The Potential of High Power Lasers in Nuclear Decommissioning - 10092

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ABSTRACT

Contaminated concrete and pipework present major nuclear decommissioning challenges in terms of the total volumes of material to be treated, the radiation levels present and the number of facilities affected. A number of concrete decontamination techniques have so far been evaluated and whilst water-jetting or mechanical scabbling tend to be the favoured options, each has drawbacks such as significant secondary wastes or the need for extensive control and deployment systems. Concrete decontamination by means of laser scabbling has the potential to avoid many of the above drawbacks. However, whilst the technique has been demonstrated at laboratory scale, to date, no representative scale demonstration has been provided which would give industry confidence in the technique.

Although cutting of pipes has been performed on numerous occasions, most of the techniques employed are slow to operate or are not optimised for remote deployment in highly active cells. Lasers are well suited for remote deployment due to the lack of reaction force, small process head and limited fume generation. However, as above, the process needs to be adequately demonstrated before active deployment will be seriously considered.

Until recently industrial lasers have often been seen as too unreliable for use in nuclear decommissioning environments, hence their usage has been limited. The advent of solid state 'fibre lasers' has, however, provided a truly robust and reliable industrial 'tool' which is not only capable of performing concrete scabbling, but also provides a rapid, easy to deploy, remotely operated pipe cutting system.

This paper will describe the results of using optical fibre delivered laser power, to remove the surface of a range of representative concrete samples and shows the capability of the laser for remote single-sided pipe and tube cutting.

INTRODUCTION

Concrete and metal pipework form a large proportion of the civil structures and process plant within many nuclear facilities. As a result contaminated concrete and pipework present major decommissioning challenges in terms of the total volumes of material to be treated, the radiation levels present and the number of facilities affected. Radioactive contamination of concrete structures is largely limited to within a few mm of the concrete surface. Removal of this contaminated zone enables the remainder of the structure to be demolished using conventional means and significantly reduces waste treatment and disposal costs. A wide range of concrete decontamination techniques have so far been evaluated with mechanical scabbling and high pressure water jetting being amongst the most currently favored options. Both techniques however have inherent drawbacks as they require extensive control and deployment systems and, in the case of water jetting, generate significant secondary wastes.

Concrete surface removal by laser scabbling offers a potential alternative technique without many of the aforementioned drawbacks. The technique relies on the generation of temperature gradients in the paste and aggregate, expansion of the paste, microcracking of the aggregate and rapid expansion of residual water in and at the periphery of the aggregates. Although demonstrated at laboratory scale [1-6] on specific concrete types, to date, no representative scale demonstration has been provided which would give industry confidence in the technique. Cutting of pipes has already been performed in several decommissioning projects however most of the techniques employed are slow to operate, not well suited to remote deployment or generate significant fumes. For cases where pipe cutting has to be performed within highly active-cells, laser cutting offers a potentially attractive solution, being ideally suited to remote deployment due to the lack of reaction force, small process head and limited fume generation. However, as in the case of laser scabbling above, the process needs to be adequately demonstrated before active deployment will be seriously considered. Laser cutting is a highly industrialised process, capable of producing 2 and 3D parts with high quality edges. The process is documented in the book by Powell [7]. More recently, [8] attention has been given to the use of lasers for dismantling nuclear power plant.

The major reason for the limited use of lasers in decommissioning is that historically, industrial lasers have been considered unreliable and not suited to on-site nuclear decommissioning environments. However, the advent of robust, high power (4+ kW) lasers, whose beams can be transmitted down optical fibres, has provided a more realistic opportunity for use of lasers in decommissioning applications. Power from a fibre or Nd:YAG (Neodymium, Yttrium Aluminium garnet) laser can be transmitted via several hundred metres of fibre optic cable, hence the laser unit can be located some distance from the active area of operations. As a result there is no risk of contamination of this high value asset, which can therefore be reused on a number of decommissioning tasks so spreading the capital cost of the equipment.

