Lasers in Manufacturing Conference 2023

Investigating cut quality degradation due to heat accumulation during the laser cutting of high thickness mild steel plates

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Abstract

Cut quality degradation due to heat accumulation is a phenomenon which can significantly hinder the performance and output of laser cutting systems. As the workpiece temperature increases, boundary conditions to the process are modified and the cut quality can be significantly affected. In the present investigation, the degradation of the cut quality is investigated through a methodological framework to relate it to the workpiece temperature, thus identifying critical conditions for the cutting of mild steel sheets of different thicknesses. An industrial 6 kW fiber laser cutting system is employed both to pre-heat under controlled conditions and cut the mild steel material. In-line measurement of the workpiece surface is achieved by means of a calibrated MWIR thermal camera whilst roughness measurements of the cut profile allowed to characterize the quality in accordance with ISO 9013. Finally, different mitigating strategies are presented to avoid or compensate defect formation.

Keywords: Laser cutting; Heat accumulation; Process development

1. Introduction

Laser reactive fusion cutting is one of the most widespread manufacturing processes used in industrial production fields and has become a well-established technology for the processing of medium to high thickness steel sheets (Caristan, 2004; Davim, 2013). In reactive fusion cutting, the assistant gas does not only drive away the molten material from the kerf, as in fusion cutting, but it also reacts exothermically with the

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melt, significantly contributing to the increase of the overall process energy. This exothermic reaction provides an energetic contribution to the cutting process. When compared to inert gas cutting, reactive fusion-cutting allows the cutting of higher material thickness, reducing the required laser power, or alternatively, increasing the cutting speed (Harris and Brandt, 2001; Powell et all, 2009).

Despite the numerous advantages associated with reactive fusion cutting, several technological challenges still remain. Amongst these, the degradation of the cut quality due to heat accumulation of the sheet being processed results as one of the most significant issues.

During reactive fusion cutting, a large fraction of the energy released from the process is absorbed by the base material due to heat losses by conduction. Moreover, the base material is unable to fully dissipate the heat produced during the cutting process, leading to an increase in its temperature.

As the workpiece temperature increases, process boundary conditions are modified, and the cut quality can be significantly affected due to instabilities and excessive thermal input of the reactive fusion cutting process. This leads to a less controlled and stable oxygen reaction, and consequently, a deterioration of the quality of the cut edge, resulting in the formation of larger striations and increased profile inhomogeneity (Levichev et al., 2020; Levichev et al., 2021).

As the plates thickness increases, the issue of heat accumulation becomes more evident. This is attributed to the higher power input and the lower cutting speed which increase the process interaction time and so gives more time for heat to propagate.

To date, only a few works have addressed the issue of cut quality degradation resulting from heat accumulation. However, experimental evidence suggests that while higher temperatures enhance the cutting efficiency (Seon et al., 2018), since less energy is required to melt the material, cuts performed in a pre-heated portion of the plate result in a lower quality, even if the parameters are the same.

The problem of the degradation of cut quality due to heat accumulation was investigated and described in detail by Levichev et al. (Levichev et al., 2021). They realized an experiment on a 15 mm thick mild steel plate in which several straight lines were cut with fixed laser process parameters. The only parameter changing between different cut samples was the temperature of the working plate, which was influenced by the presence of previous cuts. It was observed that, with an increase in the base material temperature, quality degradation started to occur. This degradation manifested in an increasing accumulation of dross, eventually leading to a complete loss of cut in which the process was no more feasible.

The thermal sensitivity of the laser cutting process quality is especially problematic in industrial applications where the laser cutting path has small features or high-density nesting. In these situations, the base material can reach a significant temperature increase, exceeding the critical value at which the degradation of the cutting kerf starts occurring. In the most severe cases, the preheating effect can lead to the need for re-production or post-processing, significantly affecting not only the quality of the cut but also the overall productivity of the process. It is extremely important to find an efficient way to solve this problem and many different mitigation strategies in order to avoid quality deterioration due to heat accumulation are suggested (Levichev et al., 2020): (1) Waiting time strategy; (2) Cutting path and nesting optimization; (3) Active cooling; (4) Process parameters modification.

In the present work, the degradation of the cut quality is investigated through a methodological framework, aiming to establish its correlation with the workpiece temperature. Consequently, a critical temperature for the cutting of mild steel sheets of two different thicknesses was identified.

