ANTICIPATING HEAT ACCUMULATION IN LASER OXYGEN CUTTING OF THICK METAL PLATES

Paper #8

Nikita Levichev[1], Gonçalo Costa Rodrigues[1], Reginald Dewil[2], Joost R. Duflou[1]

[1]Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300B, 3001 Heverlee, Belgium
[2]Department of Supply Chain Analytics, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands

Abstract

Excessive heating of the metal sheet during laser oxygen cutting can cause quality deterioration and even lead to cut loss and possible machine idle time, especially for cutting of thick plates, where the cutting speed is slower. There are at least three different strategies to handle quality deterioration by heat accumulation in flame laser cutting of thick plates: to optimize the process parameters for preheated zones, to generate tool paths that avoid such regions or to use active cooling to remove the excessive heat. For any of these strategies to work, it is crucial to correctly identify when and where heat accumulations occur. This can be done either by real-time temperature measurements, by simulating heat propagation on the metal plate or by defining empirical criteria based on experimental data.

This paper takes a close look at these methods of heat accumulation detection, their advantages and disadvantages and how they can be integrated into different approaches to tackle unwanted heat accumulations in laser cutting. Furthermore, three case studies are provided, one for each above-mentioned method, where the detection of quality degradation due to heat accumulation is demonstrated with a series of experiments. For all case studies, at least one action is proposed to improve the cut quality. All experiments were conducted for 15 mm mild steel plates using a 4 kW industrial fiber laser cutting machine.

Introduction

Laser cutting is a well-established industrial process and is widely used in manufacturing applications. The assist gas is of crucial importance for laser cutting of metal sheets. Depending on the material and gas used, two main processes are defined: fusion cutting [1], with an inert gas, and flame cutting [2], with a reactive gas. In flame laser cutting a high purity jet of O_2 is used as an assist gas, which introduces extra net heat into the metal sheet by means of an exothermic reaction of iron and oxygen. This reaction also generates a low viscosity oxidized melt that is easily removed from the cut zone by the mechanical action of the gas jet [3]. The energy released by the oxidation reaction typically contributes about half of the total energy input and, thereby, drastically enhances the cutting process efficiency [4].

Due to conduction heat loss during cutting, the temperature of the base material can rise significantly, enlarging the risk of the occurrence of quality deterioration due to a preheating effect [5]. This becomes even more evident for thick plates (> 10 mm), because the power input is higher and the cutting speed is lower, which gives more time for heat to propagate. This effect is particularly pronounced for cutting with oxygen, where the level of heat conduction loss is higher due to the exothermic reaction, which leads to strong limitations for processing of small geometric details and increase of the heat affected zone. This thermal sensitivity of the process cut quality is especially problematic in industrial applications where parts need to be nested close to each other.

In the most severe cases the preheating effect can lead to the need for re-production or post-processing and, eventually, to machine idle time. In such cases the oxidation rate of the material rises drastically leading to a significant increase in the amount of molten material that would be ejected from the cut zone by the assist gas. When this material removal rate exceeds a certain threshold, the ejection of the material out of the cut kerf gets hampered because of physical limitations. This typically results in an occurrence of dross finally leading to loss of cut.

The diagram of Figure 1 provides an overview of the possible strategies to avoid quality deterioration due to heat accumulation and the methods used to define the occurrence of such an issue.

In practice, there are three base approaches to handle heat accumulation: to optimize the process parameters and continue cutting without changing the tool path, to optimize the tool path without varying parameters, or to

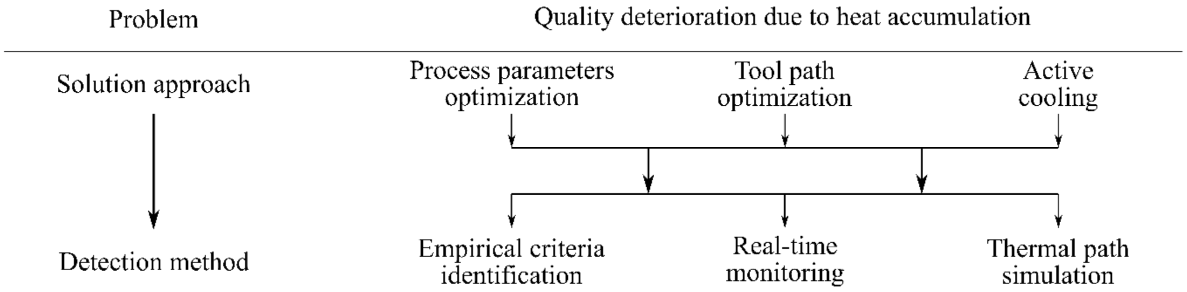

Figure 1 – Strategies for heat accumulation avoidance

use active cooling to remove the heat from the metal plate. All strategies require an effective detection of heat accumulations that can be realized with different methods: by experimentally identifying critical contour details and use them to define empirical criteria, by using sensors to detect the onset of quality deterioration in real-time or by simulating the thermal distribution in the metal plate and correlate this pattern with quality defect occurrence.