This paper describes work conducted at TWI on behalf of the Nuclear Decommissioning Authority (NDA) which demonstrates the capabilities of laser scabbling concrete of various aggregate types and evaluates the capability for the single sided cutting of stainless steel tubing from 25 to 150mm in diameter, and up to 4mm in wall thickness.

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 of the Plutonium 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, culminating in 2005, with the introduction of high power fibre 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.

This fibre laser technology has many advantages when compared to carbon dioxide laser technology. The efficiency in converting electrical power to optical power is three times higher than carbon dioxide lasers. The fibre laser contains no moving parts at all, uses complete solid state technology and as a result, is robust and very compact in size. As the beam is generated in an optical fibre, similar 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 laser sources 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 lasers have the high beam quality necessary for the laser cutting application, which requires high power densities. For the laser scabbling application, beam quality is not an issue, as a large laser spot is required and low power densities are used. It is a measure of the flexibility of fibre laser technology that a single laser source now has the capability of both raw power and high beam quality needed for the two processes described here. 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.

Fig. 1. 5kW Fibre laser.

The beam from the small diameter optical fibre taking the bundled laser power is optically isolated in a beam switch unit before being focused into the delivery fibre. This has the dual advantage of offering laser power delivered to multiple locations at the flick of a switch but also it isolates the optical fibres in the laser itself from the delivery fibre and process head. In this way, should there be any damage to the delivery fibre, this can be addressed without affecting the laser. All optical components are supplied with universal plug and play connections, if components need to be exchanged for any reason.

The diverging laser beam emerging from the delivery fibre, in all commercially available processing heads, is intercepted by a quartz lens and first made parallel, before being focused by a second lens. Typical focusing distances are of the order 100-500mm. For the scabbling process a high power density is not required and a laser beam of diameter 50-80mm is typical of that used in concrete scabbling. It would be possible to produce this optically using a single lens element to produce a wide beam. This has the disadvantage, however, of exposing the lens elements to the flying debris produced by the process. If the laser beam is allowed to come to a focus (< 0.5mm diameter), a diverging beam, below the focus position, can be used on the concrete. Up to the focus position the beam path can be protected by a nozzle with a small diameter orifice (< 1mm in diameter), greatly minimising the chance of debris damaging the lens. The surface of the focusing lens is further protected by a cross jet of compressed air, of sufficient intensity to deflect small particulate material (this technique was developed to prevent spatter damaging optics during welding operations and is in current widespread use). Cutting process heads are similar in conception but use a different configuration of optics to achieve the best laser beam configuration for the cutting operation. A high power density and a long depth of focus at the cutting point are required. In cutting, a compressed gas is directed through the nozzle tip to aid debris removal from the kerf. In conventional cutting applications, a critical parameter is the distance between the nozzle tip and the surface of the metal being cut.

To maintain this distance constant during movement, adaptive distance sensing units (based on capacitance or inductance) are available.

For single sided cutting applications however, such approaches are too difficult to implement, as the distance from the tip of the nozzle and the cutting point is both large and can also vary by as much as 100mm in a single cut.

The arrival of solid state lasers has revolutionised the design of conventional laser cutting equipment and opened up a new range of opportunities for remote cutting applications. In the context of this paper, the objective was to demonstrate the cutting of stainless steel pipe work, such as that found in reprocessing and other fuel cycle facilities.

Fig.1. shows a photograph of a 5kW IPG fibre laser. The single cabinet shown contains not only the laser source, but a heat exchanging cooling unit and a four way optical beam switch. The latter can be used to connect more than one fibre and process head to the same laser source.

