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Studies on the robustness of underwater laser cutting of S355J2+N using a Yb:YAG disk laser source

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Abstract

In this paper, an underwater laser cutting process for maintenance and replacement operations is presented and investigated regarding process robustness for the application in rough environments. A Yb:YAG laser is used with 4 kW laser power in an active cutting process with oxygen as cutting gas. For 10 mm thick constructional steel plates a process window is determined with the focus on robustness for distance interferences. The examined parameter sets include the nozzle clearance, focus positioning and cutting gas pressure adjustment, as they are significant factors of influence in underwater laser cutting. By adjusting the developed parameter sets, sheets with thicknesses up to 50 mm, as well as plates that are fixed to a concrete backing are cut. The used equipment, which completely consists of standard components, is presented along with its preparation for underwater operation.

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Keywords: underwater; laser cutting; robustness; oxygen; deconstruction

1. Introduction

There are over 7000 km of water canals used by the industry for transportation purposes, in particular bulky mass goods, solely in Germany (Ellrich, 2003). These structures are often made of sheet pilings which have an estimated operating life of 50 – 80 years (Heeling, 2010). Depending on the surroundings and the resulting effects of corrosion, their lifetime is often reduced to about 20 years (Binder & Gabrys, 2011). The maintenance often requires the removal of the whole structure which is usually done manually by divers. The average cutting speed that is achieved in those processes using oxyfuel cutting, is about $v_F = 0.06$ m/min (according to diver companies). Strong sea

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currents that may occur, as well as miserable sight and low water temperature makes the work hard and dangerous to the divers. Additionally, commonly used cutting methods that use electrical current involve the danger of injuries by electrical shock. To increase process speed and diver safety an automated system needs to be developed.

Investigations concerning underwater laser cutting were primarily performed regarding nuclear decommissioning purposes. Studies using high power CO_2 lasers were carried out by Takano et al. Stainless steel plates were cut with thicknesses up to 150 mm using 20 kW laser power and a gas mixture of 20 % oxygen and 80 % nitrogen. In Khan & Hilton, laser cutting under water with a 5 kW Yb fiber laser is investigated in terms of dross formation and compared to laser cutting in air. One of the conclusions is that there is a significantly lower mass reduction when cutting under water due to a higher amount of adhering dross. Jain et al. obtained an underwater laser cutting process with a pulsed Nd:YAG laser that was able to cut 6 mm thick steel applying an average of 250 W laser power. The main purpose of these studies was to stick as much solidified melt on the cutting edges as possible to reduce nuclear contamination of the surroundings (Khan & Hilton, 2014).

As it can be seen, there are several studies regarding underwater laser cutting using different laser sources. For industrial applications, investigations concerning robustness and productivity still need to be carried out. To cover this issue, this paper describes the studies on process robustness which are performed using commercial components with the focus on positioning robustness. The first part of this paper is about the experimental setup and the preparation of the optical components for underwater application using a continuous wave laser with up to 4 kW laser power. In the second part it deals with common use cases in sheet piling deconstruction. A process window is developed for the cutting of 10 mm thick steel plates, focusing on the applied cutting gas pressure, focus position and nozzle distance. Further the cutting of sheet packages with thicknesses up to 50 mm and the process behavior of cutting 10 mm thick steel plates with concrete backing is investigated.

2. Experimental setup

The setup used for the studies is shown in Fig. 1 a. A 6-axis robot moves the optics via an extension to allow for vertical processing of the sheet piling specimens in a water depth of about 0.5 to 0.7 m beneath the water surface, depending on the position of the specimens. The specimens are secured by a mount which is able to lift the metal sheets out of the 1 m³ water tank via linear drives. The deployed laser is a Trumpf Trudisk 16002 Yb:YAG disk laser with a fiber of 200 µm diameter attached. In order to develop a process with a low capital expenditure for the target group, including diving or maintenance companies, the optical system is constructed out of standard Trumpf D70 laser components with a limited laser power of $P_L = 4$ kW. The focus diameter is set to 200 µm. To satisfy the requirement of vertical processing, the beam is redirected by a mirror which is integrated in the connection cube between the collimation and the focusing tube. The diameter of the nozzle outlet is 1.7 mm. A tactile sensor, which is installed next to the nozzle, ensures the right positioning of the cutting head to satisfy the targeted nozzle distances and focus positions, respectively.

