treatment, size reduction and disposal of large components. These may include pressure vessels, generators, pumps, tanks and supporting systems, including thousands of metres of pipes – along with even greater volumes of construction materials. Decommissioning operations must not pose unacceptable risks to the public, the workers or the environment and therefore necessitate careful selection of decommissioning processes and, in the case of a nuclear facility, strategies to eliminate and/or significantly reduce dose uptake during handling and transporting nuclear wastes, and reduce or eliminate contaminants escaping into atmosphere during decommissioning. For offshore facilities, underwater dismantling offers financial advantages, and in the case of radioactively contaminated components, underwater processing offers significant reductions in risk. Amongst other enabling technologies, using fibre delivered laser beams underwater can offer potential benefits in reduced complexity for remote dismantling operations, and, for the nuclear sector, a reduction in secondary emissions [1-4]. Secondary emissions in laboratory conditions are defined as any by-products of laser cutting. For in air cutting these are classified as aerosols, which are exhausted to the ventilation system, deposited dross on surroundings structures and components, sedimented dross which falls under gravity, and slags/dross attached to the kerfs which are produced during the cutting process. In the case for underwater additional by-product of laser cutting are suspended aerosol particles. The mass fractions of secondary emissions produced from laser cutting of stainless steel in air and underwater are shown in Table 1 [5].

Table 1: Mass fractions of secondary emissions produced from laser cutting stainless steel [5].

Secondary Emission	In Air	Underwater
Sedimented Dross, %	90 - 99	94
Aerosol particles, %	0.8 - 10	1
Deposited dross on surroundings %	0.01 – 0.5	-------------
Suspended particles, %	------------	5

In Table 1 the aerosol mass fraction produced when laser cutting in air was reported to increase with increase in the material thickness and with decrease in the cutting speed [6]. Conversely, in underwater laser cutting, only particles of a certain size, trapped in air-pockets (bubbles), can escape as aerosols. In terms of attached slag,/dross, it has been reported that its proportion of attached slag/dross is normally higher for C-Mn steel than stainless steel [7]. Nevertheless, both in air and underwater laser cutting the most significant amount of secondary emission is in the form of sedimented dross. From the safety and economical points of view, dross management is highly important. In nuclear decommissioning, most metallic components are constructed using stainless steels, so maximising dross adhesion is important, as it then means less radioactive material from the kerf is released into the water during cutting, and more remains on the parts being size reduced for future long term storage. In decommissioning of non-contaminated offshore facilities, which are mostly made from C-Mn steels, it may be desirable to have a lower dross level, for easier separation of components.

This paper describes the important parameters in underwater laser cutting and their effects on attached slag/dross height. It also presents a 'mass reduction' comparison between underwater and in-air cutting for S275JR (C-Mn) and 304 stainless steels. Low mass reduction is highly desirable for the nuclear sector.

Experimental Method

For all underwater cutting experiments, the arrangement shown schematically in Figure 1 was used. Compressed air for underwater laser cutting was used to create a localized dry zone and to assist in flushing out the laser melted material inside the kerf. In the case of in-air cutting trials, the water from the tank was drained and the cutting trials repeated using the same equipment.

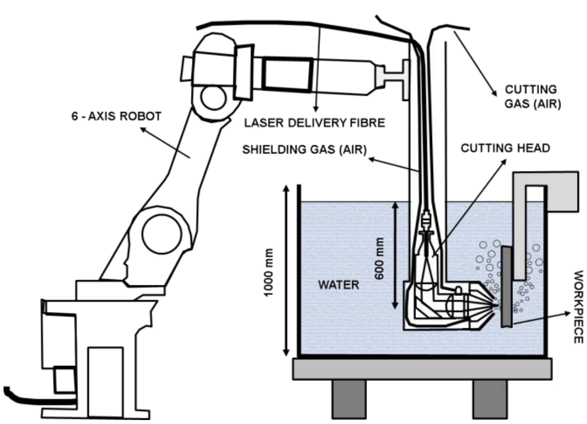


Figure 1 Schematic of the underwater laser cutting arrangement used

For the work reported here the materials were used were 6, 12 and 32mm thickness S275JR C-Mn and 304 stainless steel plates.