LASER SCABBLING

Concrete Types

Concrete is composed of a mix of hydraulic cement, water, a fine aggregate, sand, and a coarse aggregate. A broad, typical formulation is:

• Cement	350kg/m^3
• Water	170kg/m^3
• Sand	750kg/m^3
• Coarse aggregate	1150kg/m^3
• Nominal density	~2400kg/m^3

The cement chemically reacts with the water to produce an inorganic complex matrix of calcium silicates with smaller amounts of calcium aluminates and alumino-silicates, all of which are essentially inert and durable materials; this binds the aggregates to form a hard durable material. This process also results in the formation of up to about 20% weight in the cement of hydrated lime (calcium hydroxide); the amount depends on the specific cement type used. There is always a proportion of free water and loosely bound water in new and aged concrete, the quantity depending on time, the amount initially added and the quantity of cement in the mix. The sand and aggregate less than 4mm size is normally natural material, with over 90% siliceous content, although some concretes have a proportion of sand replaced by a crushed, fine limestone. The coarse aggregate, which forms the largest volume fraction of the concrete, up to 80%, generally varies with the regional location and availability; this is size graded in increasing proportions between 5 and 20mm though some early massive structures are believed to include a proportion of 40mm material. Three generic types of aggregate are used namely: limestone, basalt (an igneous rock) and quartzite (high in silica and mixed gravels)

Materials Used

The results presented were achieved on a series of precast concrete slabs of dimensions 600x300x75mm, manufactured to the composition below:

• Total OPC cement	350kg/m^3
• Sand (90% siliceous content)	750kg/m^3
• Coarse aggregate	1150kg/m^3
• Water	170kg/m^3
• Water cement ratio	max 1:2

Three coarse aggregates were used, in each case consisting of approximately 6mm sized material, limestone, black basalt and siliceous round gravel. These were designated:

- L 1-12 for slabs 1-12 made using limestone aggregate.
- B 1-9 for slabs 1-9 made using basalt aggregate.
- S 1-9 for slabs 1-9 made using siliceous aggregate.

a) Limestone aggregate b) Basalt aggregate c) Siliceous aggregate.

Fig. 2. Fractured sections from an example of each type of aggregate.

Laser System and Beam Delivery

A Trumpf HL4006 lamp pumped continuous wave Nd:YAG laser was used for all the scabbling work reported here. This laser produces its output as a continuous stream of coherent light at a wavelength of about 1μm, at powers up to 4000W. The laser power was delivered via an optical fibre, 0.6mm in diameter and then focused using a pair of quartz lenses. Beyond the focus the laser beam diverged once more and different beam diameters were available on the concrete surface by varying the height of the lens above this surface. An advantage of this method of beam incidence is that close to the beam focus the beam can be surrounded by a nozzle with a small exit hole. This prevents much of the scabbled debris from the process reaching the focusing lens and reduces the risk of damage to the optical elements. Relevant parameters for the laser beam delivery system used can be found in Table 1. The optical process head was mounted on the arm of an articulated robot, used to move the spot of laser energy across the surface of the material.

Table I. Incident laser power density for the optical systems used.

Optical system	Beam diameter incident on concrete, mm	Power density (W/cm^2) at	
		3000W	4000W
Diverging beam	23	720	960
	43	210	280
	50	150	200
	65	90	120

Results - Siliceous Aggregate

A fractured section of this type of concrete can be seen in Fig. 2c. For this concrete the laser power was fixed at 4000W. Three different laser spot sizes were used, of 65, 43 and 23mm diameter, corresponding to laser power densities from 120 to 960W/cm^2 incident on the concrete surface. Single passes were made with the surface of the samples both dry and wet.