The empirical criteria identification method determines a specific set of cutting parameters for problematic regions (e.g. sharp corners, small details, thin walls or zones near piercings) and assumes that they are the cause of the quality degradation. This solution requires a considerable technology database adjustment. Different techniques that are commonly used for laser cutting optimization [6, 7] could be applied in order to cover the complex fine-tuning procedure.

Real-time monitoring is commonly used to detect defects in laser material processing [8-10]. It has been successfully used with adaptive control to achieve stable cuts with CO_2 laser by adjusting process parameters [11], but it could as well be used with active cooling or online tool path adaptations. Such a solution has a significant impact in terms of hardware requirements and system design.

Thermal path simulation is one of the major aspects of nesting [12] and tool path [13] algorithms for laser cutting. Typically, evaluation whether a path can be feasibly executed is performed according to a critical temperature [14, 15] which depends on the material-thickness combination. Naturally, the calculation time is of prime importance for any possible implementation in an industrial environment. Any strategy developed to handle heat accumulations that relies on this method of detection will require significant changes in process planning.

The aim of this paper is to investigate the operational feasibility of the proposed methods to detect quality deterioration caused by heat accumulation during flame laser cutting of thick metal plates. The opportunities of each method are illustrated with experimental data. A description of the setup used and the applied measurement equipment is provided in the next section. Three case studies follow in which both corresponding experimental description and results are discussed, leading to a general conclusion about their possible industrial implementation.

Setup Description

The experiments were performed on a commercial fiber laser cutting machine with a 4 kW IPG Ytterbium multimode laser source emitting at 1.07 µm wavelength. The laser is delivered into a Precitec ProCutter laser head with a 200 mm focusing lens and a 100 mm collimation lens from a 100 µm core optical fiber. The beam parameter product and the beam waist diameter were measured by an Ophir BeamWatch device as 2.84 mm mrad and 223.5 µm respectively.

The cutting samples were obtained from hot rolled S355MC plates of 15 mm thickness. Table 1 provides the material chemical composition according to the Certificate 3.1 (DIN-EN-10204).

Table 1 – Chemical composition (m/m %) of the material used in the experiments

C	Mn	Cu	Cr	Ni	Si	Fe
0.057	1.3	0.036	0.021	0.017	0.012	rest

Unless mentioned otherwise, the following process parameters, as standard for the commercial machine and commonly used in industrial practice, were applied for the cutting experiments for this material-thickness combination. Oxygen with 99.95 % purity with 0.6 bar pressure was used as an assist gas together with a 1.5 mm diameter nozzle and a stand-off distance of 1.2 mm. The focus position of the laser beam was 5.5 mm above the sheet surface. The cutting was performed with a speed of 1100 mm/min, a laser power of 4 kW and a duty cycle (DC) of 100 %. In the remainder of the article, these parameters are referred to as the default conditions.

A Keyence Digital Microscope VHX-6000 was used for high-resolution imaging of cut edge profiles. Surface roughness was measured with a Mitutoyo Formtracer CS-3200 using a Gaussian filter with a sample length of 2.5 mm and a cut-off of 0.008 mm. The measurements of each specimen were performed for five lines with an evaluation length of 12.5 mm. The measuring lines were spaced by 3.25 mm starting at 1 mm from the top surface. An average Rz value for these lines was calculated to compare the quality of the cut edges.

Case I: Empirical Criteria Identification

The objective of this case study is to demonstrate that empirical criteria can be defined to improve cutting quality in preheated regions of a metal plate. For this purpose, machine process parameters were optimized for a specific geometry created to generate and trap heat. This set of parameters was selected and used in the preheated region and compared with the result of a similar contour processed with the default set of process parameters (specified in the previous section).

Experimental Description

The geometry of the sample that was used for the experiments is shown in Figure 2. Note that the piercing routines were performed at a certain distance from the last cutting path to ensure a minimal heat effect. The numbers next to the black dots, representing the piercing position, show the cutting sequence. The heat trapped during the first two contours creates a preheated region that is used for cutting the third contour (blue line) where a new set of process parameters is applied. The area enclosed by the red dashed line shows the side where the cut quality is evaluated.

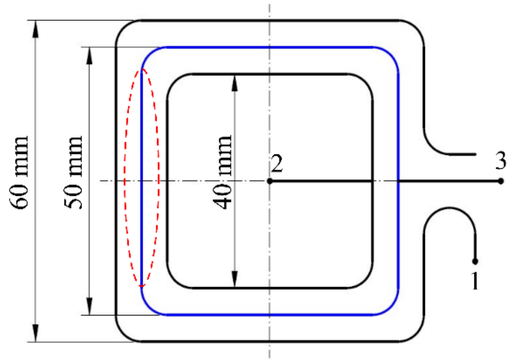

Figure 2 – Sample geometry for Case I experiments

Results and Discussion

Generally, due to heat accumulation, the amount of energy available for the cutting process is significantly higher than normal, which is not necessarily good for cutting quality. In order to restore the energy balance, the energy input per unit of length needs to be reduced. This can be realised by several direct actions such as to decrease laser power, laser DC and gas supply or to increase the cutting speed. Focal point position and laser frequency are examples of other parameters that can have an indirect influence on the energy balance.

