Material processing with a 3kW single mode fibre laser

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Intended for novel machining strategies in high power laser machining a continuous wave single mode fibre laser (YLR-3000-SM, IPG) with a laser power up to 3 kW and brilliant beam quality M² < 1.2 has been applied in the presented work. Laser beam focussing was realised by industrial standard machining setups, a large area scanning system (RLSK; HighYAG), a high speed scanning system (Superscan; Raylase) and a stationary welding optic (YW50; Precitec). In the first case laser welding stainless steel has been investigated to compare significant interacting mechanism for different machining technologies, both butt joint welding and bead-on-plate welding, under a range of various processing parameters, such as objective focal length, processing velocity and laser output power. Ablation cutting on stainless steel and high-purity Al₂O₃ ceramics have been investigated subjected to varied machining conditions. For discussion the dependence of major laser processing parameters onto ablation depths have been indicated and texture analyses show the material behaviour before and after the machining process.

Keywords: single mode fibre laser, continuous wave, ablation, welding, high rate, remote cutting

1. Introduction

In recent years application of fibre laser technology in deep penetration laser welding have been investigated. Applying 10 kW multi mode fibre lasers butt joint welding of metal sheets up to 10 mm thickness has been successfully established [1]. With high process velocities of 20 m/min deep welding depths of 5 mm have been reached [2].

Presently, because of brilliant laser beam qualities of single mode fibre lasers with M² = 1.1 small laser spot sizes can be realised resulting in deep penetration depths. Welding experiments with 1 kW single mode fibre laser on stainless steel 1.4301 have shown the dependence of the penetration depths related to optimum focal spot sizes with aspect ratios up to 1:20 [3]. On the other hand high speed laser cutting with process velocities of up to 100 m/min have been applied in cutting of electro sheets with CO₂ laser high beam quality and laser power [4].

Novel developments in laser scanner technologies applicable in high power laser processing coupled with high brilliant laser sources such as fibre or disc lasers enables the development of a direct high rate ablation technology. Due to strong material ablation no supplementary process gas is needed to blow out the molten material from cutting kerfs. In the first investigation the separation of thin metal sheets by using laser remote cutting technology has been successfully demonstrated [5].

The aim of this study was to investigate deep welding as soon as high speed welding processes by using high power brilliant fibre laser technology. Furthermore determination of both, ablation rates and cutting depths of stainless steel and Al₂O₃ ceramics depending on focus spot size, laser power, and quantity of over scans to estimate the process efficiency. Additionally micro cavities have been generated in stainless steel and evaluated to discuss applicability of the high rate ablation technology in micro processing.

2. Experimental setup

In this study a continuous wave single mode fibre laser YLR-3000 SM (IPG) with maximal laser output power of 3 kW, beam quality better than M² = 1.2 and randomised beam polarisation have been applied. Beam deflection and focusing was implemented by two different high power scanning systems, a remote laser welding head RLSK (HighYAG) and a Superscan-SC-30-Y-Dig2 (Raylase). Focal distance of RLSK objective was f = 500 mm; Superscan was equipped with an objective focal length of f = 200 mm.

Table 1  Process parameter scanning systems

| Process parameter | RLSK | Superscan |
|-------------------|------|-----------|
| focal length [mm] | 500  | 200       |
| Laser spot size d₀₀ [µm] | 78  | 21        |
| max. scanning speed [m/min] | 600 | 900       |
| max. laser power at sample [kW] | 2.82 | 2.64     |
| max. intensity at sample [W/cm²] | 5.9*10⁷ | 7.6*10⁸ |
| min. dwell time [µs] | 7.8 | 1.4       |

Table 2  Process parameter welding head YW50

| Welding head YW50 | objective 1 | objective 2 |
|-------------------|-------------|-------------|
| focal length [mm] | 500 | 240        |
| Laser spot size d₀₀ [µm] | 109 | 57         |
| max. processing speed [m/min] | 120 | 120        |
| max. laser power at sample [kW] | 3.0 | 3.0         |
| max. intensity at sample [W/cm²] | 3.2*10⁷ | 1.1*10⁸ |

Additionally, for welding investigations a welding head YW50 made by Precitec with 125 mm collimation length
and focal distances of 240 mm and 500 mm was applied. The relative movement between sample and laser beam was realised by 3 axis positioning system. Applied significant process parameters have been summarised in table 1 and 2.