Fig. 3. shows the results of a series of affected areas with single passes of the laser beam at two spot sizes of 43 and 23mm at a range of speeds for a dry surface. As can be seen, at the higher power density, all speeds between 100 and 1400mm/min produced different degrees of surface vitrification, with speeds below 200mm/min producing particularly hard surfaces which tend to be a mixture of white and black in colour. At the lower power density very little scabbling occurred for any speed between 100 and 1400mm/min. At the lowest speed a certain amount of vitrification of the surface could be seen, parts of which were very hard. Fig. 4. shows a continuation of the work on this concrete at the lower power density to include other speeds and wet surfaces. All the passes at speeds between 350 and 500mm/min were produced with a wet surface to the concrete. One of the two samples shown at the speed of 350mm/min, was a double pass, one on top of the other. In all cases where the surfaces were wet, better performance could be seen. There is a direct comparison at a speed of 500mm/min, between a dry sample (shown in Fig. 3.) and the wet sample shown in Fig. 4. What appears to be happening, when the surface of this concrete is wet, is that the laser is able to remove the concrete paste at the very surface of the material without breaking apart the large siliceous aggregate underneath. A double pass of the laser beam did not appreciably improve the process. Fig. 5. shows the results of applying an even lower power density (from a spot size of 65mm in diameter) on a dry surface. As can be seen, at the two speeds of 50 and 100mm/min shown, the laser beam produced little effect.

Results - Basalt Aggregate

A fractured section of this type of concrete can be seen in Fig. 2b.). For this concrete the laser power was fixed at 4000W. A laser spot size of 43mm diameter was used, corresponding to a laser power density of 280W/cm^2 incident on the concrete surface. Passes were made with the surface of the samples both dry and wet. Fig. 6. shows the effects of a series of single passes of the beam over the concrete surface, at speeds from 50 to 300mm/min. For speeds at and below 100mm/min, significant vitrification of the surface was seen producing a very hard black glassy result, so hard in fact that a wire brush could not remove it. Wetting the surface did not improve the situation, as can be seen if the two passes at 100mm/min are compared. No additional work was performed on this particular type of concrete.

Results - Limestone Aggregate

A fractured section of this type of concrete can be seen in Fig. 2a). For this concrete the laser power was fixed at 4000W. Laser spot sizes of 65, 43 and 23mm diameter were used, corresponding to laser power densities of 120, 280 and 960W/cm^2 respectively, incident on the concrete surface. Passes were made with the surface of the samples both dry and wet. Immediately obvious with the first slab of this concrete, processed with the spot size of 65mm diameter, was a clear scabbling process, characterised by the spalling of significantly large pieces of concrete at high expulsion velocity, leaving a scabbled surface which showed no indication of melting. Fig. 7 shows an example of a random collection of such pieces, giving an indication of the size of the debris. Fig. 8. shows the effects after the scabbling process. In this photograph no brushing or cleaning of the surface has been performed. In particular run 13 is a single pass at a speed of 100mm/min, while run 14 corresponds to a double pass, one on top of the first, at the same conditions and a travel speed of 100mm/min. Fig. 9. shows a second block where similar scabbling has occurred, in this case showing, in particular, side by side passes in run 11, again made at a speed of 100mm/min. The two black lines at the top of this pass indicate the degree of overlap between passes.

Run 13 (single pass) showed a maximum scabbling depth of 11mm and a track width of almost 80mm. At 100mm/min travel speed, approximately 55cm^3/min of material is being removed. Run 14 (double pass one on top of the other) showed a maximum scabbling depth of 20mm and a track width of 110mm, larger than for the single pass. Accounting for the double pass at 100mm/min this equates to a material removal rate of 65 cm^3/min. Run 11 (double pass side by side) showed a maximum scabbling depth of 15mm and a track width of 135mm. Accounting for the double pass at 100mm/min, this equates to a material removal rate of approximately 63cm^3/min.

Within this sequence of results the effect of wetting the surface of the concrete before the laser beam pass was investigated. Generally a wet surface improved the width of the scabbled track, (by up to 60%) but did not appreciably increase the scabbling depth. However, the volume of the material removed also increased by about 50%.