Process Parameters

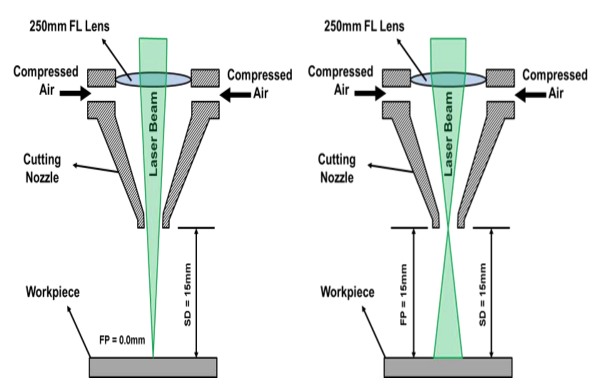
Table 2 details the laser cutting parameters used in both underwater and in-air cutting trials. Two beam focus positions were used in the cutting trials and these are shown schematically in Figure 2; for clarity:

- A focus position of 0mm is where the minimum laser beam diameter is positioned on the uppermost surface of the material.
- A focus position of 15mm is where that minimum beam diameter is located 15mm above that surface.

In all cutting trials, the stand-off distance between the nozzle tip and material surface (SD in Figure 2), was kept constant, at 15mm. The cutting assist gas used was compressed air.

Table 2 Laser cutting parameters used

Parameters	Underwater	In air
Laser power, kW	2, 3, 4 & 5	5
Collimator/Lens focal length, mm	120/250	120/250
Focus positions, mm	0 & 15	0 & 15
Stand-off distance, (SD), mm	15	15
Cutting gas pressure, bar	2, 4, 6 & 8	2, 4, 6 & 8
Cutting Speed, mm/min	50 - 2200	400 - 2000
Material thickness, mm	6, 12 & 32	6 & 12



a) b)

Figure 2 Laser focus positions with common standoff distance of 15mm used in cutting trials, a) 0 mm, b) 15 mm.

Scope of work

Attached slag/dross height assessment

In order to assess the influence of the laser cutting parameters on attached slag/dross height, a series of ~150mm long linear cuts were made in the 6, 12 and 32mm thickness S275JR steel and 304 stainless steel, plates.

For a given laser power and cutting gas pressure, the cutting head was made to traverse horizontally across a 250 x 250mm plate, mounted vertically in the water tank, 600mm below the water level. The cutting speed chosen was governed by the material thickness being cut.

After each set of cuts the height of the dross attached at the bottom (kerf exit) of the plate was measured at 10 locations using a digital dial gauge. An average of 10 readings was taken and the variation in the dross height was calculated.

Mass reduction assessment

For the mass reduction assessment, a comparison between underwater and in air cutting was performed. A laser power of 5kW was used for all experiments, and the cutting speeds were chosen from the preceding dross height assessment trials. Different cutting gas pressures were used, between 2 and 8bar. For each material thickness the cutting speed was kept constant, to allow the effects of material and environment (in air or underwater) to be assessed:

- For cutting trials performed with a focus position of 0mm, cutting speeds of 2000 and 600mm/min were used for the 6 and 12mm thickness plates, respectively.
- For cutting trials performed with a focus position of 15mm, cutting speeds of 800 and 400mm/min were used for the 6 and 12mm thickness plates, respectively.

For each combination of cutting parameters three linear cuts were made and the sample was weighed before and after the laser cutting operation. In addition, the attached dross height was measured.

Metallographic assessment

Selected laser cut samples were cross-sectioned, ground, polished and etched to reveal the microstructures of the metal surrounding the laser cut kerfs. This section included bulk material, metal dross and oxides. Each metallographic sample was examined using optical and scanning electron microscopy (SEM). In addition, using SEM with energy dispersion x-ray (EDX) analysis of selected locations of samples was used to obtain elemental compositions.