To obtain waterproofness several modifications have been made to seal areas that are critical for water penetration, as they are not sealed with O-rings as standard. These areas are the fiber coupling and the thread for the tip. To seal the coupling, a shrink tubing is applied directly above the O-ring sealing (Fig. 1 b, dashed line). Teflon tape is used to tighten the notch on the thread for the nozzle stock (Fig. 1 b, dotted line). Additionally, excess pressure is applied to the lens tubing between the focusing lens and the protective glass inside the tip holder. The used gas is compressed air with a pressure of about p = 2 bar.

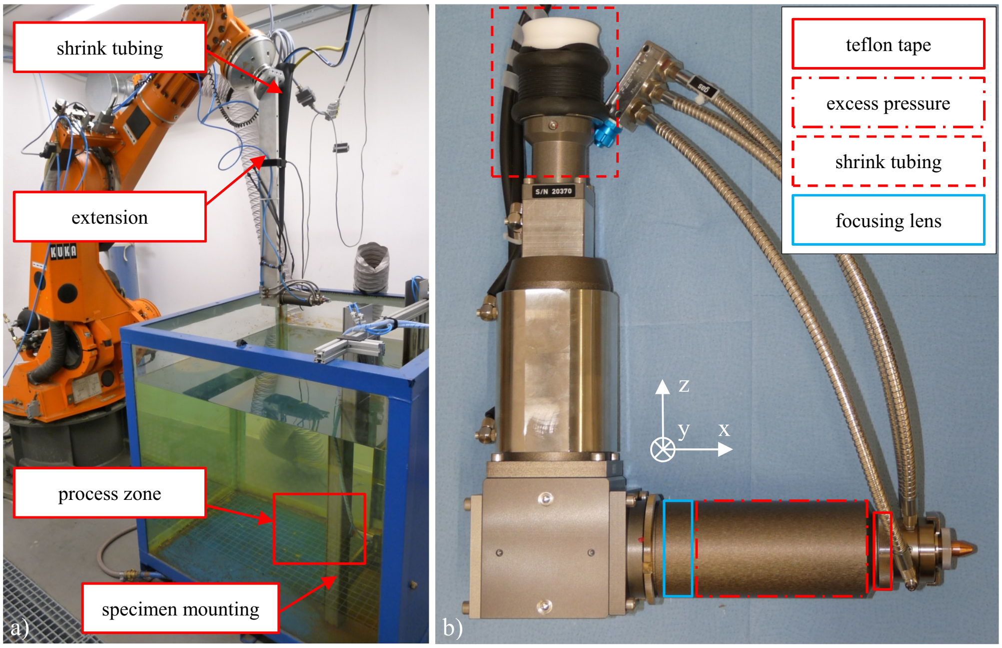

Fig. 1. (a) experimental setup, (b) applied methods to ensure water tightness of the laser cutting head and orientation of axes.

3. Methodology

The tests are carried out with S355J2+N steel plates, while the specimens are cut to pieces of 500x200x10 mm³ for reasons of operability. Before executing a cut, the actual position and geometry of the plate is measured by locating the start and the end point of the cut with the tactile sensor. When the laser is activated the system executes a drilling motion in x-direction beginning with the focus set on the specimen surface till it reaches the targeted focus position d_f. This procedure ensures proper piercing of the plate even when the focus position is set within the material. Subsequently the cut is performed along the y-axis. The focus position is changed by moving the cutting head, while the nozzle could be adjusted by a thread to vary the distance between the focus position and the nozzle tip. The parameters varied are the focus position d_f, the nozzle distance d_n, the gas pressure p and the cutting speed v_F. The laser power is set fixed to $P_L = 4$ kW during the tests. To evaluate the results, a cut is noted as confirmed when a test metal sheet of 0.2 mm thickness can be moved completely from the beginning to the end of the kerf.

4. Results and discussions

As it is a typical thickness for sheet pilings the development of the process is based on the cutting of 10 mm thick steel plates. Furthermore studies are carried out using plate packages with thicknesses from 20 up to 50 mm, what corresponds to two to five metal sheets of 10 mm thickness, respectively. At least cutting tests with a backing of concrete were carried out to simulate a typical way for the fixation of sheet pilings in canals and ports.

