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ORIGINAL ARTICLE

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Cutting thin sheet metal with a water jet guided laser using various cutting distances, feed speeds and angles of incidence

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Abstract This research deals with the cutting of thin sheet metals at various distances, feed speeds and angles of incidence using a water jet guided laser. In the water jet guided laser process a laser beam is focused into a jet of water, which transmits the beam to the workpiece. This eliminates the need for any focus control. Nevertheless, most of its applications are in planar cutting where this advantage is not utilized. For the laser parameters, jet pressure and diameter in question, the value of 50 mm was found to be a fairly reliable upper limit to the cutting distance for both normal and inclined surfaces. In addition to the laser beam being absorbed partially by the water jet, the jet was found to be susceptible to disturbances. Specimen vibration caused by the water jet also impeded cutting a continuous kerf.

Keywords Laser · Water jet · Metal · Cutting

1 Introduction

In conventional laser cutting, the cutting head must be kept at the correct standoff distance from the workpiece to keep the beam in focus and to deliver the cutting gas effectively. This requires a focus control system as well as several axes of movement to follow the workpiece. The water jet guided laser solves the task in a very different way. The laser beam is focused through a pressurized water chamber into a jet of water as shown in Fig. 1. The jet guides the laser beam to the workpiece by total internal reflection thus enabling cutting from a considerable distance and eliminating the need for z-axis movement [1]. This way, 3D parts with large dimensions along the z-axis can be processed without the need for 5-axis laser beam manipulating heads or focus control systems.

A hair-thin jet, as opposed to a conventional cutting head, has the advantage of fitting into confined recesses. In addition, there is no danger of colliding with the workpiece even when encountering sudden dimensions along the z-axis. However, most applications of the invention are in planar cutting, where the water jet is used only for cooling and waste removal. In addition to cutting silicon wafers, current applications in metal cutting are stencils for applying solder paste on printed circuit boards, air gaps in toroidal ferrite cores, and medical stents used for dilating congested blood vessels. These have been presented by the manufacturer in many conference papers and published articles [2, 3]. This independent work investigates cutting thin sheet metal at various distances, feed speeds and angles of incidence, which are necessary variables for processing formed sheet metal objects such as parts of mechanical devices.

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2 Theory

Water jet guided lasers utilize Nd:YAG lasers because of their good pulsing properties. According to the manufacturer, the laser pulses form plasma when contacting the workpiece, thus momentarily separating the high-pressure water jet from the workpiece. After each pulse the water jet cools the surface and expels the cutting waste with a smaller but more concentrated force than in the case of cutting gas.

The cutting distance is restricted by the stable water jet length and interactions between the water and the laser beam. The jet length depends chiefly on the nozzle diameter and the water pressure. According to the

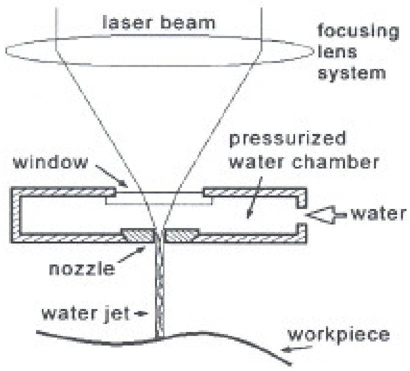


Fig. 1 Operating principle of the water jet guided laser

manufacturer, a ∅100 μm nozzle will produce a 200 mm long jet at an optimum water pressure of 25 MPa while a ∅50 μm nozzle will yield a 100 mm jet at 50 MPa [1].

Absorption of light by the jet is an important factor when considering how much of the original laser power is transmitted to the workpiece. Figure 2 illustrates roughly the absorption coefficient of pure water as a function of the wavelength of light [4–6].