Results

Attached slag/dross height assessment

Figure 3 shows examples of underwater laser cuts (undersides shown) in 12mm thickness S275JR steel and 304 stainless steel plates. Similar experimental parameters were used for both materials. It can clearly be seen that the attached dross on the S275JR steel plate is significantly more than that on the 304 stainless steel plate.

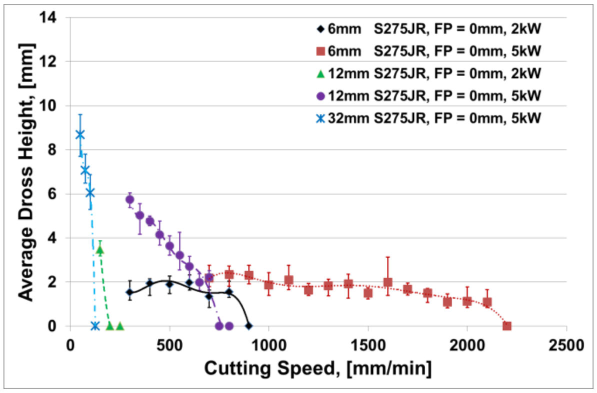
a) b)

Figure 3 A view of underwater laser cut kerf exits in 12mm thickness material: a) S275JR C-Mn steel, b) 304 stainless steel

Figure 4a) shows, for underwater cutting, a plot of the average dross height, as a function of cutting speed, produced in 6, 12, and 32mm thickness S275JR steel plates, for a focus position of 0mm and laser powers of 2 and 5kW. Figure 4b) shows similar plot with focus position of 15mm, for 6 and 12mm thickness S275JR steel plates. Where the average dross height tends to zero, a cut was not achieved.

As can be seen from Figures 4a) and b):

- The attached dross height decreased with an increase in cutting speed.
- The attached dross height generally increased with an increase in thickness of S275JR C-Mn steel.
- The average dross height produced with a focus position of 15mm, was generally higher than that produced with a focus position of 0mm, for a given cutting speed.



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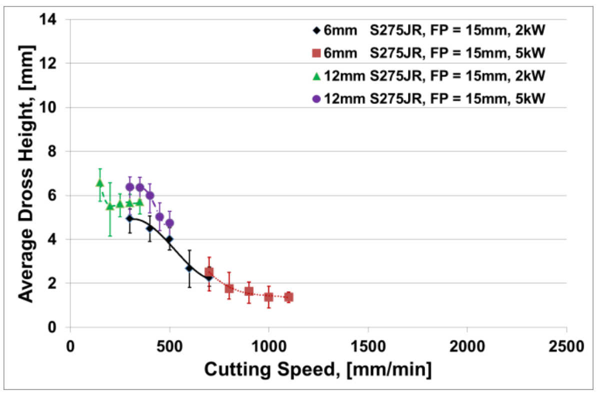


b)

Figure 4 Influence of cutting speed and laser power on dross height in 6, 12 and 32mm thickness S275JR steel plate with focus position, a) 0mm and b) 15mm, cut underwater.

Figures 5a) and b) show average dross height produced in underwater laser cutting of 6, 12, and 32mm thickness 304 stainless steel plates, as a function of cutting speed, focus position and laser power. Where average dross height tended to zero, a cut was not achieved.

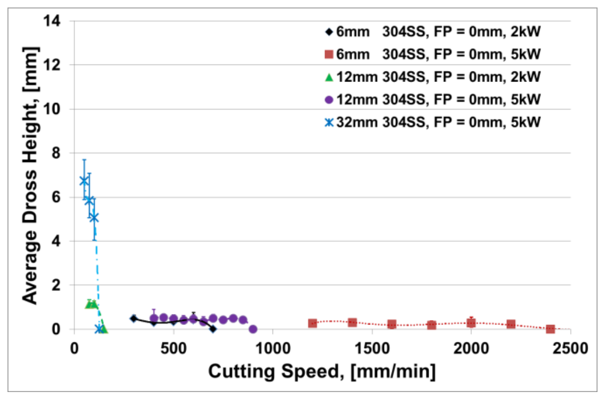
As can be seen in Figure 5a):

- The dross height in 304 stainless steel increased with a decrease in cutting speed, or increase in material thickness.
- An increase in laser power appeared to produce little difference in dross height.
- For similar laser cutting parameters, the dross height in 304 stainless steel compared with S275JR C-Mn steel was significantly lower (up to ~70–88%).