4.1. Process development of cutting 10 mm thick plates

The first underwater cutting attempts on $d_p = 10$ mm thick steel plates were used to qualitatively compare the resulting kerfs using air and oxygen as cutting gases. Using air produces kerfs which tend to partially fill up with melt again while it is in liquid state, resulting in an unconfirmed cut. Matching these kerfs with the results of the laser cutting with oxygen, the exothermic energy of the active process directly leads to wider kerfs. Depending on the chosen focus position and nozzle distance, adhering dross will occur on the inside of the kerfs or even more likely on the backside of the plate. Beside the clearer cut, caused by the supplementary exothermic energy, a further advantage of the cutting with oxygen lies in the oxidation of the molten metal. While the adhering dross caused by the process with air as cutting gas is of high strength, the majority of the oxidated melt of the oxygen supported cut is brittle and broke easily. As the objective is to achieve a cutting process that focusses on high robustness the gas which is actually applied is oxygen.

To start determining the process of underwater laser cutting the nozzle distance d_n and the focus position d_f are set fixed to examine the effect of the gas pressure p on the resulting cuts. The nozzle is set with its tip at a distance of 11.5 mm from the focus position, while the focus stays 6 mm under the surface of the material. This position was chosen as a starting point, as it shows good results in first tests. It results in a distance from the nozzle to the plate surface of d_n = 5.5 mm. The oxygen pressure is varied from 4.5 to 8.5 bar and tests are carried out with cutting speeds of 0.3, 0.6 and 0.9 m/min. Each speed is applied two times for each pressure value, which results in a total of six cuts per pressure.

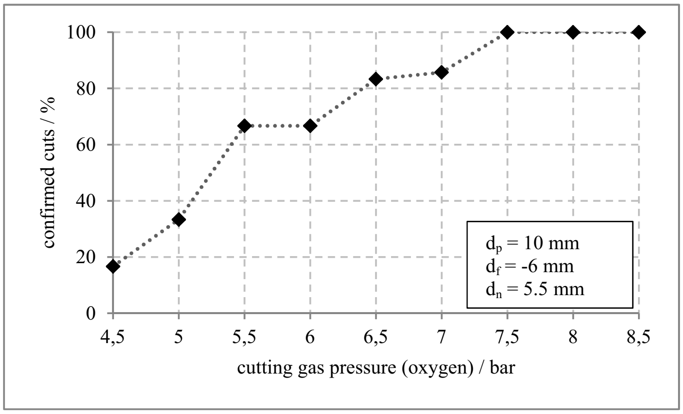

Fig. 2. Success rate of cutting varying the cutting gas pressure (oxygen).

The percentage of the resulting confirmed cuts is shown in Fig. 2. It can be seen that there is constant progression in the number of confirmed cuts, until it reaches the 100 % at the cutting gas pressure of p = 7.5 bar. In the investigated pressure range of p = 4.5 to 8.5 bar an unconfirmed cut is characterized by a kerf that is filled up again with melt which is not to be removed manually like described above. Even though, there is no melt building up on the front surface of the specimen that could contact and damage the nozzle. By lowering the cutting pressure below this range, the risk of damaging the nozzle increases, as the process tends to not pierce the material and most melt comes out at the front side of the plate.

To study the robustness of the process the positioning of the focus and the distance of the nozzle tip to the plate would be some of the most critical parameters in the field. They can change during the cutting process depending on the water movement, which could affect the cutting head position, and inhomogeneities of the plate caused by corrosion or wear. In Fig. 3, the influence of the focus position d_f and the nozzle distance d_n on the ratio of confirmed cuts is shown in form of a matrix. For this study, the oxygen pressure is set to 7.5 bar, according to the results of Fig. 2 and the used cutting speed is 0.6 m/min. The nozzle distance is measured from the nozzle tip to the plate surface, while the focus position is counted negative going into the material, while zero represents the plate's front surface (see explanation of abbreviation in Fig. 3). The numbers in the cells are indicating the spacing between the nozzle tip and the focus position. The ratio of confirmed cuts is shown by the cell color and is calculated as the average out of a total of five cuts. Analyzing the results for the focus position (columns) separately, the climax of the success rate is located in the range of -7 to -4 mm. Beyond these borders the stability of the process decreases. The variation of the nozzle distance (rows) shows at least 80 % confirmed cuts for distances of 4 to 8 mm regarding the respective focus positioning.