The selection of an optimized set of cutting parameters was done after a series of systematic screening tests that were based on the optimization procedure described in details in [16]. For this case only cutting speed, laser power and laser duty cycle were selected as optimization parameters due to their high impact on the process energy balance. The exercise resulted in the optimized set of parameters that included a higher cutting speed (1400 mm/min) and the standard values for laser power and laser DC.

Table 2 provides the results for the roughness measurements performed in the cut edges obtained in different cutting conditions. Note that the use of the default process parameters for a preheated contour leads to a drastic (50 %) increase in average roughness. Despite the fact that applying this optimized set of parameters in the preheated zone cannot guarantee the quality of standard cutting, it decreased the average roughness by almost 25 % in comparison to the default set of parameters.

Table 2 – Average roughness for cutting in different conditions

Condition†	1	2	3
Rz, µm	80.6±4.0	122.7±6.1	95.3±4.8

†1 – standard cutting with default parameters;
2 – preheated contour with default parameters;
3 – preheated contour with optimized parameters.

The optimized parameters are characterized by a significant increase in cutting speed (27.3 %). However, it is worth noticing that cutting with this set of parameters at ambient temperature results in severe dross attachments and significant edge quality degradation. In fact, the additional heat expands the process window for a cut-through condition.

This case demonstrated that a set of optimized cutting parameters could be found for a given geometry, which otherwise would suffer from the heat accumulation issue. In theory, an empirical rule could be defined for the cutting of contours that are enclosed by a certain distance by antecedent contours. Naturally, this strategy could be expanded with more empirical rules for other problematic regions. A rule-based system could be implemented at the process planning stage to improve the cutting quality. However, the robustness of such an empirical approach might depend on several factors (e.g. material-thickness combination, process parameters, machine characteristics) and will require the creation of extensive databases.

Besides the use of an optimized set of cutting parameters, there are other strategies to handle the heat accumulation issue by setting empirical rules. In the case of the specific geometry tested in this case study, the use of active cooling for contour 3 (e.g. CoolLine nozzle of Trumpf) or tool path optimization (e.g. waiting time) could also be implemented.

Case II: Real-Time Monitoring

The purpose of this case study is to investigate the feasibility of using a real-time monitoring system to detect quality deterioration caused by the preheating effect. In this specific case, the process light emitted from the melt pool is measured in different spectral ranges by means of photodiodes and the signal is compared with the obtained cutting quality.

Experimental Description

Two types of photodiodes were used in order to investigate this method for heat accumulation detection: a Si photodiode (FDS100), mainly sensitive in the visual spectral range from 350 to 1100 nm, and an InGaAs photodiode (FGA21), responsive to the near infrared radiation with wavelengths from 800 to 1700 nm.

A coaxial monitoring setup was developed by replacing a conventional laser head mirror by a dichroic one that transmits towards the photodiode the radiation with a wavelength shorter than 800 nm and longer than 1200 nm. After the dichroic mirror, an OD 6 notch filter was placed to remove the scattered and reflected laser radiation, which is significantly higher than the thermal radiation from the process zone, even after the attenuation of the dichroic mirror. Additional optical elements, such as focusing lenses and a folding mirror, were included to ensure optimal process radiation transmittal to the photodiode sensor.

The photodiode signals were recorded by means of a data acquisition card with a sample rate of 50 kHz. Appropriate signal amplification and low pass filtering were applied. The obtained data were processed using a moving average to reduce the process noise.

The sample geometry was chosen in such a way as to gradually accumulate heat on each subsequent cutting interval. The cutting was performed according to the sequence of the line numbers provided in Figure 3. The length of each linear cut is 100 mm and the distance between every two lines is 5 mm. Note that the initiation of neighbouring lines was shifted by 10 mm to avoid interaction between the piercing routines.

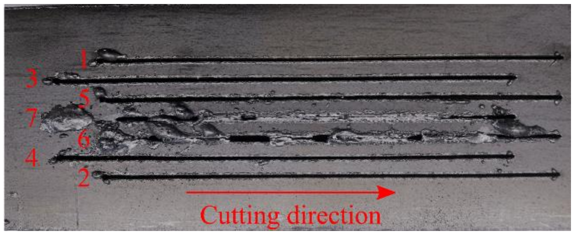

Figure 3 – Sample obtained by cutting test with real-time monitoring showing no cut through in the most preheated regions

Results and Discussion

The bottom view of the cut sample is shown in Figure 3. The first four lines were cut without any significant change in the cut edge profile. In line 5, even though visible dross was not observed, the accumulated heat led to significant degradation of the cut edge smoothness, as demonstrated by the roughness values provided in Figure 4. Lines 6 and 7 are cut in the most preheated zone and result in heavy dross attachments and, for some segments, in a no cut-through situation.