Discussion on Scabbling

When the scabbling process worked (on concrete containing limestone aggregate) a maximum removal rate of concrete was measured at $65 cm^3/min$, from a double pass. This also produced the deepest scabble at 20mm. A similar removal rate was observed for a side by side pass, at $63 cm^3/min$, but in this case the maximum depth was 15mm. When wet, the process appeared to be improved in terms of width of track and removal rate, but not in terms of the maximum depth of scabble obtained. For concrete containing siliceous aggregate, it was clear that the concrete paste forming the surface of the block could, under some conditions, be removed. However, in most cases this was less than 1mm thick. Removing this surface exposed the large siliceous aggregate, which was for the most part, unaffected by the laser beam, until the power density became so large that melting appeared to set in. There was no evidence of separation of the concrete at the boundaries between the aggregates. When the concrete was wet, there was some evidence of better performance, but this was slight. When using the basalt aggregate no evidence of explosive scabbling, either for wet or dry concrete was found. In addition, when the power density was increased, the resulting melting produced a surface that was too hard to easily remove by wire brushing.

[------------Spot size 43mm-------]   [---------------------Spot size 23mm---------------------]

Travel speed, mm/min:
500   1000   100   1400   1400   1200   800   400   200   100

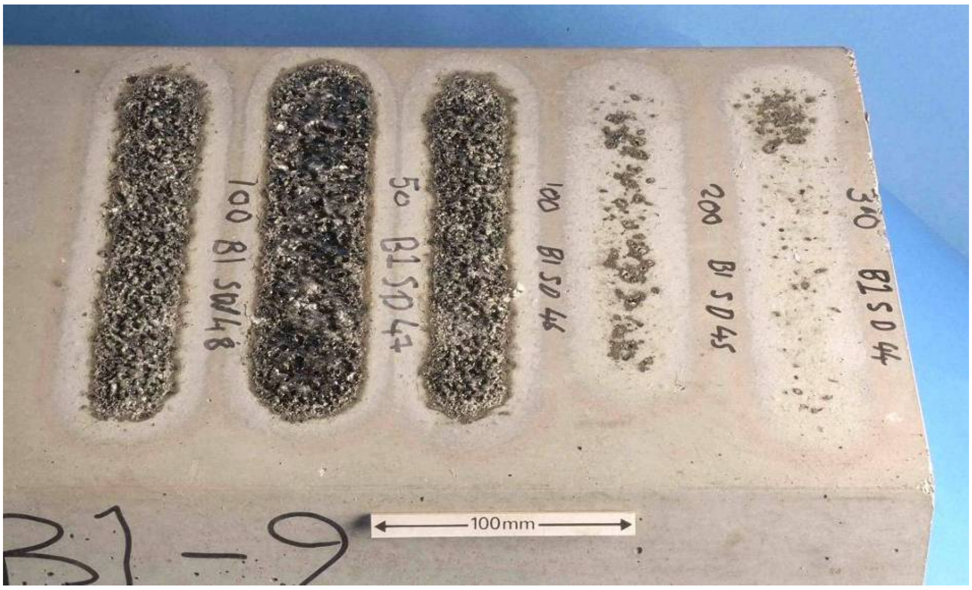
Fig. 3. Siliceous aggregate. Laser passes at 4000W on a dry surface.

Travel speed, mm/min:					
250	500	400	300	350	350
Condition:					
Dry	Wet	Wet	Wet	Wet	Wet Double pass

Fig. 4. Siliceous aggregate. Laser passes at 4000W using a spot size of 43mm diameter.

Travel speed, mm/min:		
	100	100
Condition:	Dry	Wet

Fig. 5. Siliceous aggregate. Laser passes at 4000W using a spot size of 65mm diameter.



Travel speed, mm/min:
100 50 100 200 300
Condition:
Wet Dry Dry Dry Dry

Fig. 6. Bassalt aggregate. Laser passes at 4000W using a 43mm diameter spot size.