In terms of robustness during a cut, the stability could be read by the cells with identical spacing of the focus position and the nozzle tip d_Δ, indicated by the numbers in the cells. The parameter sets located in the center of these diagonals, which are marked with black hatch lines, offer the highest robustness of the investigated parameter sets in case of position changes of the cutting head. Using the corresponding values for the focus position and the nozzle distance shown in the diagramm leads to process robustness of ± 2 mm. To avoid the risk of hitting inhomogeneities on the plate surface, a focus position to nozzle tip distance of d_Δ = 14 mm should be used to obtain a nozzle distance of d_n = 7 mm and thereby the largest spacing between the cutting head and the specimen with robustness of ± 2 mm. If assumed that the trend continues with increasing d_Δ, it could be possible to reach even higher nozzle distances, to further increase robustness. In the used setup, the focus to nozzle spacing was limited to d_Δ = 9 to 14 mm.

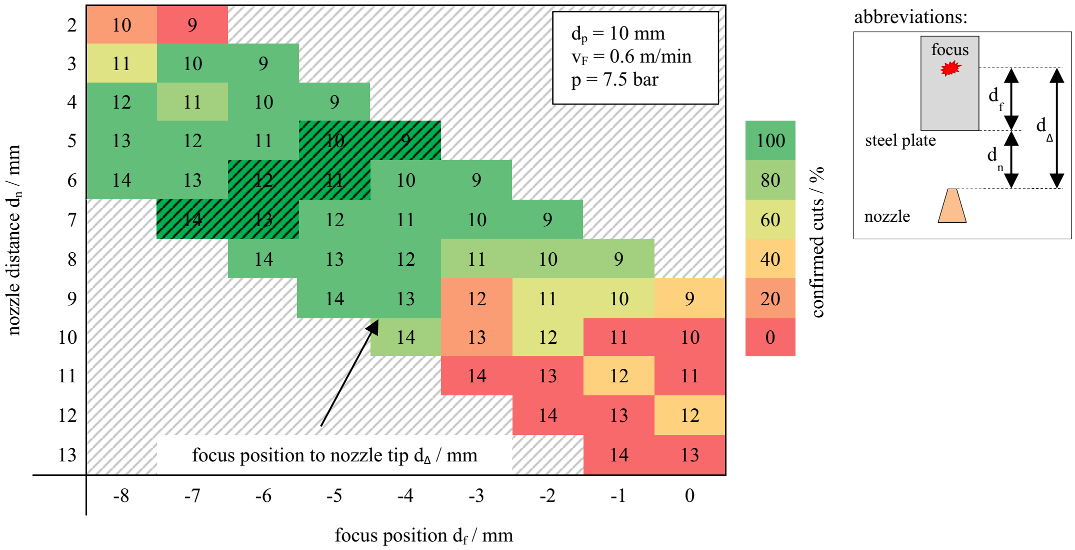

Fig. 3. Influence of the nozzle distance and the focus position on cutting robustness.

These results could be used as an advantage for applications, where safety distances are needed to deal with rough surroundings. As Fig. 2 implies, the process seems to remain stable with higher gas pressure. Assuming this, the green marked parameter window in Fig. 3 could possibly be shifted to even larger nozzle distances using pressures beyond p = 7.5 bar.