Moreover, in order to avoid or compensate for defect formation, different mitigating strategies were investigated. Firstly, evaluation of the waiting time necessary for the cooling of the material was assessed, whilst alternatively, a modification of the reference process parameters was attempted.

2. Material and Methods

2.1. Material

Raex 400 mild steel sheets with a thickness of 10 mm and 15 mm were used as feedstock material in this study since these material thicknesses are known to be subjected to notable defect formation in case of high density nesting (Levichev et al., 2020; Levichev et al., 2021).

The nominal chemical composition of these batches is shown in Table 1.

Table 1. Nominal chemical composition of Raex 400 mild steel (wt%).

Element	C	Si	Mn	P	S	Cr	Ni	Mo	B
Concentration [%]	0.16	0.50	1.60	0.025	0.01	1.20	1.00	0.25	0.005

2.2. Experimental setup

The experiments were performed on a customized version of the LC5 cutting machine (*Adige-SYS, BLMGroup, Levico Terme, Italy*) (Figure 1a). An industrial high-power multi-mode fiber laser source that can deliver up to 6 kW of power at a central emission wavelength of $\lambda = 1070\ nm$ (*YLS-6000-CUT, IPG Photonics Coorp., Oxford, Massachusetts*) is employed both to pre-heat under controlled conditions and cut the material. The transport fiber is a graded-index optical fiber having a core diameter of $d_{core} = 100\ \mu m$ and is coupled to an HPSSL (*Precitec GmbH & Co., Gaggenau, Germany*) cutting head. The optical process chain is composed of two optical elements, respectively a collimation ($f_{col} = 100\ mm$) and a focusing lens ($f_{foc} = 200\ mm$). From theoretical calculations, the beam waist diameter in the focal position was computed ($d_{waist} = 200\ \mu m$). The overall specifications of the laser cutting system are reported in Table 2.

Table 2. BLMGroup, LC5 laser cutting machine, and IPG YLS-6000-CUT laser source: optical specifications and laser parameters.

Parameters	Symbol	Values	Units
Maximum emission power	P_{max}	6000	W
Emission wavelength	λ	1070	nm
Beam quality factor	M^2	11.7	
Collimation lens	f_{col}	100	mm
Focal lens	f_{foc}	200	mm
Fiber core diameter	d_{core}	100	μm
Beam waist diameter	d_{waist}	200	μm

In-line measurement of the workpiece surface temperature is achieved by means of a calibrated MWIR thermal camera operating in super-framing acquisition mode. The FLIR X6901sc (Figure 1b) is equipped with an InSb sensor, sensitive in the 3-5 µm range, with a resolution of 640x512 pixels, capable to reach a framerate of 1000 Hz. To obtain a reliable measurement of the material surface temperature an accurate calibration of the emissivity is required since it depends on physical and thermal properties of the surface, such as roughness, oxidation, temperature, and the heat wavelength at which the measurement is taken (Sadiq et al., 2013; Conroy et al., 1987). A type K thermocouple (*Tersid TEK/TEK-30-KK, 30 AWG6 wire*) with a TC-08 Pico Technology acquisition system is used for the calibration of the material emissivity with the thermal camera.

Thermocouple measurements used as reference values during the camera calibration, up to a temperature of 310°C, were made by heating the sample with a resistive heater (*AREX Heating magnetic stirrer*) while recording with the thermal camera. The calibrated emissivity values for the 10 mm and 15 mm thick mild steel material are respectively 0.92 and 0.71.

The surface roughness of the cut edge profile was measured with a Mahr PGK profilometer equipped with an MFW-250 feeler and a 5 µm radius tip. In accordance with the UNI EN ISO 4287:2009 and ISO 4288:1996 standards for profile measurements, the acquired sample primary profile is filtered by a frequency filter with a 2.5 mm cut-off wavelength. The resulting mean peak to valley height roughness profile R_z is extracted. For each specimen a measuring line of 12.5 mm length is acquired at a distance of 1 mm from the top edge profile.