3. Experimental details

Investigations of laser welding have been performed on stainless steel 1.4301 by means of 35 mm long scanned lines focused onto sample surface. For high speed laser welding with Superscan the material thickness used was 1 mm. For the study of deep penetration welding, processing was done with a welding head YW50 and varied focal distances (table 2) at sample thicknesses of 20 mm. Using a welding head YW50 machining speed was applied in the range of 0.5 to 10 m/min and in high speed laser welding the processing speed reaches a maximum of 200 m/min respectively. However, at machining with higher process velocities transition from welding to ablation effects has been detected.

To investigate high speed laser ablation tracks, 40 up to 50 mm length have been scanned with varied numbers of overscans. A delay between the separate overscans ensures constant focus positions onto sample surface; otherwise a focus shift has been measured due to thermal lens effects at high energy inputs.

However, the experiments show that for stable ablation processes machining speed should be above a material’s specific minimum working speed. Minimum scanning velocities thresholds depending on focus spot size have been summarised in table 3 with 78 µm and 21 µm laser spot size for RLSK and Superscan system respectively.

Table 3 Processing speed threshold for ablation [m/min]

| Material            | RLSK | Superscan |
|---------------------|------|-----------|
| Stainless steel 1.4301 | 500  | 300       |
| Al<sub>2</sub>O<sub>3</sub>-Ceramic | 100  | n.a.      |

Fig. 1 Material bulges at stainless steel surface after laser welding with 60 m/min processing speed, laser power in kW / number of scans: a) 0.27/1  b) 0.27/5  c) 0.43/1  d) 0.62/1, Superscan.

Laser machining of either carbon steel or stainless steel below processing speed thresholds entirely has shown a strong melting with an insufficient blow out of the molten material. Figure 1 illustrates results obtained with machining speed below the required processing speed. Instead of obtained clear lines irregular structures were obtained. A further reduction of the processing speed leads to deep penetration welding effects. Processing of ceramic below processing speed threshold shows comparably strong material melting effects.

4. Experimental results

4.1 Evaluation methods

Machining results obtained at the different positions of the weld seams have been evaluated by means of polished and etched cross sections perpendicular to welding direction. Ablation and cutting depths of the steel texture have been analysed by using digital light microscopy and they have been determined by measuring the clear cross sectional area of the cutting depth. The measured values obtained for the cutting depth and width are not constant because of the redeposition and resolidification of molten material within the cutting kerfs.

4.2 Deep penetration welding at high processing speed

In deep penetration welding, welding head YW50 has been applied. Applying 240 mm focusing lens within investigated velocity range of up to 10 m/min results show deep penetration depths with no evidence of a significant dependence on processing speed (figure 2). However, because of a short distance between laser working zone and objective due to the short focal length an expansion of large plasma plumes has been occurred. Thus process handling has been complex as small dust or debris deposition at the lens protection glass has destroyed the beam profile. Appropriate drops in penetration depths are visible in figure 2 when processing with 2 kW at a rate of 7.5 m/min. Consequently implementation of a doubled cross jet and a permanent cleanliness control of the lens protecting glass supplies constant machining conditions.

Fig. 2 Penetration depths vs. processing speed and laser power achieved on stainless steel 1.4301 with welding head YW50 and 240 mm focal distance.

Figure 3 illustrates cross sections of spiky bead-on-plate welds on stainless steel 1.4301 processed with welding head YW50, 240 mm focal distance, 3 kW laser power and increasing machining speed (5 m/min, 7.5 m/min, 10 m/min). At faster machining speeds higher aspect ratios with deeper welding depths and smaller seam widths have been achieved.
Fig. 3 Cross sections of bead-on-plate welds achieved on stainless steel 1.4301 with YW50 and 240 mm focal distance.
Left: laser power: 3 kW; processing speed: 5 m/min; penetration depth and width: 5.3 mm / 0.2 mm
Centre: laser power: 3 kW; processing speed: 7.5 m/min; penetration depth and width: 5.9 mm / 0.18 mm
Right: laser power: 3 kW, processing speed: 10 m/min; penetration depth and width: 6.2 mm / 0.18 mm

Welding depths depending on applied scanning speed and laser power obtained with welding head YW50 and a larger focal distance of $f = 500$ mm summarise figure 4. Compared to welding results achieved with shorter focal lengths processing with large objectives lead to smaller penetration depths. However, due to a larger distance between focusing element and material surface efforts for lens cleaning has been reduced and consistent penetration depths have been obtained.

