Abstract

Over the last recent years an increasing number of reactors have reached the end of their useful life and their safely decommissioning is a topic of public concern. In response, the laser process has been studied for dismantling work for more than 10 years. In order to use laser cutting in nuclear decommissioning the safety case needs to be established. The objective of this research was to obtain data to support the safety case, through a series of experiments conducted using a fiber laser system. Since in the nuclear decommissioning sector cutting is largely applied to thick materials and there are relatively few research works addressing the effect of the high power fiber cutting for thick sections, further research is needed. Also, fumes generated during laser cutting are inevitable during the process, however there is almost no data available concerning fumes and gases emissions during laser cutting. Thus, the focus of this work was to perform two different experiments with two different objectives. First, to achieve efficient trials, minimizing the kerf width, by using different nozzles combinations, and second to point out ways of controlling fumes emissions and the amount of dross (material removed from the cut kerf), using different cutting parameters. The results obtained show the performance that can be reached with 10kW fiber lasers, as well as an analysis of the effect of laser cutting parameters on fume emissions.

Keywords: Fiber laser cutting, parameters analysis, high power lasers, nozzle combinations, laser secondary emissions, fume generation, dross released.
1. Introduction

Nowadays an increasing number of reactors have reached the end of their useful life and their safely decommissioning is a topic of public concern. “Time, cost and safety are key drivers for nuclear decommissioning”. Laser is a technology which has the potential to reduce time, reduce cost and therefore to be used for multiple cutting jobs with also an increase safety [1]. In order to use laser cutting in nuclear decommissioning the safety case needs to be established. The laser process has been studied for dismantling work for more than 10 years [2]. However, to meet the safety case mentioned above further research has to be done to analyze the laser drawbacks. Amongst others, these drawbacks include the fume generated during the process. Also, there is almost no research works addressing the effect of the high power fiber lasers for cutting thick sections.

In the nuclear sector there are significant quantities of thick material that needs to be effectively separated. The objective of efficiently conducting cutting trials should aim at minimization of the kerf width in order to keep material losses low and the energy requirements small [3]. The physical processes involved in laser cutting of thick sections are complex. Among the cutting processes available the multi-kilowatt laser is the process most investigated. Developments and tests with pulsed YAG laser and CO2 laser, with maximum average power outputs of 1.2 and 5kW respectively, have been done in France and Japan. Still in France, the last studies to assess the performance of high power lasers were up to 8 kW. Also, it can be found cutting developments with high power lasers not dedicated to the nuclear industry [2].

The control of fume emissions is also desired for safe use of laser cutting. Taking into account the danger associated to cutting fumes, as well as its relation with the dross (material removed from the cut kerf) released, the second part of the this work is related with the control of secondary emissions. The generation of fumes during cutting and welding processes is an inevitable part of the process, thus, the control of the fumes is of increasing importance in promoting a healthy and safe environment, and has been studied for the past years [4]. In fact, there are a significant number of publications related with fumes generation of welding processes. However, for laser cutting there is almost no data available concerning fumes and gases emissions. Currently, developments have been done, in order to determine the feasibility to use this technique in the nuclear sector [5], as well as for powder metallurgy applications and for other scientific and technological uses [6].

Considering the above mentioned, the purpose of this work was to conduct cutting trials, using a fiber laser system, to meet the safety case. The main focus is to understand the effect of different laser parameters in the fume emission and dross quantity, as well as to assess the cutting performances with an output power of 10 kW. Two different and separated experiments were undertaken are described below.
2. Materials and methods

The cuts were produced using a 10 kW IPG fiber laser operating at maximum power for the high power experiments, and working at either 5 or 3 kW for the fumes analysis. The delivery system consisted of a fiber with a core diameter of 200 µm, a 120 mm collimating lens and a 250 mm focusing lenses.

The high power experiments involved fixing the laser power (10 kW) and assist gas pressure (8 bar), varying the stand-off distance (SD) and focus position (FP). By using spacer rings, seven parameters sets were tested with different stand-off distances and focal positions (definitions in Figure 1), without defocusing the laser beam.

The trials consisted in moving the laser beam from one side of the sample to the other, at constant speed. The first part of the experiments was to discover how far it was possible to cut, in a single pass, for each speed. In the second part of the experiments the cuts were used to analysis the cross section geometries and measure the cut area.

The material used was S355 C-Mn Steel, widely used in the nuclear sector. For the first cut experiments, bars with thicknesses until 70 mm were used. Then, six more cuts and analyses were undertaken with plate’s thicknesses of 6, 12 and 40 mm to cover a range of thicknesses useful for practical cases. After cutting, specimens were cut from transverse sections at the final position of the cut and the surfaces prepared for metallographic inspection.

To study the influence of different parameters on the fumes and dross produced during laser cutting, a set of 30 experiments was performed.