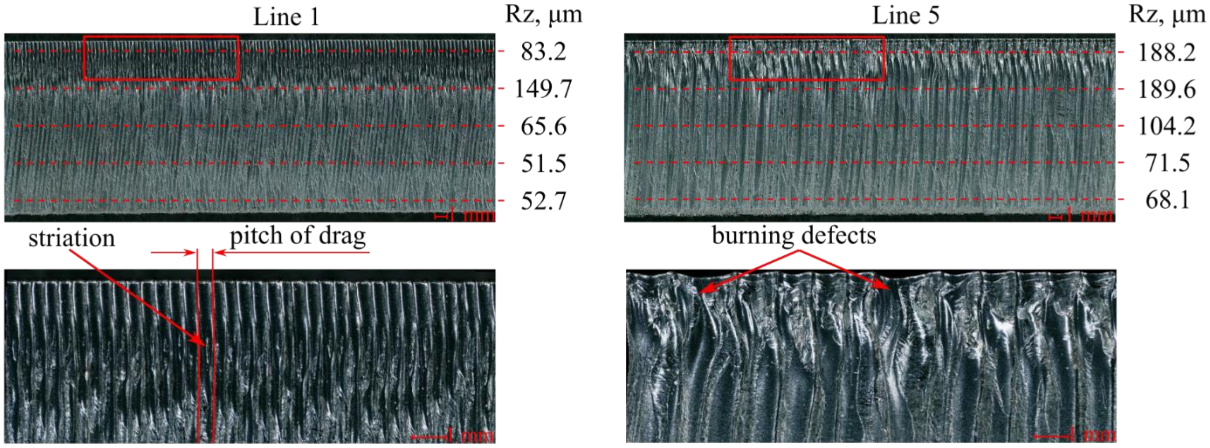

Figure 4 – Difference in the cut edge quality caused by the preheating effect

The cut edge profile significantly changed in the area close to the top surface resulting in the occurrence of burning defects. These defects are characterized by several crater-like profiles that are the main reason for the drastic increase in roughness. The height profiles depicted in Figure 5 demonstrate the strong difference in edge smoothness between lines 1 and 5.

The profile of line 1 is characterized by deep wave-shaped projections or striations. The period of these projections is a pitch of drag or a distance between two neighbouring drag lines that enclose a striation (see Figure 4). The calculated average pitch of drag is more than two times higher for line 5 and equal to 1.12 mm, comparing to just 0.44 mm for line 1. The profile of line 5 has two notable minimums which correspond to the burning defects occurrence. Such craters are more than two times deeper than height profile values and represent typical quality degradation caused by the preheating effect.

Despite the fact that the pitch of drag is much higher for line 5, no significant change in drag of striations was observed. The average drag of striations value according to ISO 9013:2017 is 1.3 mm for both line 1 and line 5 profiles.

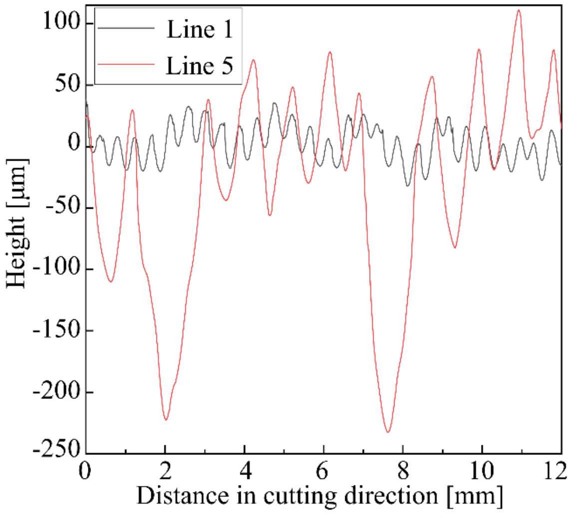

Figure 5 – Height profile of the cut edge (measured at 1 mm from the top surface)

The corresponding IR and VIS photodiode signals are depicted in Figure 6. The signals during the piercings for each line were removed for better visualization. It is clear from both graphs that the signal changes significantly only after line 4, which gives a good correlation with what is observed in the edge quality. Note that even though the temperature of the solid material around the melt pool should considerably increase due to the preheating effect, the responsivity spectral range of each sensor will only allow it to capture radiation from the liquid metal or the solid metal at a high temperature. The intensity of this radiation depends not only on the temperature of the melt pool but also on several geometrical aspects (e.g. change in kerf shape or melt flow dynamics).