Absorption coefficient values for Nd:YAG lasers are as follows:

$11.4\ m^{-1}@1064\ nm$

$0.05\ m^{-1}@532\ nm$

$0.02\ m^{-1}@355\ nm$

Using Beer-Lambert's equation, it is possible to calculate how much of the original laser power actually reaches the workpiece, such that:

$$P = P_0 e^{-\alpha d}, \quad (1)$$

where:

P remaining power
P_0 original laser power

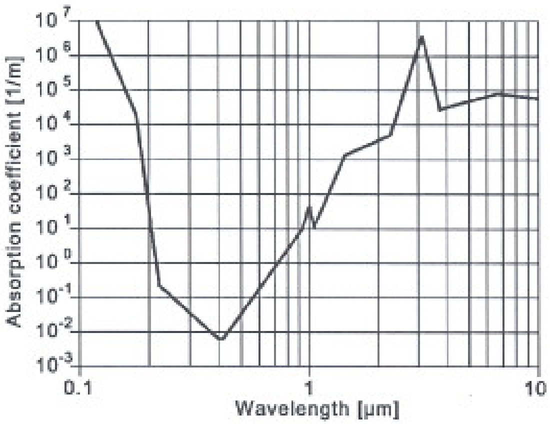


Fig. 2 Absorption coefficient of water vs wavelength

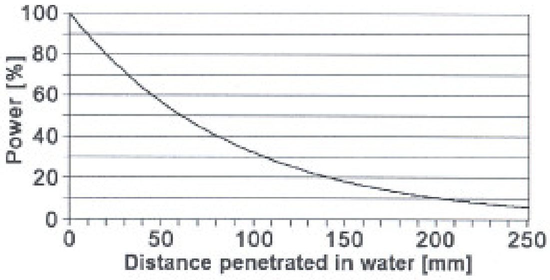


Fig. 3 The remaining laser power after water absorption

e Euler's number, 2.718
α absorption coefficient
d distance penetrated in water

The remaining power for a wavelength of 1,064 nm as a function of the distance penetrated in water is shown in Fig. 3. The wavelengths 532 and 355 nm are barely absorbed at all and are therefore not displayed in the figure. However, with the high intensities of light generated by lasers, nonlinear effects can also raise the actual losses [7].

3 Experimental procedures

The objective was to investigate the effects of cutting distance and angle of incidence for thin sheet metals with the main focus on whether cutting is possible or not. The equipment used consisted of a 150 W 1,064 nm pulsed Nd: YAG combined with a water jet laser unit and a separate *xyz* table. The open construction of the setup provided a good view of the cutting process as can be seen in Fig. 4.

0.1 and 0.2 mm thick strips of 99% aluminium, Cu37Zn brass and 18Cr9Ni stainless steel were cut with a nozzle standoff distance of 30, 50, 70, 90 and 110 mm combined with feed speeds of 25, 100 and 200 mm/min at an incidence angle of 0°. With the feed speeds used and a laser pulse frequency of 300 Hz the respective distance between individual pulses are 1.39 μm, 5.56 μm and 11.11 μm. As the jet diameter is ~100 μm, the laser pulses overlap