4.2. Cutting of 20 - 50 mm thick metal packages

To investigate the ability to cut thicker material, the cutting of packages of 2 to 5 plates was executed, leading to packages with thicknesses up to 50 mm that are mounted on the plates by screws. The focus to nozzle distance was set to d_Δ = 10 mm, with the focus position d_f at -7 mm in the package. Oxygen is used as cutting gas with a pressure of p = 7 bar. The cuts are executed starting on 10 mm thick plates with a change of the material thickness during the cut (Fig. 4). With an increasing package size the process gets less robust, what can be compensated by lowering the cutting speed. While the 20 mm thick packages could be cut with a cutting speed of up to $v_{F,20}$ = 0.18 m/min, the speed needs to be decreased to $v_{F,30}$ = 0.06 m/min to achieve confirmed cuts on 30 mm thick steel packages. By adding more plates, the process needs to be slowed down further to $v_{F,40}$ = 0.03 = m/min for the 40 mm and the 50 mm packages. The cuts that are performed at thicknesses of 30 mm and above are not completely cut at the edges of the packages (Fig. 4). This is caused by the gas flow, which tends to escape sideways when passing a transition of a multiple to single plate section and vice versa. For the classification as a confirmed cut this effect is not taken into account, which means cuts are rated confirmed when the middle section of the kerf is consistently cut.

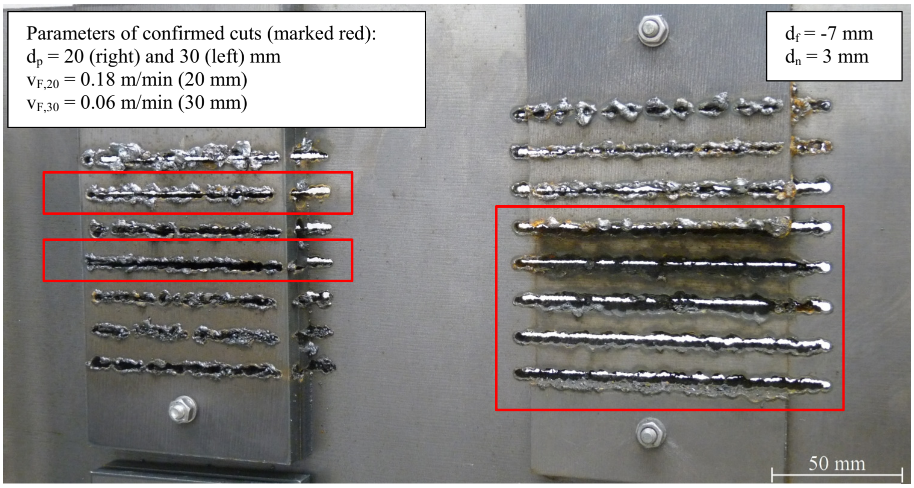

Fig. 4. Exemplary cuts on 30 mm (left) and 20 mm (right) thick steel packages.

4.3. Cutting of 10 mm thick plates with concrete backing

By mounting a plate of concrete behind the 10 mm thick steel plates, the cutting of backfilled sheet pilings is simulated. The concrete plates are attached with screws and have a thickness of 35 mm. To avoid liquid melt escaping out of the front surface of the plate interfering the nozzle, the laser head is set to an angle with the nozzle pointing in the direction of the y-axis (refer to Fig. 1 b).

With the laser head in an angle of 20°, confirmed cuts with speeds up to v_F = 0.6 m/min are achievable. Exemplary cuts are shown in Fig. 5, with confirmed cuts marked in red. The image of the front shows the effect of the angled cutting head on the melt that is coming out of the front side of the plate. Some of the melt is adhering on the concrete as there could be a small gap between both materials. The used parameters for the confirmed and marked cuts are listed in

Table 1. Except the angled cutting head and a limitation of the cutting speed to v_F = 0.6 m/min, the parameters for this application are similar to the cutting of 10 mm thick steel without a backing.