In figure 5 cross sections of slight and spiky welding seams machined with larger focal length are shown. At similar processing parameters machining quality is comparable to results of 240 mm objective exceptionally aspect ratios have not been reached.

4.3 Micro deep welding with highest processing speed
Investigations at high speed, micro deep welding have been accomplished on 1 mm stainless steel metal plates with the Superscan system and a focal distance of 200 mm. Figure 6 indicates an inverse relation between achieved penetration depths and processing speed whereby with higher laser power deeper welding depths have been measured. At first with increased machining speed from 5 m/min up to 180 m/min considerably lowered welding depths have been obtained.

For results obtained with 180 m/min processing speed and above cross sections show a distinctive kerf development accompanied with ablation characteristics at the top of the welding seams. Within the velocity range of 180 m/min to 240 m/min a transition from welding to ablation mechanism has been derived whereby transition area depends on incident laser power. However, with 620 W laser power and 30 m/min processing speed the stainless steel plate has been welded through.

Fig. 4 Penetration depth vs. processing speed and laser power achieved on stainless steel 1.4301 with welding head YW50 and 500 mm focal distance.

Fig. 5 Cross sections of bead-on-plate welds achieved on stainless steel 1.4301 with YW50 and 500 mm focal distance.
Left: laser power: 3 kW; processing speed: 5 m/min; penetration depth and width: 5.1 mm / 0.24 mm
Centre: laser power: 3 kW; processing speed: 7.5 m/min; penetration depth and width: 4.0 mm / 0.23 mm
Right: laser power: 3 kW, processing speed: 10 m/min; penetration depth and width: 4.8 mm / 0.24 mm

Fig. 6 Penetration depths vs. processing speed and laser power achieved at 1 mm thick stainless steel metal plate (1.4301) by bead-on-plate welding with Superscan.

Cross sections of bead-on-plate welds on 1mm stainless steel metal sheets illustrates figure 7 for various laser powers and processing velocities. For high speed processing a welding through the metal sheet has been obtained either with 530 W at 15 m/min or 620 W at 30 m/min processing speed respectively.
4.4 Ablation cutting

4.4.1 Stainless steel 1.4301

For stainless steel ablation cutting with RLSK scanning system figure 8 illustrates ablation depths versus number of overscans. The highest cutting depth was 500µm with 10 overscans at 500 m/min processing speed and maximal available laser power of 2.82 kW.

For machining of stainless steel 1.4301 with Superscan and 500 m/min processing speed a drop in achievable cutting depths at little laser power of 0.62 kW have been detected due to massive deposition of molten material within the cutting kerf (figure 9). Furthermore between 5 and 10 overscans no more significant growth in cutting depth is observable.

Analysis of process efficiencies have shown for Superscan and 500 m/min machining speed an energy input of 600 J/m to achieve 100 µm cutting depths. With increasing scanning speed of up to 600 m/min no significant changes in energy input have been detected. Consequently a consistent ablation process independent from scanning speed and number of overscans can be assumed. Exceptionally at either too high or too less laser power a higher energy input per section was required to achieve ablation kerfs deeper than 50 µm.

Applying Superscan at processing speed of 500 m/min only 120 J/m energy input per section has been calculated to ablate 100 µm in depth. Thus machining with higher laser intensities due to smaller focus spot size at Superscan system ablation process was up to 5 times more efficient.

Due to the observed stable cutting process at high scanning velocities completed experiments has been possible with Superscan and up to 900 m/min machining speed. The results summarised in figure 10.

The plot shows that with 900 m/min the ablation process was repeatable up to 5 overscans. Within 5 test series a maximum deviation of 3 % in cutting depths has been detected. However, compared to 500 m/min processing speed, for more than 10 overscans increasing ablation depths have been achieved with much higher laser power; process efficiency has been decreased non-linearly. To cut through a metal sheet of 0.5 mm thickness the obtained cumulated cutting speed of 75 m/min is much higher than for remote cutting reported in the literature to be up to 60 m/min [6].
little laser energy of 270 W determined energy need per section of 100 J/m was lesser than calculated for 500 m/min processing. For 2.64 kW, energy needed was 425 J/m respectively, which signifies a less process efficiency at higher laser power. However, in the plot advantages of high power laser processing, deep cutting kerfs at consistent process conditions are clearly recognisable.