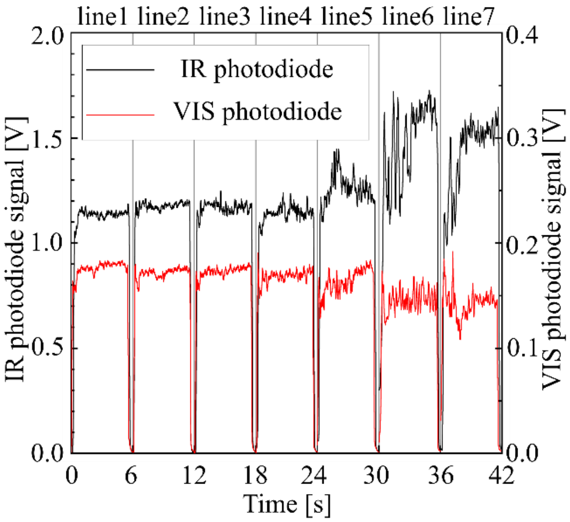

Figure 6 – Photodiodes signal during cutting with consecutive levels of heat accumulation

The signal level of the IR photodiode starts to rise for line 5 which is characterized by quality deterioration. Furthermore, it is significantly higher for lines 6 and 7 if compared with the first four lines. Despite the fact that occurrence of dross is unstable, leading to signal variation, the average signal during the cutting of each line undergoes an increase of 10 % for line 5 and more than 20 % for lines 6 and 7 compared to line 1. Moreover, the signal deviation is more pronounced at the segments where dross appears.

In contrast to the IR range, the VIS photodiode signal level decreases when the quality deterioration occurs. The average signal slightly reduces for line 5 and drops down by 15 % for lines 6 and 7 where dross occurrence appears.

The signal behaviour seems to strongly correlate with quality aspects regardless of the used spectral range. Nevertheless, it is different depending on the photodiode type. A possible explanation of this result could be that due to the preheating effect the melt pool area expands, increasing the material amount that has to be removed. At the same time, the temperature of the melt pool and heat affected zone should change, possibly decreasing due to the extra energy needs. While both sensors will be getting more intensity due to larger melt pool zone, the decrease of temperature will have a stronger effect in reducing the intensity measured by the VIS photodiode according to Planck`s and

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Wien`s laws. This difference in the measured signals becomes more evident when dross appears because the additional resolidified material has lower temperature and will be emitting more radiation in the near infrared interval.

A real-time monitoring system is a promising method for the detection of quality deterioration due to heat accumulation. A certain threshold could be defined for which the occurrence of quality deterioration due to the preheating effect is imminent and an action could be activated. Moreover, the cross-correlation of two photodiodes getting information from different spectral ranges could be used to improve the detection of quality degradation [17].

Different solution approaches for the preheating effect are relevant when using real-time detection of quality deterioration. The most common one is adaptive control, which adjusts process parameters to successfully perform a cut [18]. In theory, the tool path could also be changed when quality deterioration is eminent in order to provide time for cooling of the current preheated contour. This would require tool path optimization to be performed on the fly or to apply a rule-based system to add waiting times or to skip contours that could be processed later. An active cooling approach could also be based on a real-time monitoring system that provides a signal to initiate cooling.

Case III: Thermal Path Simulation

The motivation for this case study is to demonstrate that efficient thermal simulation can be used to predict locations in the cut path where quality degradation due to heat accumulation will occur.

Experimental Description

For this case study, a 2-dimensional model originally developed for tool path optimization research [19] was adapted and validated for flame laser cutting of metal plates. The heat input, which consists of the absorbed laser beam energy and the contribution of the oxidation reaction, was calibrated experimentally for both cutting and piercing.

The power transfer due to conduction is calculated in accordance with Fourier`s law. The developed model takes into account natural convective heat flow for both top and bottom surface of the metal plate. Heat transfer across the side edges is considered to be neglected. Since the oxygen jet induces forced convection which is one of the main cooling mechanisms, the convective heat coefficient for forced convection was experimentally calibrated and included to the model. Gray body radiative heat flow is implemented according to the Stefan-Boltzmann law. Note that the assumptions of the model are valid only when a cut through is performed. Dross appearance significantly increases heat conduction losses since it acts as an unpredictable extra heat source and, thus, leads to a significant underestimation of plate temperatures. A mesh size of 1 mm was used in the simulations.

The same sample geometry that was used for Case II was applied for the thermal path model tests. During the cutting experiment, the temperature was measured by means of a type K thermocouple with a sample rate of 1 kHz. The thermocouple was placed at a depth of 7.5 mm into the metal plate.

Results and Discussion

Figure 7 provides the temperature evolution in the centre of line 7 for both simulation and thermocouple measurement. The model overestimation slightly increases during consistent cutting until line 6 where dross starts to appear. Despite the fact that the occurrence of dross reduces the model prediction ability, it is important to note that the goal here is to detect the quality deterioration that appears in line 5 and to avoid dross attachment, as observed in lines 6 and 7. The largest simulation error does not exceed 10 %.