In each trial the material thickness, stand-off distance, laser power or gas pressure was changed. By using different focus position (the definition is represented in Figure 2) three stand-off distances were obtained: 15, 40 and 65 mm.
The experimental setup was developed to perform laser cuts in a confined volume. The trial consisted in making one or more laser cuts of about 250 mm in length, on a single sample, with each set of experimental parameters. For each cutting condition, the data collected consisted of the mass loss in the plate (derived from measurements before and after cutting), the collected mass of dross in the cabinet and the collected ‘fume’ mass in the cyclone fume cup. In addition, each parameter set includes a data set generated by the Spraytec analyzer (during the cut and for 30 minutes after the cut).

The material used was SS 304L, the predominant constituent of the nuclear sector, at three thicknesses: 6, 12 and 25 mm. The compressed air pressures used were 2 and 6 bar. For the metallographic analysis a sample was mounted, grinded and polished. The microstructure images were acquired using a scanning electron microscope (SEM).

3. Results and discussion

3.1 High power cutting parameters optimization

The results of plotting, for each parameter set, the cut depth and kerf width as a function of the corresponding cutting speed, are presented in Figure 3 and 4, respectively. It can be seen that the evolution of cut depth is similar for each case; however the difference for the measured kerf widths is significant. The cut depth and kerf width follow the usual trend that is the depth and the kerf width decrease exponentially with the cutting speed.

![Figure 3 – Cut depth and corresponding cutting speed for each parameter set (for constant power and gas pressure).](image-url)
Analyzing Figure 3, it can be observed that the cut depth is slightly influenced by SD and FP. A detailed look at the kerf width results (Figure 4), comparing for example the focal spot position on the surface of the material (FP=0) and two different SD, shows that the differences due to choice of standoff distances are not significant. Similarly, independently of the SD, the lower kerf widths are obtained for smallest FP. Thus, the factor which appears to significantly affect the kerf width is the focal position, which represents different beam diameters.

Considering the narrower kerfs obtained, two parameters sets were chosen for further analysis. These are able to produce narrower kerfs for the same thickness in case of use CO2 lasers [7]. These are shown in Table 1. It will be investigated if the SPE (Specific Point Energy) concept – that allows the welding characteristics of different laser systems to be directly compared – [8] can be applied to this work.

Table 1 – Two chosen set of parameters

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<tr>
<td></td>
<td>Stand-off distance = 10 mm</td>
<td>Stand-off distance = 25 mm</td>
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<tr>
<td></td>
<td>Focus position distance = -15 mm</td>
<td>Focus position distance = 0 mm</td>
</tr>
<tr>
<td></td>
<td>Beam diameter = 1.14 mm</td>
<td>Beam diameter = 0.36 mm</td>
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The variation of maximum cut depth, for the speed involved, as function on specific point energy was plotted. Figure 5 shows that SPE analysis can be applicable to laser cutting within the parameters used in this study [8].
Figure 5 (left) shows that the same thickness can be cut by decreasing SPE, decreasing the beam diameter. Also, for the same power density, the maximum cut material thickness increases with increasing SPE [8]. In this study this means the same cut depth can be achieved for less interaction time. Comparing these cuts, it can be seen that both the smallest and the largest beam diameters lead to a similar maximum kerf width, although the smallest takes less interaction time. Figure 5 (right) also shows that there is no variation of the kerf width, close to 150ms onwards.

The kerf cross-section and the measured “cut area” resulting of the second part of experiment are shown in Figure 6. For thick plates the difference is significant, the experiment with the minimal focal spot on the work piece surface presents more material removed, for the same speed.

**Beam diameter = 1.14 mm**

- $A = 35.143 \text{ mm}^2$
- $A = 8.736 \text{ mm}^2$

**Beam diameter = 0.36 mm**

- $A = 53.859 \text{ mm}^2$
- $A = 10.115 \text{ mm}^2$
- $A = 5.170 \text{ mm}^2$
- $A = 4.602 \text{ mm}^2$

Figure 6 – “Cut area” measure for 40 (above), 12 (middle) and 6 mm (below) C-Mn steel.

The calculated material removal rate for different focus position, globally, shows that the minimum rate is given for a focal position inside the surface of the material. These removed section, per minute, as function of the interaction time shows that, for both diameters, the removed area increases with interaction time. Also, the smallest beam diameter shows a bigger variation in the slope of the trend line, which translates in more material removal for the same interaction time.
3.2 Fume and dross resulting from cutting processes

The collected results, both the dross and the fume, will be shown in this section.

- **Mass loss in plate and mass of collected dross**

Figures 7 shows, for the highest laser power (5 kW), lower pressure (2 bar) and thinner material (6 mm), the mass loss in plate and the mass of collected dross. It is generally very clear that, for all conditions, the mass loss in the plate is always less than the mass of recovered dross. This can be explained by the material’s oxidation. Also, the minimum plate mass loss and minimum recovered dross mass occurs for the conditions where the laser beam focus is on the surface of the material. Generally, mass loss in the plate and the mass of collected dross increase with thickness and stand-off distance.