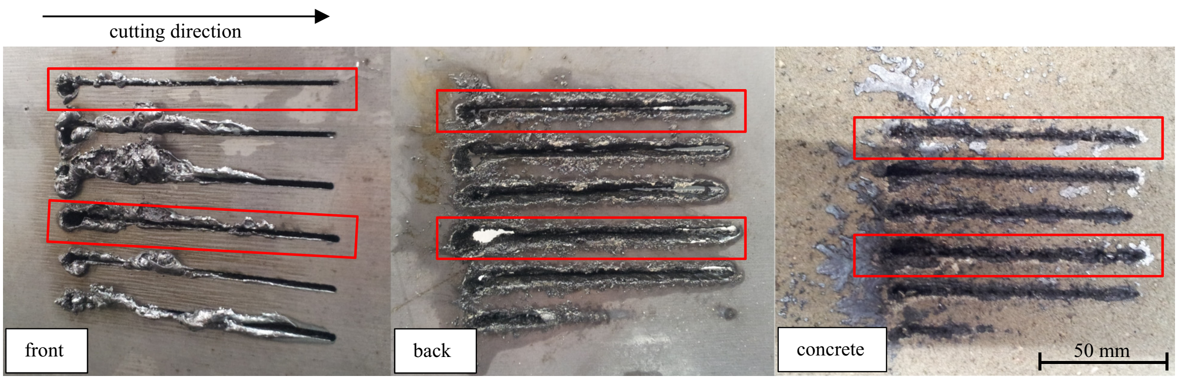

Fig. 5. Kerfs of underwater laser cutting with concrete backing, confirmed cuts are marked red.

Table 1. Underwater laser cutting parameters used for cutting 10 mm thick steel plates with concrete backing.

Parameter	Value
v_F	0.6 m/min
d_f	-7 mm
d_n	3 mm
p	5 bar
angle of the laser head	20°

5. Conclusion

In this paper the preparation for waterproofness of a standard laser cutting head and the investigation regarding robustness of the cutting process underwater is shown. By separately studying the effect of cutting gas pressure, cuts with speeds up to 0.9 m/min could be achieved on 10 mm thick steel sheets using oxygen as cutting gas and 4 kW laser power, which is about fifteen times faster than the average manual cutting speed of a diver. For the purpose of a robust process, the stability in terms of focus and nozzle positioning can be enhanced to ± 2 mm. The developed positioning matrix which was performed with a cutting speed of 0.6 m/min, provides information about the relationship between nozzle and focus positioning and the effect on the resulting cut. Within a range of spacing between the focus position and the nozzle tip from 9 to 14 mm (possible range in this setup), the highest robustness was achieved with the 14 mm spacing and a nozzle tip to plate distance of 7 mm. The applicability of the process for packages of plates was tested with package thicknesses of 20 to 50 mm. While packages with thicknesses of 20 mm could be cut with a cutting speed of 0.6 m/min, the thicker packages need to be cut with decreased cutting speeds. Backfilled sheet pilings are simulated with a concrete plate mounted on the backside of the steel plate and could be successfully cut by positioning the cutting head in an angle of 20° with the nozzle pointing in the opposite of the cutting direction. These cuts were validated confirmed with cutting speeds up to 0.6 m/min.

As the process tends to increase stability with higher cutting gas pressures, it could be assumed to achieve even better results by further studying the relationship of cutting gas pressure and the cutting head positioning. Researches concerning this topic are in progress with the objective of achieving faster cutting speeds and the ability of cutting thicker material.

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References

Binder, G., & Gabrys, U., 2011. FuE-Abschlussbericht Bewertung der Korrosion von Spundwänden. Karlslruhe: Bundesanstalt für Wasserbau.

Ellrich, M., 2003. Infoblatt Kanäle / Wasserstraßen in Deutschland. Geographie Infothek Ernst Klett Verlag GmbH. Stuttgart.

Heeling, A., 2010. Ein Vierteljahrhundert Spundwanddickenmessung mittels Ultraschall bei der Bundesanstalt für Wasserbau. Fachtagung Bauwerksdiagnose (pp. 1-9). Berlin: Deutsche Gesellschaft für Zerstörungsfreie Prüfung e.V.

Jain, R., Agrawal, D., Vishwakarma, S., Choubey, A., Upadhyaya, B., & Oak, S., 2010. Development of underwater laser cutting technique for steel and zircaloy for nuclear applications. Pramana - Journal of Physics, 1253-1258.

Khan, A., & Hilton, P., 2014. Optimisation of underwater laser cutting for decommissioning purposes. ICALEO 2014 Congress Proceedings. San Diego.

Kruusing, A., 2004. Underwater and water-assisted laser processing: Part 2—Etching, cutting and rarely used methods. Optics and Lasers in Engineering, 329-352.

Takano, G., Beppu, S., Matsumoto, O., Sakamoto, N., Onozawa, T., Sugihara, M., & Miya, K., 1995. Development of cutting technique of reactor core internals by CO laser. ICONE JSME/ASME Joint International Conference on Nuclear Engineering, (pp. 1775-1778). Kyoto.