As can be seen in Figure 5b:

- Underwater laser cutting of 304 stainless steels with a focus position of 15mm, tends to produce a higher dross height than with a focus position of 0mm, for a given material thickness and laser power.
- For similar laser cutting parameters, the dross height produced using this focus position was higher (~17–50%) compared with the 0mm focus position.
- For similar laser cutting parameters, the overall dross height in 304 stainless steel compared with S275JR C-Mn steel was significantly lower (~36–80%).

Interestingly, it was not possible to cut 32mm S275JR C-Mn underwater, with a focus position of 15mm, even when cutting at 50mm/min. However 32mm thickness 304 stainless steel could be cut, using a maximum cutting speeds of 100 and 75mm/min, with focus positions of either 0 and 15mm, respectively.



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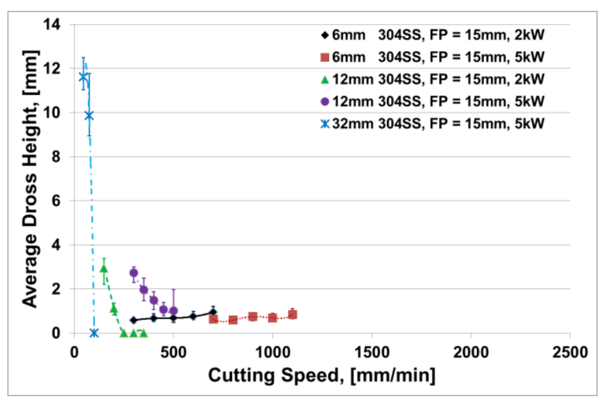


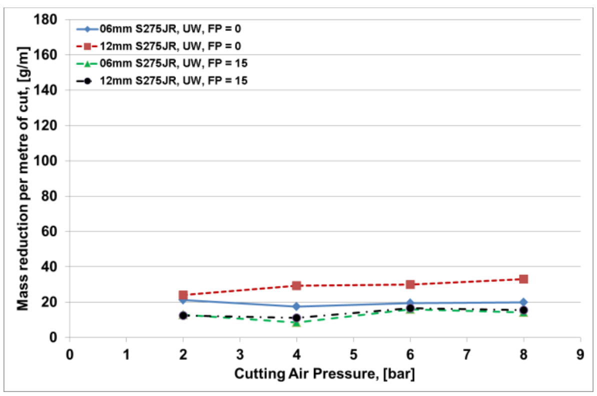
b)

Figure 5 Influence of cutting speed and laser power on dross height in 6, 12 and 32mm thickness 304 stainless steel plates with focus position, a) 0mm and b) 15mm, cut underwater.

The overall dross height measured on both of the 32mm thickness materials when cut at 0mm focus and 100mm/min was nearly the same. Nevertheless, when compared to what was achieved with a focus position of 0mm, when underwater laser cutting 32mm thickness 304 stainless steel, using a focus position of 15mm produced an exceptionally high level of dross height.

Mass reduction assessment

Figure 6 shows the mass reduction after underwater and in-air laser cutting of S275JR C-Mn steel, as a function of cutting gas pressure. The mass reduction was calculated for a 1m length of cut and is defined as the total mass of secondary waste (dross and fume) that was discharged in to the environment during the cutting operation. The recorded mass reduction in the underwater laser cutting of S275JR C-Mn steel, for both 6 and 12mm thicknesses, at a focus position of 15mm, was lower compared with a focus position of 0mm, Figure 6a).