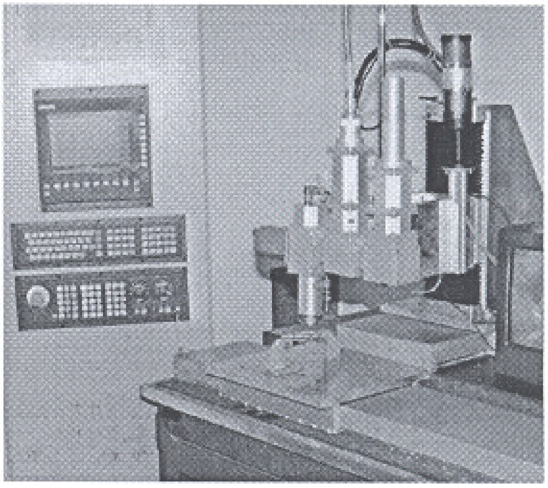
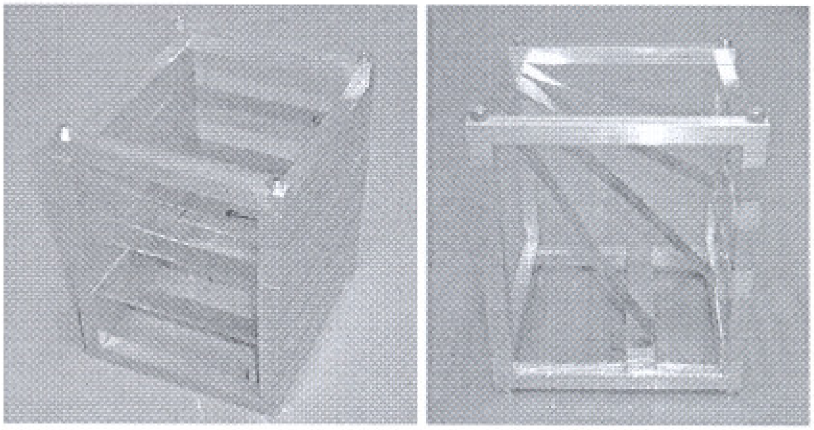


Fig. 4 The water jet guided laser at ITW-Chemnitz

Fig. 5 Experiment setup



multiple times. To study the effect of the angle of incidence, aluminium and stainless steel strips were also positioned at incidence angles of 30° and 60° and cut at 100 mm/min using the above cutting distances. The angle of incidence is measured from the surface normal. Figure 5 shows the setup of the strip-like specimens in the supporting frameworks used. The total heights of the frameworks are around 150 mm. The cutting direction was across the strips, starting from the edge, i.e. along contour lines. To cut the specimens, the nozzle of the water jet laser was moved only in an *xy* plane above the framework. Performing the cutting task with a conventional laser would be extremely difficult due to space limitations. Also, keeping the laser in focus on the flexible workpieces would be problematic.

The laser parameters used are displayed in Table 1. The given power and energy values are valid only at the laser source due to the fact that the water jet partially absorbs the laser. The pulse energy has been calculated by dividing the mean power by pulse frequency and the mean pulse power has been calculated by dividing the pulse energy by pulse length. The actual water jet diameter is smaller than the nozzle because of the Vena contracta effect. According to the manufacturer, a multiplier of 0.83 can be used [2]. The jet expulsion speed has been calculated from the water pressure using Bernoulli's equation for dynamic pressure.

The upper surfaces of the resulting kerfs were photographed through a Euromex MIC 210 optical microscope (Euromex, The Netherlands).

Table 1 The used laser parameters

Wavelength	λ	1064 nm
Mean power	P_0	105 W
Pulse frequency	f	300 Hz
Pulse energy	E_p	0.35 J
Pulse length	t	0.1 msec
Mean pulse power	P_p	3,500 W
Nozzle diameter	D	120 µm
Jet diameter	d	100 µm
Water pressure	P_w	20 MPa
Jet expulsion speed	v	200 m/s

4 Results and discussion

Photographs of the upper surfaces of the resulting kerfs are displayed in Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16. The cutting distance is divided into columns and the feed speed or angle of incidence into rows. The angle of incidence is the jet angle from the surface normal. The images have been chosen from locations that represent the whole kerfs relatively well. Kerfs with no disruptions are located to the left side of the dotted lines in Figs. 6, 7, 8, 9, 10, 11. Needless to say, the results are directly valid only for the laser parameters, water jet diameter and pressure in question. However, the results do indicate cutting possibilities for other metals to some extent, as aluminium and brass are not easy objects due to their low laser absorbance and high thermal conductivity.