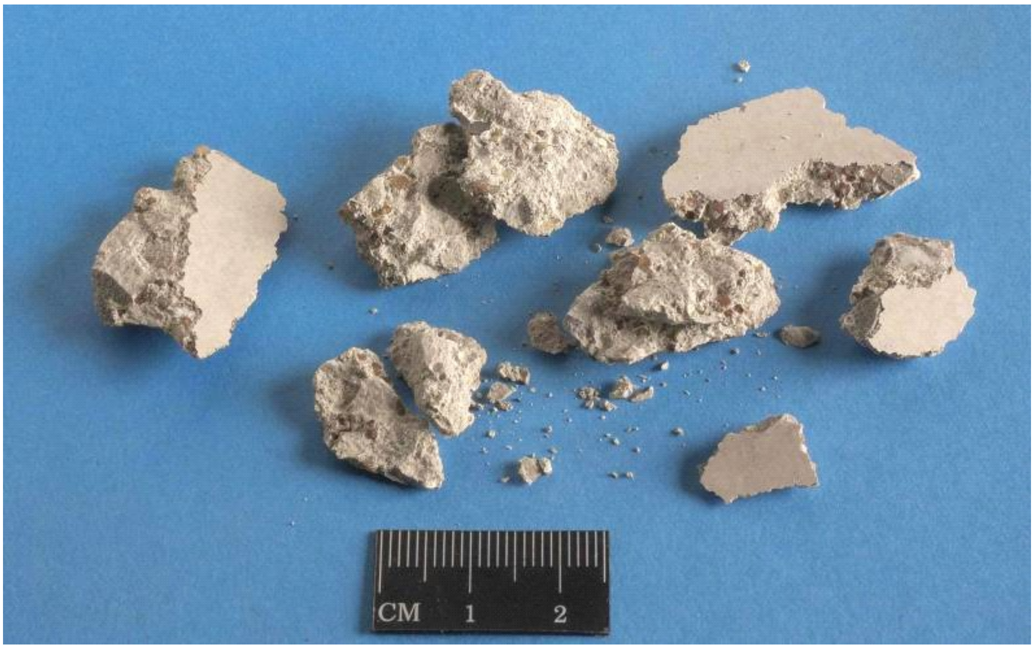


Fig. 7. Typical debris from the scabbling process on limestone aggregate concrete.

Fig. 8. The scabbling process on concrete containing limestone aggregate:
Run 13 - single pass at 100mm/min;
Run 14 - double pass, one on top of the other, both at 100mm/min.

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Fig. 9. The scabbling process on concrete containing limestone aggregate:
Run 11 - double side by side pass, each at 100mm/min.

SINGLE SIDED LASER TUBE CUTTING

In the cutting process, a finely focused laser beam, usually with a diameter of about 0.2mm, is used in conjunction with an assist gas, to perform the cut. Typical thicknesses for cutting steel with commercially available laser equipment range from less than 1mm to about 20mm. In this range the laser has the capability to produce a smooth cut face, in some cases good enough to be welded without any further work. For such good cut quality, it is critical that the focus position of the laser beam is on or just below the material surface and the distance from the nozzle delivering the process assist gas to the material surface is constant at ~1mm. In the nuclear industry there are many applications where metallic structures need to be cut into pieces to assist decommissioning. In most cases the quality of the resulting edge is not important provided complete separation of the parts is achieved. For remote tube cutting operations, the most convenient and simple approach would be to keep the beam focus position at a constant height in front of the tube. If the beam focus were to be positioned on the material surface, a much reduced power density would be available in the lower parts of the beam which interact with the underside of the tube. If the focus is positioned at half the diameter of the tube, then the power density is optimised for cutting the thickest part of the tube, but the nozzle must be positioned at least half the diameter of the tube away from the focus. It can thus be seen that single sided tube cutting is quite far removed from conventional flat sheet precision laser cutting. In fact very little R&D has been performed in this area.