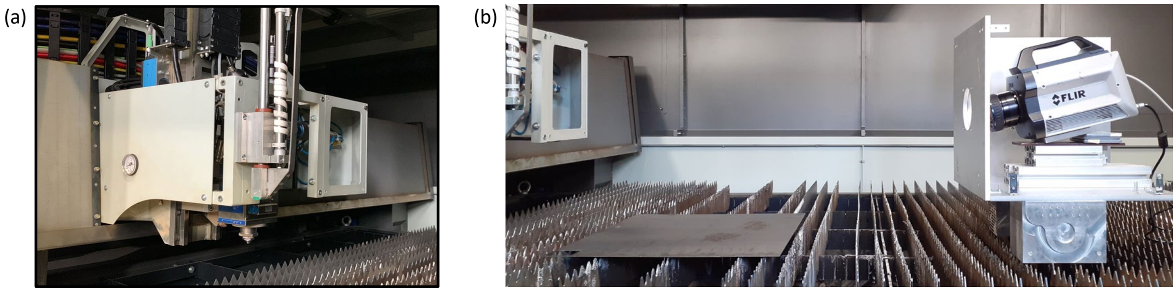

Fig. 1. (a) BLMGroup - LC5 cutting machine equipped with a Precitec HPSSL cutting head and (b) MWIR FLIR X6901sc thermal camera

2.3. Pre-heating strategy

As previously mentioned, reactive fusion cutting is a thermal process that could lead to a significant increase in the working material temperature. To control the material temperature increment, a novel preheating strategy was developed and tested in this experimental work (Figure 2c).

In this strategy, the laser beam itself serves as a thermal energy provider, following a specific marking path illustrated in Figure 2a. By appropriately settings the power, speed, and stand-off distance, the material is only marked and not cut. It is known that any changes in surface characteristics may affect the emissivity value of the material, but, from initial observations, these changes resulted to be non-significant in this study.

To ensure uniform preheating in all areas of the sample, a stress geometry was designed, as shown in Figure 2b, consisting of three distinct parts:

- Three external cuts (green path) describe a circle with 3 breaks at 120° from each other. These are meant to isolate the sample area, avoiding the heat dissipation of the preheating passages.
- A variable number of pre-heating passages (grey path) with a spiral shape to obtain homogeneous heating in the whole sample area. The number of passages determines the energy released to the material and its overall temperature.
- The cutting path (red path) has a square shape with a 40 mm side and rounded corners of 4 mm radius.

The heating of the sample to be cut is obtained by a variable number of pre-heating spiral paths with a high-power and highly defocused laser beam. The base material temperature is measured as the mean value of an Ellipse ROI using the calibrated FLIR thermo-camera and its temporal evolution is recorded.

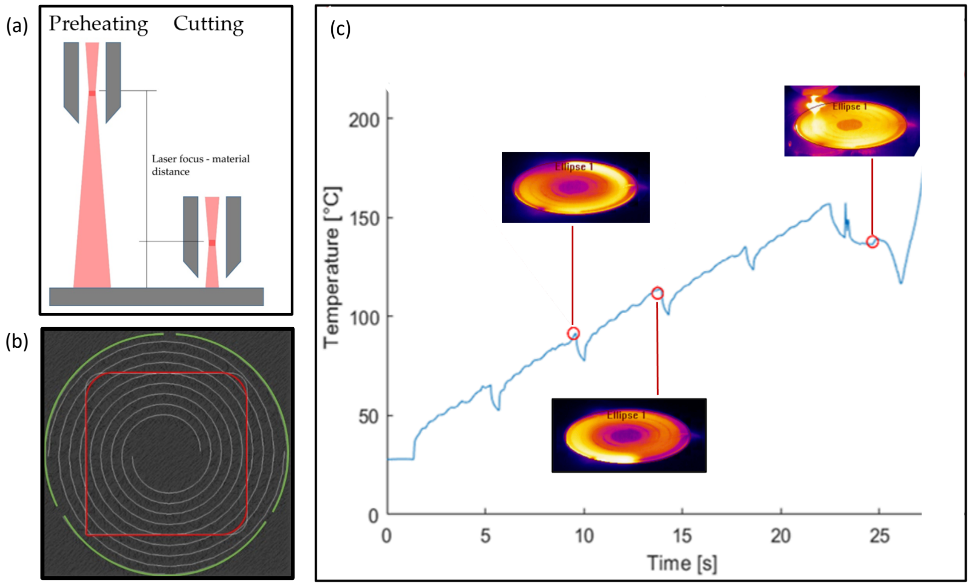

Fig. 2: (a) Laser configuration in pre-heating and standard cutting processes. (b) Schematic design of the test sample. (c) Thermal camera acquisition of the sample surface temperature during the pre-heating process.