As a general guideline, 50 mm seems to be a fairly reliable cutting distance. In addition to the laser being absorbed by the water jet, increasing the distance caused occasional disturbances of the water jet, which show up as discontinuities in the kerf. This was not expected as, according to the manufacturer [1], the jet was supposed to stay stable for up to about 200 mm. The disturbances were most likely caused by air bubbles in the water. As a solution the water degasser offered by the manufacturer is highly recommended. The fact that the problem was more pronounced at greater distances reveals that the bubbles were not large enough to temporarily disrupt the water flow through the nozzle but rather cause a small disturbance in the flow, which gradually grows, resulting in the jet breaking up later. Even the laser pulses might disturb the jet [8]. Plasma induced shock waves propagating upstream of the water jet might be another possible source of disturbances as the jet speed (~200 m/s) is much lower than the speed of sound in water (~1,500 m/s).

Although the higher feed speeds reveal even a short disturbance as a discontinuity in the kerf, the feed seems to have much less significance than the cutting distance in the tested feed range. Admittedly, all the cutting speeds used provided multiple overlapping of the laser pulses as presented in the experimental procedures section. Figure 12 reveals what happens when the feed is increased dramatically (up to ~2,000 mm/min) as the laser was left

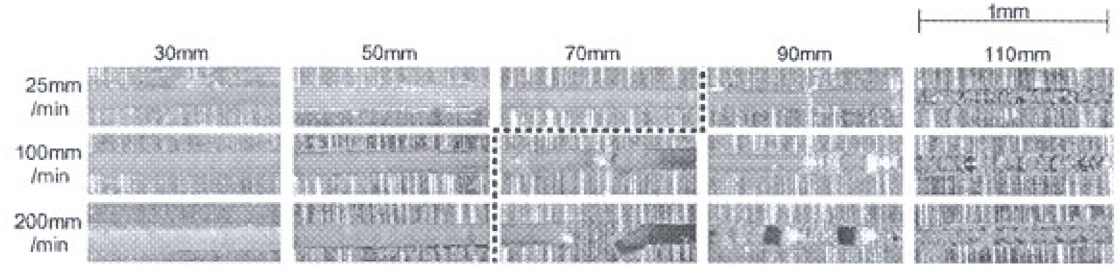


Fig. 6 0.1 mm aluminium cut at various distances and speeds at 0° incidence

on by mistake during rapid feed. The material in question is 0.1 mm stainless steel and the cutting distance is 30 mm. The feed is so fast that individual pulses can be identified in the kerf. Despite the high feed, individual pulses manage to penetrate the material. However, insufficient pulse overlap causes a splash of melt to solidify on the upper side of the material, probably before the material is penetrated. Pulse overlap is thus required to enable the water jet to pass smoothly through the material, expelling the melt with it. In this case melt is solidified up to around 70 μm from the kerf edge. The same phenomenon can be seen with stainless steel in Figs. 10 and 11 when the material must be penetrated after a discontinuity in the kerf. Aluminium and brass do not respond in the same way, which might be due to an oxide layer preventing the melt from welding itself. Another possible reason is the higher solidification temperature of steel, which causes the melt to solidify before the water jet has time to remove it in the liquid phase. A topic of further research could be the effects of laser parameters and cutting speed on melt resolidification.

At a cutting distance where the laser is not even capable of scribing the workpiece surface, such as at a distance of 110 mm as in Figs. 7, 8, 9, decreasing the feed makes no difference. This suggests that the workpiece temperature does not increase gradually pulse after pulse even when there is more pulse overlap. Consequently, the water jet must cool the workpiece effectively between the laser pulses. While the water jet cools the workpiece between the laser pulses, the following finding suggests that some heat is conducted even during a 0.1 ms laser pulse or immediately after it. The kerfs cut into stainless steel accumulate a thin layer of rust when exposed to water, which proves the existence of a heat-affected zone. Another finding is that at further cutting distances, where the remaining laser intensity is only adequate to scribe the surface of a 0.1 mm specimen, the equivalent 0.2 mm counterpart is often totally intact. This could be explained by the higher thermal capacity of the thicker specimen, which keeps the surface temperature lower by conduction. Earlier unpublished studies also found that cutting 0.1 mm thick copper with a plastic coated underside resulted in the plastic melting up to 0.1 mm from the kerf. The cutting waste also takes some time to cool down, as it was seen as flying sparks below the specimen. This can even be seen in the pictures of some published articles written by the manufacturer [9]. The effect of laser parameters on HAZ size with a water jet guided laser could be an interesting topic of research. A theoretical approach of describing the water jet and the laser interaction with material could be another topic.