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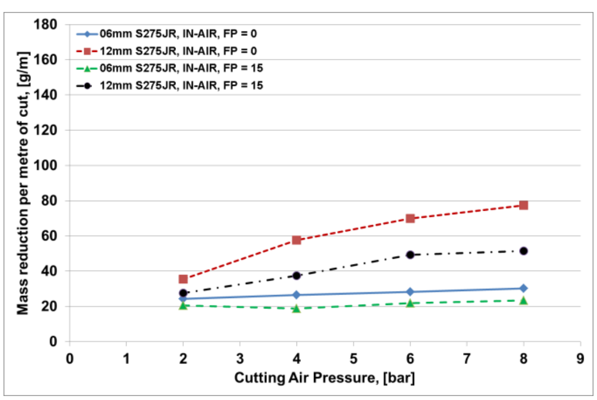

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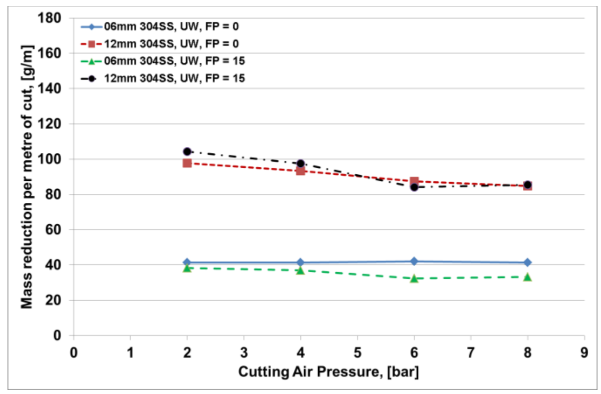
Figure 6 Influence of cutting gas pressure on mass reduction in S275JR C-Mn steel of thickness 6 and 12mm, using focus positions of 0 and 15mm, and environments; a) Underwater, b) In air

For cutting in air, the mass reduction per metre of cut measured in air cutting was higher when compared with underwater cutting. Furthermore, for 12mm thickness S275JR C-Mn steel, an increase in mass reduction with increased cutting gas pressure was noted. Figure 7 shows similar mass reduction data for laser cutting of 304 stainless steel. Comparing Figure 6 and 7 indicates that under the same laser cutting conditions. the mass reduction in 304 stainless steel was higher than that for S275JR C-Mn steel. Interestingly, a significant reduction in mass reduction, with a change to a 15mm focus position, was only observed when cutting 12mm thickness 304 stainless steel in air.



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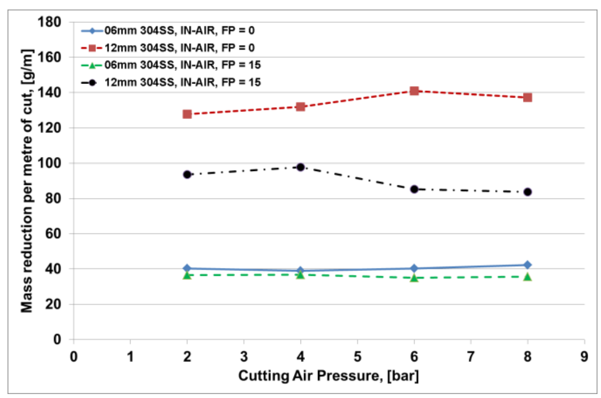

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Figure 7 Influence of cutting air pressure on mass reduction in 304 stainless steel for thicknesses of 6 or 12mm, focus positions of 0 and 15mm, and environments; a) Underwater, b) In air

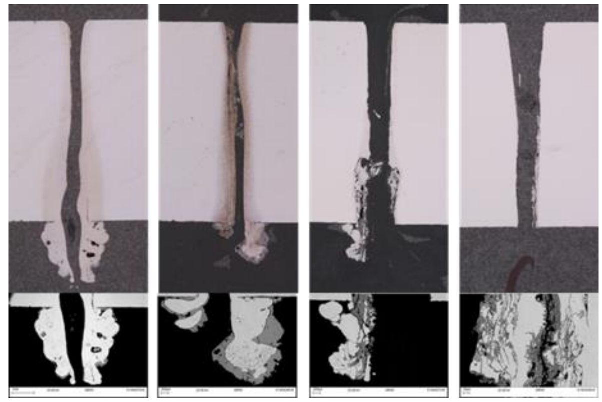
Metallographic assessment

For comparison purposes, four laser cut cross-sections were analysed using optical and scanning electron microscopes. The laser cutting parameters used were the same for the four cuts. Figure 8 shows cross-sections through cuts in the 12mm thickness materials. It can be seen that:

- Laser cut kerfs were irregular in shape; contained residuals of molten metal in the form of dross and metal oxide. These were present both inside and underneath the laser cut kerfs.
- Laser cut kerfs produced in 304 stainless steel appeared to be wider compared with S275JR C-Mn steel.
- Underwater laser cut kerfs showed increased metal dross attachment underneath the material surfaces compared with in air laser cut kerfs.
- Compared with underwater laser cut kerfs in both steels, a larger amount of metal oxide also appeared present inside the air cut kerfs. This is particularly notable in S275JR C-Mn steel.
- The amount of residual metal dross inside the S275JR C-Mn steel kerfs was also significantly higher than that inside the 304 stainless steel kerfs.
- The metal dross in S275JR C-Mn steel kerfs was in the form of long filaments surrounded by metal oxide, compared with intermittent layers of smaller granular metal dross and oxide in 304 stainless steel kerfs.
- For underwater laser cut S275JR C-Mn steel, the metal oxide surrounding the metal dross was significantly thinner than that present in air laser cutting.
- Conversely, for underwater laser cut 304 stainless steel, the intermittent metal oxide thickness was larger than that present in air laser cutting.
- In other words, for underwater laser cuts, the 304 stainless steel cuts had a higher metal oxide content than those in S275JR C-Mn steel.

EDX analysis on the cross-sections shown in Figure 8a and 8c) was also performed, to obtain compositional information on parent material, metal dross and oxide. Figure 9a) and b) show this information for underwater laser cut 12mm thickness S275JR C-Mn and 304 stainless steel, respectively. In both samples it was clearly seen that the composition of the metal dross was very similar to the corresponding parent material. EDX analysis of S275JR C-Mn steel metal oxide, Figure 9a, indicated that it consisted mostly of iron oxide with traces of manganese. Although not presented in this paper, the metal oxide composition observed in air cutting contained slightly higher levels of oxygen compared with that in underwater cuts.

In Figure 9b), EDX analyses of 304 stainless steel metal oxide suggested chromium oxide was the main oxide constituent, with manganese and silicon also being present. X-Ray analysis of dross produced in underwater laser cutting of 316L stainless steel carried out in an earlier study [3] also showed enrichment of these elements.

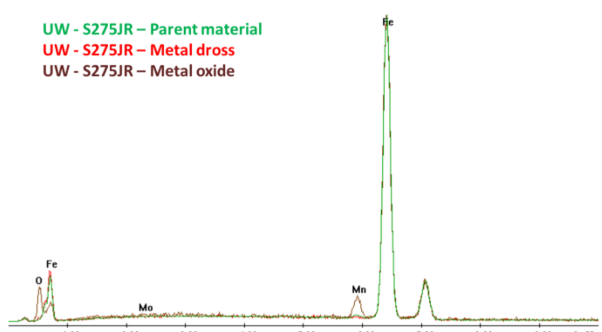


a) b) c) d)

Figure 8 Cross-sections (top row) of laser cut kerfs produced in 12mm thickness materials using 5kW, at a 15mm focus position, with 8bar cutting gas pressure, at 400mm/min, and associated dross microstructures (bottom row). In each case, the upper image is an optical micrograph and the lower a scanning electron micrograph. In Figure 8d), as dross was not present at the bottom of the kerf, the SEM image shown is that of residual melt inside the kerf itself.

a) Underwater laser cut S275JR C-Mn steel
b) In air laser cut S275JR C-Mn steel
c) Underwater laser cut 304 stainless steel
d) In air laser cut 304 stainless steel

In Figure 9b), EDX analyses of 304 stainless steel metal oxide suggested chromium oxide was the main oxide constituent, with manganese and silicon also being present. X-Ray analysis of dross produced in underwater laser cutting of 316L stainless steel carried out in an earlier study [3] also showed enrichment of these elements.