Materials Used

The cutting was conducted on a range of 304grade stainless steel tubing, of diameter 25, 60, 100 and 154mm, with wall thicknesses from 1.5 to 4mm. For some diameters two wall thicknesses were investigated. The tubes were either positioned horizontally and cut from above (side to side) (orientation A), or cut from the side (from top to bottom) (orientation B). Some tubes were also positioned vertically and cut from the side in the horizontal plane (orientation C).

During the trials, compressed air, argon and nitrogen gas were used as cut assist gas.

Laser System and Beam Delivery

The laser used for the tube cutting was an IPG Photonics 5kW fibre laser, equipped with a four way beam switch. (the laser shown in Fig. 1.). The optical fibre used was 150 microns in diameter, and this was connected to a custom designed cutting head fitted with collimating lenses of 120 and 160mm in focal length and focusing lenses between 160 and 500mm in focal length. This provided a wide range of focus spot size and depth of focus. The smallest spot size produced the highest power density but the shortest depth of focus. For each available lens the cutting nozzle was configured to terminate in a copper nozzle, with an exit for the beam and assist gas appropriate to the lens being used and a nominal distance of 100mm from the end of the nozzle to the position of the laser beam focus. This optical assembly was positioned on the arm of an articulated robot which provided the necessary movement of the laser beam during cutting. Experimental variables included, laser power, focussed spot size, assist gas, assist gas pressure, cutting orientation, cutting speed and focus position with respect to the closest part of the tube surface, for each tube investigated.

Results

This section is restricted to the results when cutting with the tubes horizontal and the laser beam incident from above the tube. Fig. 10 shows a graph of the maximum cutting speed possible for single sided cutting of stainless steel tube diameters from 25 to 155mm. All results are presented using the same cutting lens and the same laser power. In addition the process assist gas used and its pressure in the top of the cutting nozzle were also the same. The numbers inside the graph correspond to the tube wall thickness. This set of results has been chosen to show the range of tube diameters and wall thickness which might be successfully cut varying only the process speed and keeping all other parameters constant.

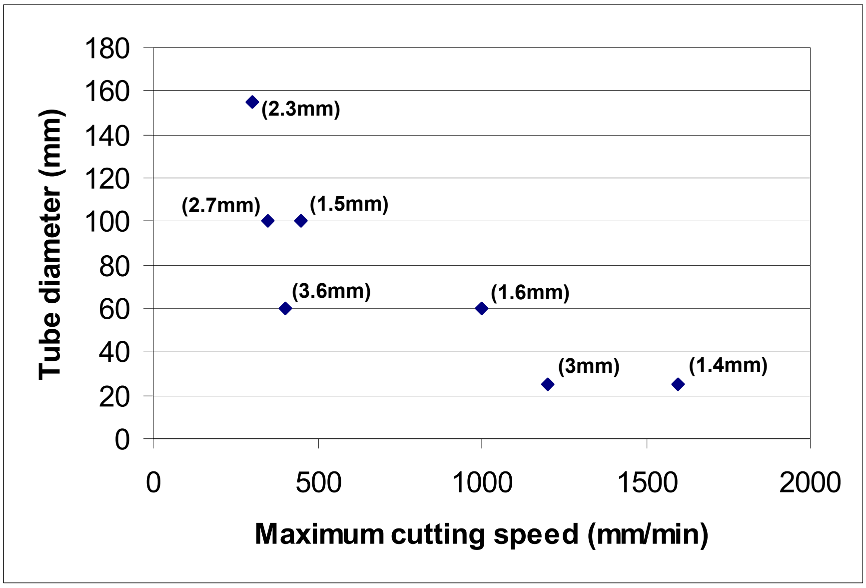

Fig.10. Maximum cutting speed for various tube diameters. The figures in brackets indicate the tube wall thickness.