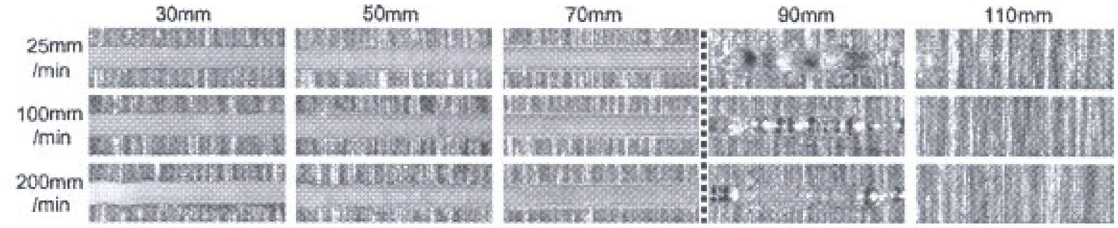


Fig. 7 0.2 mm aluminium cut at various distances and speeds at 0° incidence

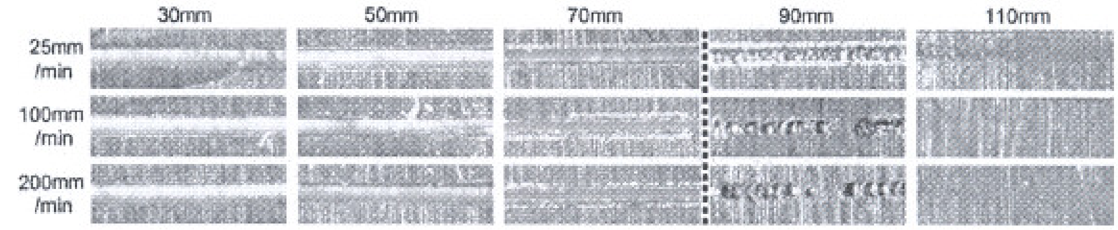


Fig. 8 0.1 mm brass cut at various distances and speeds at 0° incidence

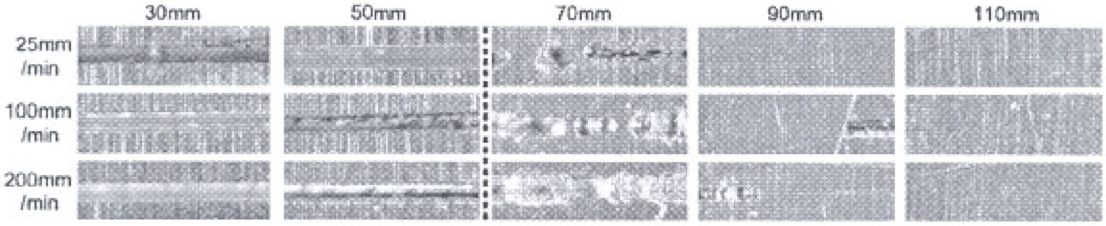


Fig. 9 0.2 mm brass cut at various distances and speeds at 0° incidence

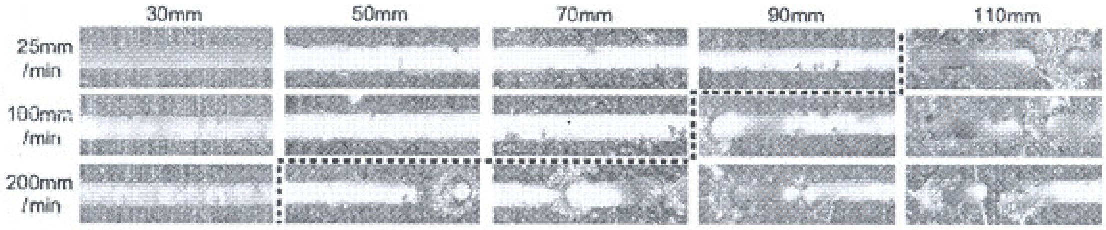


Fig. 10 0.1 mm stainless steel cut at various distances and speeds at 0° incidence