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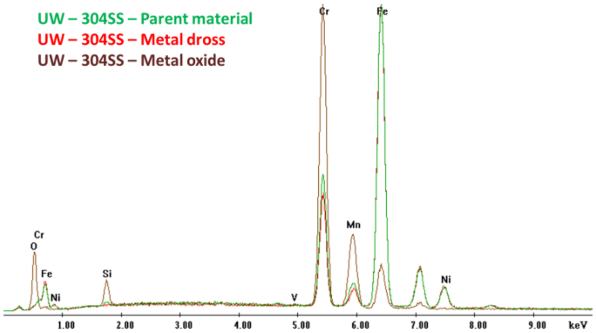

b)

Figure 9 EDX analysis of parent material, metal dross and metal oxide of underwater laser cut kerfs in:

a) 12mm thickness S275JR C-Mn steel
b) 12mm thickness 304 stainless steel

Discussion

Dross height

Comparing Figures 4 and 5 clearly shows that dross height (mixture of molten steel and oxide) around the kerf exit was more pronounced for underwater laser cutting of S275JR C-Mn steel, compared with 304 stainless steel. A reduction in cutting speed, or an increase in material thickness or laser beam focus position, tended to result in increasing dross height, as did an increase in laser power under certain conditions.

These trends indicate that in order to achieve higher dross height, it may be beneficial to cut very slowly, thus using less incident power density. Furthermore, for both steels, it appeared that there was a transition to increased levels of dross height when underwater laser cutting below 500mm/min. It was also noted that, especially in S275JR C-Mn steel, dross height was considerably higher, when laser cutting underwater, compared with cutting in air, Figure 8.

Figure 8 shows cross-sections of 12mm thickness steels, produced by laser cutting, both underwater and in air. It was apparent that more metal oxide was formed when in-air laser cutting (Figure 8b & 8d) than underwater laser cutting (Figure 8a & 8c). It was also noticed that amount and thickness of metal oxide present inside both steel kerfs were higher for in air laser cutting process compared with underwater laser cutting, which suggests that the oxidation process continues to occur even after the laser material interaction has ceased. This implies that immediately after laser cutting, the laser cut kerf generated for in air cutting was sufficiently hotter.

Furthermore, owing to the higher thermal conductivity (42.7 W/mK) of C-Mn steel, compared to 304 stainless steel (21.4 W/mK), it is likely that the cooling rates experienced by the parent metal and dross in S275JR C-Mn steel were higher. Underwater cutting is likely to further increase the quenching effect, owing to the heat extraction by the surrounding water. In addition, it is possible that metal oxides formed during and after laser cutting may also play a significant role, which can affect both the cooling rate as well as the molten metal dross flow characteristics.

Clear differences in the heights of the attached dross can be seen in the cross-sectional views for the steels laser cut underwater and in air. In addition, variations in the distribution of metal oxides in the dross can be seen between the two cutting environments and steels, especially in the SEM images. Close examination of the SEM images showed that greater volume fractions of metal oxide were present in the underwater laser cut 304 stainless steel samples, compared to S275JR steel samples. The stainless steel dross was a more intermittent mixture of metal dross and metal oxide compared to the C-Mn steel dross, for which most of the metal oxide was on the surface. In the case for 304 stainless steel, this layering of metal dross and oxide is likely to have poor mechanical properties, making fragmentation of 304 stainless steel dross matrix more likely. In contrast, the metal oxide in the C-Mn steel dross was mostly confined to the outside surface of metal dross, which flowed to create relatively long filaments, the length of which appeared to increase with a decrease in cutting speed.