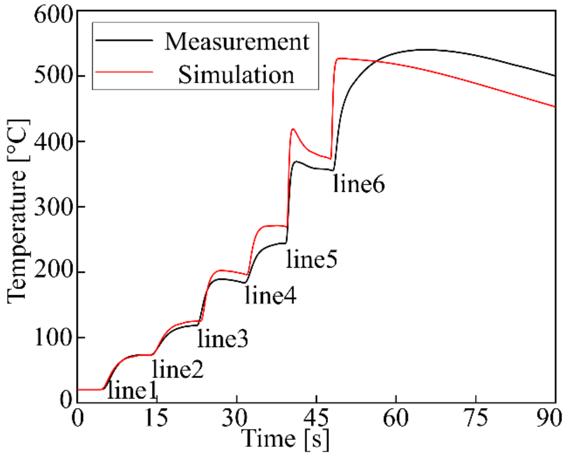

Figure 7 – Measurement and simulation results of temperature evolution at the measurement position (see Figure 8)

Figure 8 provides an example of the temperature distribution during the cutting of line 5. The dashed lines represent cutting lines that were not cut yet. The red point is placed in the position where the temperature measurement of Figure 7 was performed. Due to heat accumulation, the temperature in the region that is supposed to be cut next reaches approximately 250 °C which corresponds to anticipated quality deterioration. This temperature is known to be above a critical limit for quality degradation of the cut edge.

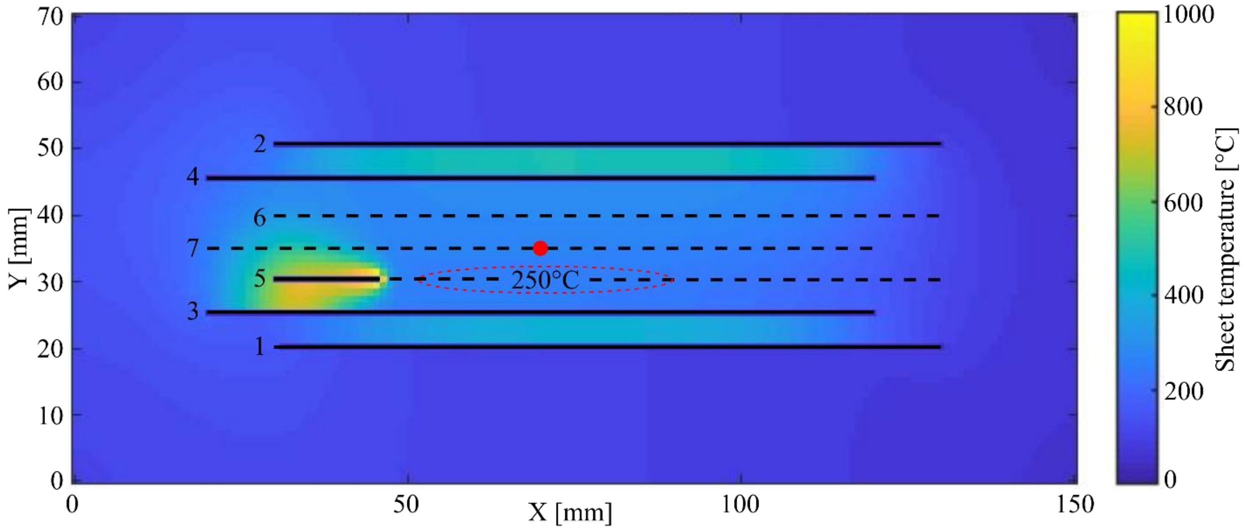

Figure 8 – Temperature distribution during cutting with the preheating effect. The red dot represents the position of the thermocouple measurement

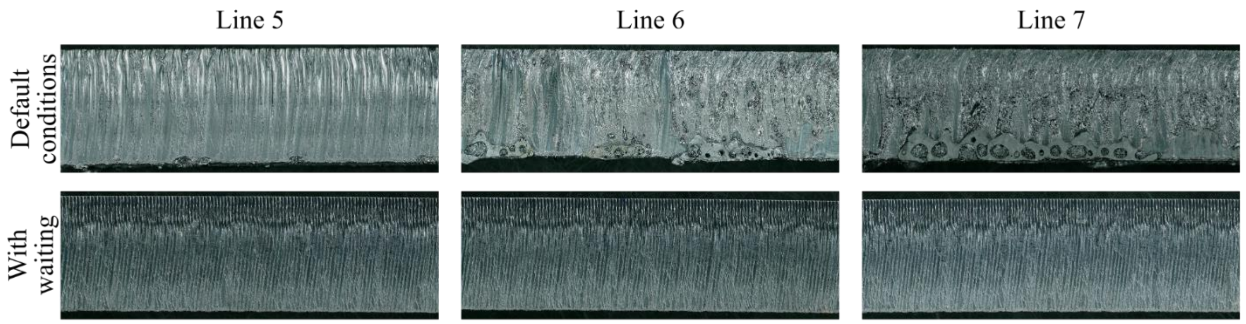

Figure 9 – Edge profiles after cutting with default process conditions and with additional waiting time

The easiest way to avoid unacceptable quality deterioration of cut pieces would be to wait until the plate cools down by the effect of the convective and radiative heat flows. Before the next contour is cut the process can stop until the temperature in the zone of the next contour becomes acceptable.