2.4. Experimental design

The aim of this work is to investigate cut quality degradation through a methodological framework to relate it to the workpiece temperature thanks to the preheating strategy developed. For each number of pre-heating passages, the base material temperature is measured, and a relation between the two factors is retrieved. The pre-heating laser process parameters are reported in Table 3 where the only variable factor is the number of pre-heating passes varying from the value 0 (corresponding to ambient temperature) up to the value 8.

Then, three replicates of the test sample for each initial condition are cut with the parameters reported in Table 4, and the resulting surface roughness profile is measured and related to the base material temperature, thus, identifying critical conditions for the cutting of mild steel sheets of different thicknesses.

Table 3. Pre-heating laser process parameters for 15 mm and 10 mm mild steel thickness: fixed and variable parameters.

Fixed process parameters	**Values for t = 15 mm**	**Values for t = 10 mm**	**Units**
Laser Power	2000		W
Speed	6000		mm/min
Duty cycle	50		%
Frequency	500		Hz
Focus surface distance	85		mm
Standof Distance	80.5	81.3	mm
Spot diameter on the surface	6.13		mm
Variable parameters	**Values**		**Units**
Number of pre-heating passes	[0 ; 1 ; 2 ; 3 ; 4 ; 5 ; 6 ; 7 ; 8]		

Moreover, to avoid or compensate for defect formation by reducing the quality deterioration due to heat accumulation, different mitigating strategies were investigated. Firstly, evaluation of the waiting time necessary for the cooling of the material was assessed. Alternatively, a modification of the reference process parameters was attempted.

Table 4. Standard process parameters for 15 mm and 10 mm mild steel thickness for oxygen cutting.

Cutting process parameters	**Values for t = 15 mm**	**Values for t = 10 mm**	**Units**
Laser Power	4500	5000	W
Speed	1300	2100	mm/min
Assistant Gas	O_2	O_2	
Gas Pressure	0.7	0.7	bar
Focal position	+4.5	+3.7	mm
Stand off Distance	1.0	1.5	mm

The waiting time strategy is based on the stop of the laser cutting process when the critical condition is reached (or exceeded), in order for the material to cool down below the critical temperature thanks to the "natural" heat dissipation. This is probably the simplest solution to apply, but at the same time, it could reduce a lot the process productivity due to the potentially long waiting time required for the cooling.

The sample material is heated up by a variable number of pre-heating spiral paths. The temperature of the sample during both the heating and cooling process is measured and recorded using the thermo-camera. An exponential function has been considered for the fitting of the cooling curve and the waiting time relation as a function of the base material temperature is obtained. The experimental design parameters are the same as previously employed and are reported in Table 3, while the fitting function is of the type: $\Delta T = a \cdot e^{b \cdot t} + c$

Table 5. Laser cutting process parameters for 15mm and 10mm mild steel thickness: fixed and variable parameters.

Fixed process parameters	**Values for t = 15 mm**	**Values for t = 10 mm**	**Units**
Number of pre-heating passes	5	7	passes
Assistant Gas	O_2	O_2	
Stand off Distance	1.0	1.5	mm
Nozzle type	D3F 1.5	D3F 1.5	
Variable process parameters	**Values for t = 15 mm**	**Values for t = 10 mm**	**Units**
Laser Power	[4100 ; 4200 ; 4300 ; 4400]	[4200 ; 4400 ; 4600 ; 4800]	W
Speed	[1350 ; 1400 ; 1450 ; 1500]	[2200 ; 2300 ; 2400 ; 3500]	mm/min
Gas Pressure	[0.5 ; 0.6]	[0.5 ; 0.6]	bar
Focal position	[3.80 ; 4.15 ; 4.85 ; 5.20]	[3.20 ; 3.45 ; 3.95 ; 4.20]	mm

The alternative mitigation strategy is based on the modification of the laser process parameters with respect to the reference ones. From an energetic point of view, the parameters considered are the ones that most significantly affect the energetic level of the cutting process: laser power P, cutting speed V, gas pressure Pr, and focal position F. The laser power gives the actual energetic input to the process while the cutting speed regulates the interaction time between the laser and the material. The gas pressure determines the oxygen exothermic reaction rate, and the focal position controls the energy distribution in material thickness.

An experimental design has been carried out by varying the parameters previously mentioned as reported in Table 5.

3. Results

3.1. Cut quality degradation due to heat accumulation

At first, an attempt was made to find a relationship between the cut defect and the sample base temperature through a quantitative and methodological investigation.