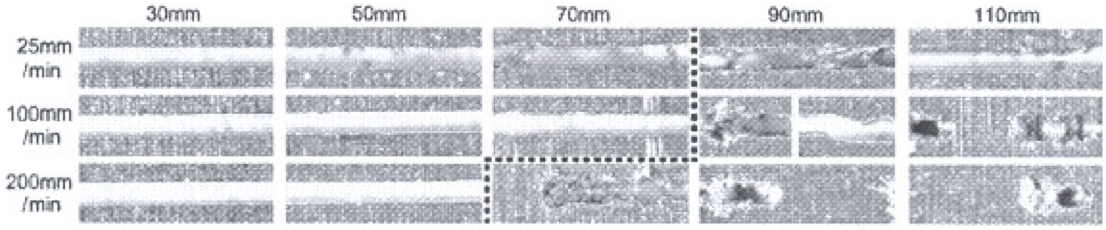
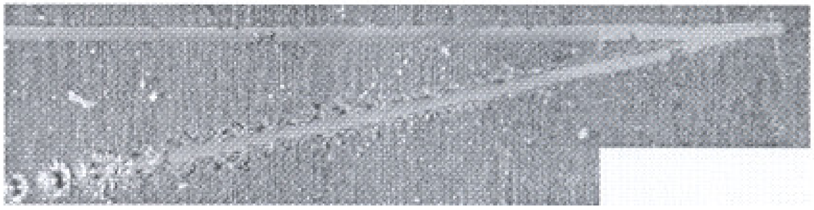


Fig. 11 0.2 mm stainless steel cut at various distances and speeds at 0° incidence

Fig. 12 Laser left on by mistake during rapid feed



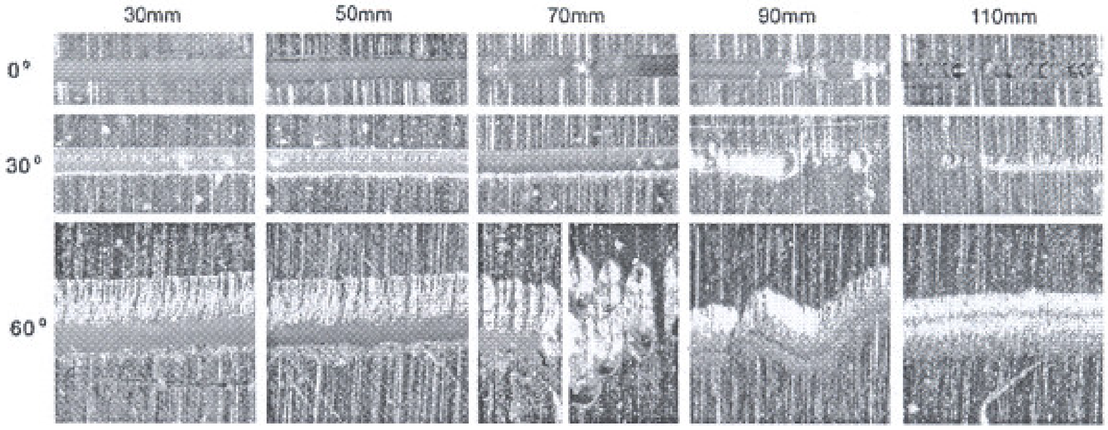


Fig. 13 0.1 mm aluminium cut at various distances and angles of incidence at 100 mm/min cutting speed