The simulation model can be used to predict a minimum waiting time between contours so that the temperature in a region before cut initiation is below a predefined limit. If a temperature of 250 °C is considered, such exercise results in about 6 minutes of waiting time between the different cuts. In industrial practice, parts are nested in much bigger plates and this time could be used for cutting other contours, for which the temperature is below the critical limit.

Subsequently, the test was repeated, but now waiting times were included after the fourth, fifth and sixth line to guarantee that the critical temperature limit was not surpassed. The cut edge profile of the most problematic lines is shown in Figure 9. It is clear that lines 6 and 7 can be cut without dross if appropriate waiting times are applied. Moreover, the edge smoothness of all lines drastically improved and became similar to the quality of line 1 (the measured average roughness values differ by less than 10 %).

The kerf width measurements at the top surface for all lines with both default conditions and with waiting times are depicted in Figure 10. The width increases with consecutive cuts. However, this increase is considerably more pronounced for the most preheated contours, line 5, 6 and 7 of default conditions. The last three lines with waiting time condition have clearly a more narrow kerf in comparison to the default conditions. For these lines, the kerf is wider in comparison to the first four lines since the temperature in these regions is still higher.

However, the cooling mechanisms are quite slow and a lot of time will be lost if only waiting times are used. Therefore, tool path optimization or the implementation of active cooling could significantly improve the potential of using this detection method. Moreover, cutting can be continued if a specific set of process parameters was selected in order to reach better quality in a preheated region.

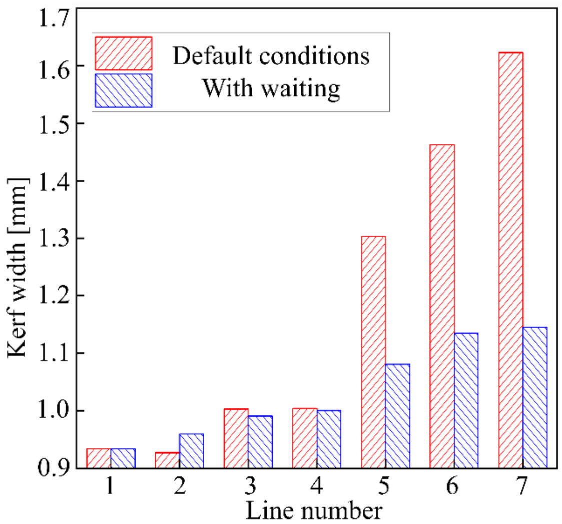

Figure 10 – Kerf width at the top surface after cutting with default conditions and with additional waiting time for lines 5, 6 and 7

Conclusion

Quality aspects of laser cutting such as roughness, kerf width, occurrence of burning defects, dross appearance and pitch of drag were analysed in order to investigate quality degradation caused by heat accumulation. The experimental results demonstrated that moderate levels of preheating lead to burning defects and significant roughness increase. Further increases in plate temperature lead to dross occurrence and drastic cut kerf expansion since the exothermal reaction is limited by heat and mass transfer.

Different approaches to handle quality deterioration due to excessive heat accumulation in flame laser cutting of thick plates were defined. The three main methods to detect this problem were investigated and several strategies were proposed to improve laser cutting in preheated regions. Moreover, the obtained results point out for possible use of the synergetic effect of these methods to provide a robust solution for industrial implementation.

Currently, tool path optimization procedures, described in the literature and typically used in practice, mostly focus on the decreasing of the non-productive air moves and assume a fixed cutting speed. The insights from the case studies offer a clear motivation to investigate optimization algorithms that integrate both cutting settings and the tool path as optimization parameters to tackle the preheating issue.

Furthermore, the real-time monitoring system investigated in Case II proved to be an important step forward towards a solution to the heat accumulation problem. The signal, obtained from this monitoring system and correlated with cut quality, could, for example, be used as input for an online control system that adapts the process parameters and/or acts according to a predefined set of rules.

References

[1] Riveiro, A., Quintero, F. & Pou, J. (2018) Laser Fusion Cutting of Difficult Materials, in J. Lawrence (ed.) Advances in Laser Materials Processing, Woodhead Publishing, 43-67.

[2] Ivarson, A., Powell, J. & Magnusson, C. (1991) The Role of Oxidation in Laser Cutting Stainless and Mild Steel, Journal of Laser Applications 3, 41-45.