Furthermore ultra high speed photography shows the development of stronger process plasma at higher laser power, which can be assumed for a higher energy need at machining with high laser power.

As illustrated in figure 12 high power laser machining with suitable processing parameters results in neglected heat affected zones; widths of generated micro structures have been achieved with less than 10 µm and aspect ratios up to 1:10.

Achieved ablation rates of stainless steel were varying between 15 and 40 mm$^3$/s as ablation rate was decreasing with higher numbers of overscans and less laser power.

4.4.2 Al$_2$O$_3$ - Ceramics

High power laser machining of Al$_2$O$_3$ ceramics with sufficient scan velocities of more than 400 m/min results in melt free and crack free micro ablation as observed in figure 13. Machining with low scanning speed leads to a slightly molten material deposition.

4.5 Generation of micro cavities

Generation of micro cavities applying high rate ablation technology has been successfully investigated on stainless steel 1.4301 by scanning line by line and layer by layer. Varied machining parameters were laser power, numbers of overscans and hatch distances. Ablation depth per scan was comparable to results described in 4.2.2 for varying laser power. Quality of ablated surface was mainly influenced by hatch distance, investigated in the range from 10 µm up to 40 µm.

However, separation of ceramic sheets of 1 mm thickness have been realised with 10 overscans at laser powers ranging from 0.92 kW to 2.35 kW and 100 m/min processing speed. Results of cut through experiments obtained with 2.35 kW laser power and varying processing speed have been summarised in figure 14. Ablation process shows two different interaction characteristics; especially recognisable is the one at the highest machining speed of 400 m/min. Initially, within 5 scans only 100 µm up to 300 µm of the material thickness have been ablated. With the next 5 overscans ablation rate was increased considerably and it was possible to cut through the ceramic sheet. This was due to efficient coupling of the laser beam in deeper regions through the transparent melting.

A significant higher energy need has been required compared to stainless steel processing. To achieve a 100 µm cutting kerf with 300 m/min processing speed an energy input of 1000 J/m has been applied. For machining with suitable laser parameters energy need per section has been halved to 500 J/m for 100 µm cutting depth. Achieved ablation rates between 15 and 20 mm$^3$/s were approximately the half of the rates obtained on stainless steel.
5. Conclusion and future work

In this study high brilliant high power continuous wave laser radiation and novel scanning technologies have been investigated to demonstrate their applications in high speed laser processing of stainless steel and ceramics.

In high speed laser welding spiky weld seams with high aspect ratios have been achieved. Furthermore penetration depths decrease with higher processing speed and transition in material ablation has been observed. However, the small weld seam size meets challenges in welding process related to work piece positioning and fixation. Due to high process efficiency and particularly spiky weld seams substitution of electron-beam welding in future applications might be possible.

Furthermore investigations regarding high reflective material and overlap welding as soon as development of alternative beam alignment and beam switching will be future challenges in welding.

In high rate laser ablation cutting of stainless steel and ceramics with high processing velocities and negligible heat affected zones has been successfully demonstrated. Ablation depths achieved with Superscan system have been up to 3.7 times deeper compared to RLSK scanner at similar laser power (figure 16). Results obtained correlate to relation of ablation depths to applied focus spot diameter and are in good agreement to [7]. The ratio of ablation depth to focal spot diameter obtained at focal spot 78 µm is comparable to ratio at focal spot 21 µm because machining with smaller spot sizes intensity increase with squared diameter otherwise dwell time decreases depending on laser spot size relation.

Future investigations aim to increase laser process velocities to analyse energy input per unit by machining with high laser power. Scanning velocities of up to 12,000 m/min are possible to use by applying novel polygon scanning technologies.

Furthermore in complementary investigations varied focusing lenses and focal lengths will be studied to optimize relations between laser power and intensity for enhanced machining qualities.

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Fig. 16 Cutting depths vs. number of overscans and scanning system at similar laser power input in stainless steel 1.4301, processing speed: 600 m/min.