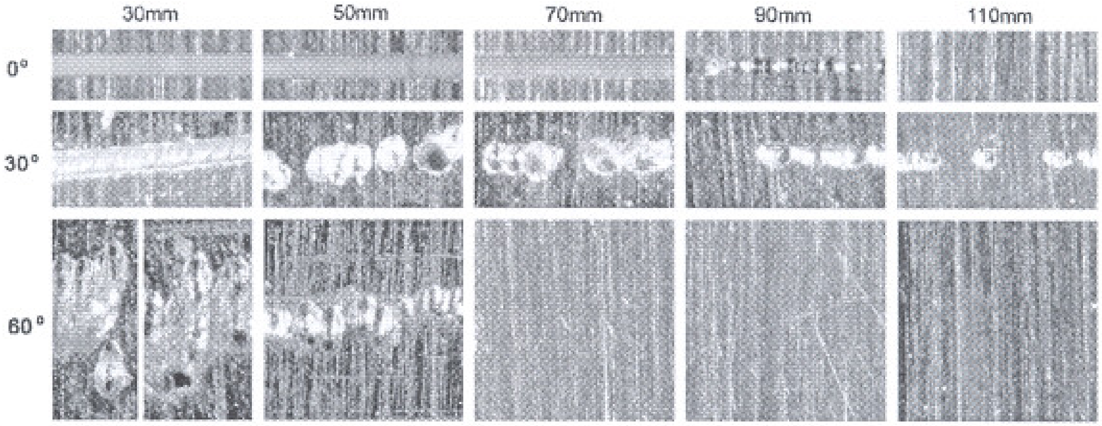


Fig. 14 0.2 mm aluminium cut at various distances and angles of incidence at 100 mm/min cutting speed

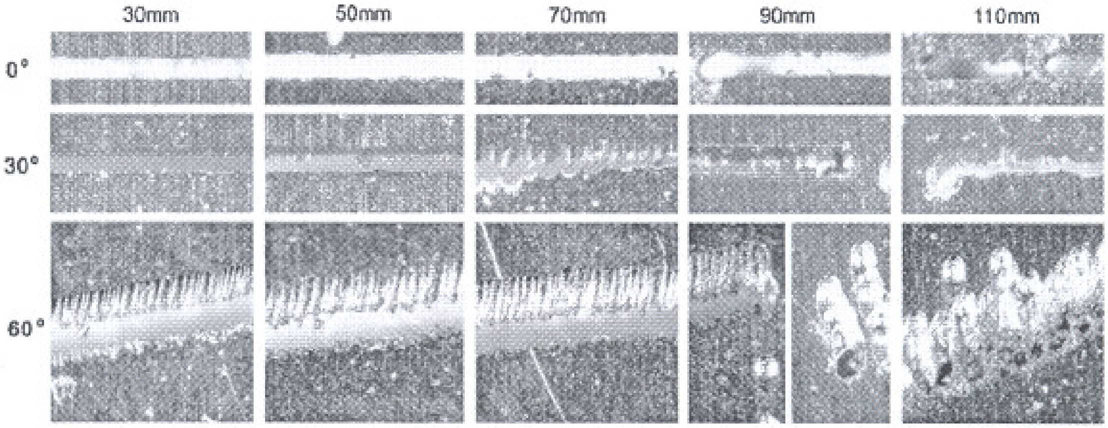


Fig. 15 0.1 mm stainless steel cut at various distances and angles of incidence at 100 mm/min cutting speed