[3] Powell, J., Petring, D., Kumar R.V., Al-Mashikhi S.O., Kaplan, A.F.H. & Voisey, K.T. (2009) Laser–oxygen cutting of mild steel: the thermodynamics of the oxidation reaction, Journal of Physics D: Applied Physics 42, 015504.

[4] Yilbas, B.S. (2004) Laser cutting quality assessment and thermal efficiency analysis, Journal of Materials Processing Technology 155-156, 2106-2115.

[5] Duflou, J.R., Kruth, J.-P., De Keuster, J., Sastry, K.Y. & de Graaf, R.F. (2003) On CO_2 laser cutting of thick steel plates, in Proceedings of the 10th International Conference on Sheet Metal, Jordanstown, UK, 141-150.

[6] Dubey, A.K. & Yadava, V. (2008) Multi-objective optimisation of laser beam cutting process, Optics & Laser Technology 40, 562-570.

[7] Gadallah, M.H. & Abdu, H.M. (2015) Modeling and optimization of laser cutting operations, Manufacturing Review 2, 1-15.

[8] You, D.Y., Gao, X.D. & Katayama, S. (2014) Review of laser welding monitoring, Science and Technology of Welding and Joining 19, 181-201.

[9] Purtonen, T., Kalliosaari, A. & Salminen, A. (2014) Monitoring and adaptive control of laser processes, Physics Procedia 56, 1218-1231.

[10] Yan, Z., Liu, W., Tang, Z., Liu, X., Zhang, N., Li, M. & Zhang, H. (2018) Review on thermal analysis in laser-based additive manufacturing, Optics and Laser Technology 106, 427-441.

[11] Fallahi Sichani, E., Kohl, S. & Duflou, J.R. (2013) Plasma detection and control requirements for CO_2 laser

cutting, CIRP Annals – Manufacturing Technology 62, 215-218.

[12] Struckmeier, F. & Puente León, F. (2019) Nesting in the sheet metal industry: dealing with constraints of flatbed laser-cutting machines, Procedia Manufacturing 29, 575-582.

[13] Dewil, R., Vansteenwegen, P. & Cattrysse, D. (2016) A review of cutting path algorithms for laser cutters, The International Journal of Advanced Manufacturing Technology 87, 1865-1884.

[14] Han, G. & Na, S.(1999) A Study on Torch Path Planning in Laser Cutting Processes Part 1: Calculation of Heat Flow in Contour Laser Beam Cutting, Journal of Manufacturing Processes 1, 54-61.

[15] Kim, Y., Gotoh, K. & Toyosada, M. (2004) Global cutting-path optimization considering the minimum heat effect with microgenetic algorithms, Journal of Marine Science and Technology 9, 70-79.

[16] Costa Rodrigues, G., Pencinovsky, J., Cuypers, M. & Duflou, J.R. (2014) Theoretical and experimental aspects of laser cutting with a direct diode laser, Optics and Lasers in Engineering 61, 31-38.

[17] Schleier, M., Adelmann, B., Esen, C. & Hellmann, R. (2018) Cross-Correlation-Based Algorithm for Monitoring Laser Cutting With High-Power Fiber Lasers, IEEE Sensors Journal 18, 1585-1590.

[18] Duflou, J.R., Fallahi Sichani, E., De Keuster, J. & Kruth, J.-P. (2009) Development of a real time monitoring and adaptive control system for laser flame cutting, in Proceedings of the 28th International Congress on Applications of Lasers and Electro-Optics, Orlando, USA, 527-536.

[19] Dewil, R. (2014) On generating tool paths for laser cutters, Ph.D. thesis, KU Leuven, Belgium.

Meet the Authors

Nikita Levichev is pursuing a PhD at the Department of Mechanical Engineering of KU Leuven, Belgium. He obtained his master degree in Plasma Power Plants from the Bauman Moscow State Technical University, Russia. His main research focused on the laser-material interaction in high-power laser technologies. Currently, he is involved in the development of a monitoring system for fiber laser cutting of thick plates.

Gonçalo Costa Rodrigues obtained his master degree in Mechanical Engineering in 2012 from FEUP, Portugal. For the next 6 years, he worked as a research engineer for KU Leuven to explore diode laser technology, beam shaping and polarization control for industrial laser cutting applications. Since defending his PhD in 2018, he has been active as a research expert managing the laser cutting technology research activities.

Reginald Dewil holds master degrees in Industrial Engineering and Industrial Management and a PhD in Engineering from KU Leuven, Belgium. Currently, he is an assistant professor at the Vrije Universiteit Amsterdam doing research in heuristic and metaheuristic optimization for production scheduling and routing problems.

Joost R. Duflou holds master degrees in Architectural and Electro-mechanical Engineering and a PhD in Engineering from KU Leuven, Belgium. Since 1997 he is active at the Mechanical Engineering department of KU Leuven, since 2006 as a tenured professor. He leads a research group focussing on sheet metal oriented manufacturing processes, with special attention for laser cutting. He is a CIRP fellow and has published over 500 international publications.