![Graph showing mass analysis](image)

**Figure 7** - Mass analysis, 6 mm thickness stainless steel, 5 kW laser power and 2 bar pressure.

For the 6 and 12 mm thick material, changing the laser power from 3 to 5 kW has little influence on the dross produced. For the 25 mm thick material, for minimal dross production, the tolerance to stand-off distance appears the biggest.

It would seem that, over the range of parameters investigated, stand-off distance changes have a larger effect on the amount of dross produced, than changes in cutting gas pressure.

- **Adhered dross remaining on plates**

Figure 8 shows the resultant adherent dross on the reverse side of selected cuts and the cutting conditions used. Generally, it can be seen an oxide layer in each sample, resulting of 21% of oxygen present in compressed air used in the process.

![Photographs showing dross](image)

**Figure 8** - Photographs of the back of the samples, after experiments, for 6 bar pressure and 3 kW laser power. Left: 15 mm stand-off; Right: 65 mm stand-off distance.
From the measurements made, it was observed that, independently of the cutting speed, the collected mass of dross is always higher in the cuts performed at 6 bar, compared with the ones realized at 2 bar. Also, increasing stand-off distance significantly increases the amount of dross adhering to the plates. However, it is clear from the results that a sample with a significant amount of clinging dross doesn't necessarily mean that the mass of dross released is low.

- **Particles size distribution**

In terms of safety for nuclear decommissioning the interest is to know the whole range of particles sizes produced but particularly those below 10 microns, the size that can be inhaled by humans. Thus, the influence of parameters on particles size distribution is crucial in evaluating the use of laser cutting in decommissioning.

The cumulative volume percentage as a function of particle size diameter was plotted, for all different parameters. It was also plotted, for the same criteria, the particle frequency distribution. However, from these graphs there appears to be no obvious relation between the particles size distribution and the cutting parameters.

![Graph showing particle size distribution](image)

Figure 9 shows the average frequency distribution from the results obtained with 6bar gas pressure, for stand-off distances of 15, 40 and 65 mm. It can be seen that the smallest particles detected appear to be about 0.5 µm in diameter, regardless of stand-off distance. Also, fewer small particles are generated at a stand-off of 65 mm, followed by 40 and 15 mm stand-off distance. Figure 10 shows the average frequency distribution from the results obtained with 2 bar gas pressure. Here, the size of particles in the first peak of the distribution occurs for 5 µm, for stand-off distances of 65 mm. The graph shows that, in general, the lower gas pressure leads to higher percentage of secondary emissions with larger diameter, as seen in CO2 lasers [6].
The average of %V<10 µm for all the configurations that were carried out shows that, for 6 bar pressure, the %V<10 µm decreases and Dv(10) increases with stand-off distance, which represents less percentage of small particles and bigger particles size.

- **Metallography analysis**

In order to better understand the results shown above, an SEM examination of the collected dross was undertaken. In terms of shape, the majority of particles seen were spherical in nature but other particles, irregular and often elongated in shape, can also be seen. The right sample reveals more non-spherical particles. It appears that the smallest particles are more spherical, and these spherical shapes appear to have maximum diameter of the order 45/50 µm for both samples.

4. **Conclusions**

The high power laser is a promising cutting tool for decommissioning. The results obtained have shown that:

- The cut depth is not significantly influenced for different nozzles combinations. However, the factor which appears to affect the kerf width is the focal position. Minimum laser spot diameters are thus advised, for smaller kerf widths.
- The same thickness can be cut by decreasing the beam diameter, for constant laser power and cutting speed. However, after certain interaction time, independently of the beam diameter, a decrease of cutting speed doesn’t influence the kerf width.
When cutting below the surfaces of the plates, which means using the biggest diameter, the performances were not so high. This is translated in less material removal for the same cutting speed.

Quantification and control of fumes, by modification of the parameters of process, can contribute to a reduction of emissions. The results obtained have shown that:

- The most tolerant condition for producing minimal dross is when operating with the beam focus on the surface of the material. Also, to minimize the production of dross low cutting gas pressure and laser power should be used.
- It is not possible to establish a clear relation between the mass of dross collected and the adherent dross on the plates. What can be seen about dross in plates is that the bigger amounts are related with 2 bar pressure and 65mm stand-off distance.
- The particles size analysis shows that the range of particles size changes from a minimum of 0.34µm to a maximum of 400µm. Also, the lowest volumes of particles below 10µm were revealed at the largest stand-off distance and for the thickest material. For 6bar larger particles were produced for thicker material and higher stand-off distance. However, the lower gas pressure leads to higher percentage of fume with larger diameter.
- Analysis by SEM of collected dross confirmed that the particles are more spherical at smaller dimensions.

5. References