EDX analysis of underwater laser cut samples indicated that elemental composition of metal dross was similar to that of parent material for both steels. However, elemental composition of S275JR C-Mn steel indicated mostly iron oxide and followed by manganese was present. In the case of 304 stainless steel metal oxide which was found to be enriched in chromium oxide and also high level of manganese. This enrichment of chromium and manganese for laser cutting of stainless steel has been noticed in another earlier study [8]. It was reported that aerosols produced from in air laser cutting were enriched in chromium by factor up to 2.7, manganese by factor up to 2.1 and nickel by factor up to 4. For underwater YAG laser cutting, an enrichment in chromium was by factor of 2, manganese by factor of 20, but depletion in nickel by factor of 2.6 was underlined, [3]. These elemental results are important when dismantling a nuclear component and needs to be taken into count when cutting of active (contaminated) component since the ratio of Mn/Fe will be higher in the HEPA filters than in the cut pieces.

Mass reduction

The mass reduction study showed that in underwater laser cutting of both S275JR C-Mn and 304 stainless steel, secondary emissions, in the form of dross and fumes, are greatly reduced compared to cutting in-air, especially when material thicknesses greater than 6mm and focus position of 0mm are under consideration. Generally, a higher mass reduction was associated with laser cutting 304 stainless steel. Combination of larger kerfs and fragmentation of metal dross and oxide matrix may be the cause of increased mass reduction noticed in 304 stainless steel. With respect to increasing material thickness increase the amounts of secondary emissions is more likely, more so in the case of in-air cutting. From the point of view of mass reduction, it would be better to laser cut these steels (in either cutting environment) with reduced laser power density. (In this work corresponding to the 15mm focus position). The mass reduction study also established that when laser cutting both steels at 6mm thickness, the cutting gas pressure would have negligible influence on secondary emissions and it is anticipated that when laser cutting of even smaller thicknesses, the influence of focus position will also be negligible. Therefore a benefit in underwater laser cutting of 304 stainless steel, would be that secondary emissions, in the form of dross and fumes, would be suspended in water rather than being airborne.

Conclusions

The work performed on underwater cutting of S275JR C-Mn and 304 stainless steels and in-air comparisons, has allowed the following conclusions to be drawn:

1 Dross height at the base of the underwater laser cut S275JR C-Mn steel was significantly larger than that produced when cutting 304 stainless steel. The reason for this is believed to be that because oxide formation in underwater laser cutting of CMn steel is reduced, a significant volume of the dross produced is metal which tends to attach at the base of the cut in long filaments. These filaments re-solidify at a faster rate, when compared to filaments in stainless steel. Laser cutting with focus position of 15mm and slower speed is most likely increase surface to volume ratio and combined with quenching of long metal dross filaments by water is possible another mechanism which can influence dross adhesion.

2 For underwater laser cutting a constant laser beam focus position, the level of dross height increases with steel thickness, laser power and a reduction in cutting speed. However, the influence of laser power on 304 stainless steel was small compared to S275JR C-Mn steel.

3 Dross height was found to be significant in both steels when cutting using the lower incident power density (larger diameter beam incident on the material surface).

4 The dross height was proportional to the material thickness.

5 When underwater laser cutting both steels, the recorded mass reduction was significantly lower than that found for in-air laser cutting. The difference seen between the two cutting environments, increased with steel thickness and when cutting with focus position of 0mm.

6 For nuclear applications it will be desirable to underwater laser cut 304 stainless steel with higher focus position of 15mm. As a consequence, in an active trial, lesser quantity of contaminated secondary emission would remain suspended in water; thus minimising post clean-up operation.

Acknowledgements

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Meet the Authors

Dr Ali Khan received his PhD in optimising the design of laser cutting nozzles. After working for several years at Cambridge University he joined The Welding Institute as Principle Project Leader. Whist at The Welding Institute, he has worked extensively on the development of laser cutting for applications involving size reduction for nuclear decommissioning.

Dr Paul Hilton has been with The Welding Institute for over 20 years, working in the field of laser materials processing. He has twice been the President of AILU, the UK's Association of Industrial Laser Users and is the current Chairman of ELI, the European Laser Institute. He is also a Fellow of LIA.