For a given tube diameter it is possible to improve cutting performance shown in Fig. 10, by adjusting one or more of the available processing parameters. However, it should also be pointed out that in the trials reported, the range of cutting speed for each tube/wall combination was also established, the only acceptance criteria being separation of the tube. At a cutting speed of 300mm/min, it was in fact, possible to cut all the tubes used in the trials.

Fig. 11. Tube edge quality (20-155mm tube).

Fig. 12. Tube edge quality (thicker wall).

Fig. 11. shows the cut edge quality for the four tube diameters used and wall thicknesses from 1.4 to 2.3mm. Fig. 12 shows the same for the thicker walled tubes up to 100mm in diameter. What is clear in all cases is, not unexpectedly, that the half of the tube closest to the side of approach of the laser beam is easier to cut than the remaining part. In the instances where a complete separation is not made, the un-cut material is almost always on the far side of the tube.

SUMMARY AND CONCLUSIONS

Scabbling

Although the results of this work have demonstrated the scabbling of wet and dry concrete to be a process with the potential to deliver the concrete removal rates required in decommissioning, performance is very dependant upon the type of concrete being processed. Further work is ongoing to better quantify the laser scabbling process and to establish its tolerance to concrete type.

The conclusions drawn from this scabbling work are:

1 For scabbling of limestone aggregate based concrete, a maximum material removal rate of $63cm^3/min$ was observed, using a laser power of 4000W. This is equivalent to removing $1m^2$, to a depth of 5mm, in about 80 minutes.

2 Where scabbling occurred, a surface wetted or soaked with water improved the efficiency of the process.

3 The only aggregate tested that resulted in explosive scabbling of the bulk material (ie to depths greater than 1mm) was limestone-based.

4 Under the conditions examined, no conditions were found to laser scabble the concrete containing the basalt aggregate. The resultant surface was however, degraded and so easier to remove using modest mechanical techniques, than untreated concrete.

5 Partial surface scabbling was observed on the concrete containing siliceous aggregate. As with the basalt material, the surface was degraded.

This work has raised important questions about the laser scabbling process in general, which it is believed, can still be considered a viable possibility for some concrete decontamination applications. In particular, under the conditions examined, which included, for the first time, work performed on a range of concretes containing different aggregates made under controlled conditions, the difficulty of scabbling the concrete containing the basalt and siliceous aggregates was very clear. It was also apparent, that even between the concrete slabs manufactured using the limestone aggregate, different results could be obtained under the same scabbling conditions. Further trials are therefore being undertaken on the laser scabbling process, to determine the relevance of not only the type of aggregate used in the concrete but also its size, and the condition of the surface of the concrete prior to application of the laser beam. The trials will also determine if the process which, when it works, works well, scales with applied laser power. For future practical realisation of laser scabbling, an assessment of the composition of the concrete concerned will have to be made, to determine its suitability for this process.

Cutting

For the first time, the results of using high power focused laser beams for **single sided** cutting of stainless steel tubing at up to 155mm in diameter have been presented. Performance is very encouraging both in terms of the range of tube diameters and wall thicknesses that can be successfully severed. The process is therefore deemed capable of performing many of the in-cell size reduction tasks that will be required during decommissioning of various nuclear fuel cycle facilities.

The conclusions drawn from the work to date are:

1. Using a laser power of 4kW, stainless steel tube of diameter 155mm and wall thickness 2.3mm, has been cut from one side, at a speed of 300mm/min.

2. Using a laser power of 4KW, stainless steel tube of diameter 25mm and wall thickness 1.4mm, has been cut from one side, at a speed of 1600mm/min

3. Using a laser power of 4KW, stainless steel tube of diameter 25mm to 155mm can be cut from one side using a single cutting speed of 300mm/min.

Further work is ongoing to characterise this process on different relevant materials and tube sizes to establish the limits of the process. In particular a better understanding the role of the cut assist gas is required when using non standard large diameter cutting nozzles and optimising this to assist with removal of material from the base of the cut.

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