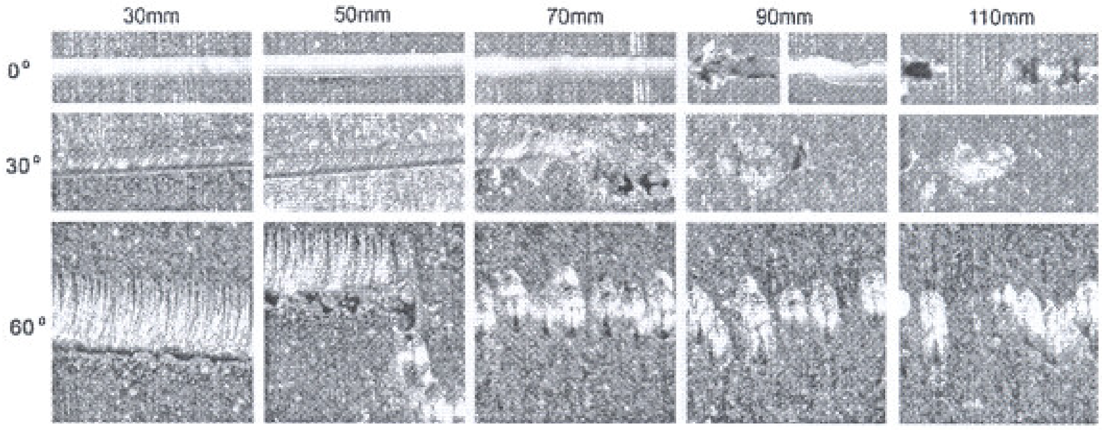


Fig. 16 0.2 mm stainless steel cut at various distances and angles of incidence at 100 mm/min cutting speed

The two most important factors arising from the angle of incidence are its effect on laser intensity and the distance through the sheet. When the jet strikes an inclined surface, the contact area between the jet and the surface is stretched from a circle to an ellipse. This decreases laser intensity by a multiplier of the cosine of the incidence angle. This holds true only in the beginning of the cutting process while the surface of the workpiece is still intact. The distance through the sheet is also dependant on the cosine of the incidence angle, only inversely. For example, with the surface inclined 60° the distance through the sheet is doubled. Brewster absorption has little influence, as the laser is unpolarized due to internal reflections in the water jet. Factors causing uncertainty are phase interference and surface roughness, as they can have unpredictable effects on absorption. The optical path length through a surface film, such as an oxide layer, changes with the angle of incidence. Surface roughness on the other hand might affect absorption by enabling multiple reflections between the surface ridges more effectively at certain angles. The tests could have been performed on recently polished surfaces to study the effect of the angle of incidence with as little disturbing factors as possible. These experiments, however, represent real-world results. As a downside, the relationship between the cutting parameters and the results is less direct. It seems the angle of incidence had less effect on the 0.1 mm specimens while the 0.2 mm specimens became increasingly difficult to cut when increasing the angle of incidence. The effect of the angle of incidence on the distance through the sheet is, of course, more pronounced with the thicker specimens. Increasing the angle of incidence also caused redeposited melt to build up on the sharp edge of the upper side of the kerf. This is clearly visible in Figs. 13, 14, 15, 16 at 60° incidence where melt is solidified up to about 35 μm from the kerf edge.

The kerfs of many inclined specimens would surely have been more successful without the specimen vibration, which caused the laser pulses to scatter over a large area. Despite the relatively small force of 0.2 N generated by the water jet, flexible structures, like the specimens tested, should have more support. It is also worth noting that, despite the small force, the jet has quite high pressure, which might pose a problem with some weaker materials.

5 Conclusions

- The 1,064 nm wavelength of Nd:YAG lasers is not very well suited for use with longer jets because of the absorption of the laser beam into water.
- For the laser parameters, jet diameter and pressure in question, the value of 50 mm was found to be a fairly reliable upper limit to the cutting distance.
- Inclined surfaces could also be cut with a shorter jet, which transmits sufficient laser intensity to the workpiece. Occasional vibration of the angled specimens caused the laser pulses to scatter over a large area impeding the cutting of a continuous kerf. Despite the low force imposed by the water jet, flexible structures require support to reduce vibrations.
- The water jet was susceptible to disturbances with a long jet as even small disturbances escalate to jet break-up further downstream.
- Melt redeposition and signs of a heat-affected zone were observed despite the cooling water jet. It is suggested that pulse overlap is required to enable the water jet to pass smoothly through the material in order to expel the melt without redeposition. Also, increasing the angle of incidence caused some melt redeposition.

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