The pre-heating temperature of the base material is related to the number of pre-heating passages as represented in Figure 3a and Figure 4a for 15 mm and 10 mm material thickness respectively. For each number of pre-heating passages, the base material temperature is measured, and an almost linear relationship between the two factors could be observed.

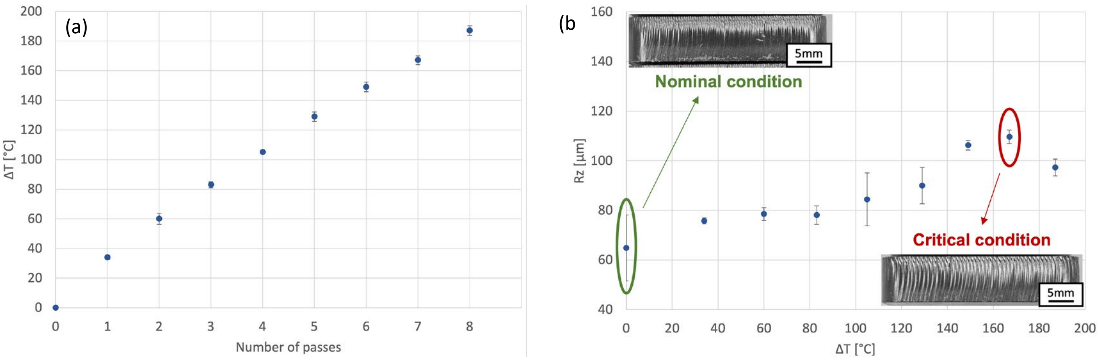

Fig. 3: (a) Surface sample temperature as a function of the number of pre-heating passages and (b) roughness peak profile (R_z) at different pre-heating passages for 10 mm material thicknesses. The mean value is represented, together with ±σ error bar. The nominal and critical conditions are underlined, and an image of the cut surface profile is shown.

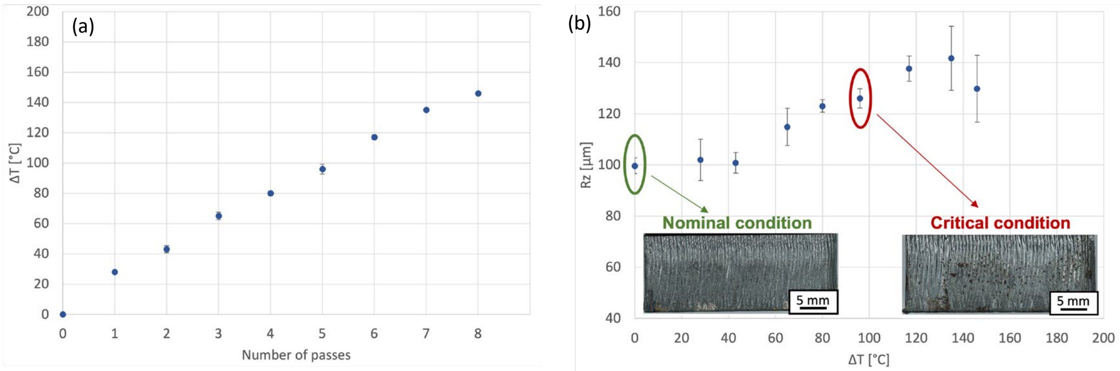

Fig. 4: (a) Surface sample temperature as a function of the number of pre-heating passages and (b) roughness peak profile (R_z) at different pre-heating passages for 15 mm material thicknesses. The mean value is represented, together with ±σ error bar. The nominal and critical conditions are underlined, and an image of the cut surface profile is shown.

The degradation of the cut quality in terms of roughness profile R_z is related to the workpiece temperature as represented in Figure 3b and Figure 4b and the critical conditions are identified, corresponding to the temperature differences $\Delta T_{15mm} = 96°C$ and $\Delta T_{10mm} = 167°C$ for 15 mm and 10 mm thicknesses respectively. For a plate temperature below the critical one the overall cut quality is considered acceptable, while for higher temperatures the degradation became significant, and the cut quality is no more acceptable.

3.2. Mitigating defect formation via waiting time strategy

As already mentioned, the temperature of the sample $\Delta T = T - T_{amb}\ [°C]$ during the material cooling process is recorded using the calibrated FLIR thermo-camera and represented in Figure 5a and Figure 5b at different values of pre-heating passes for 15 mm and 10 mm material thicknesses respectively.

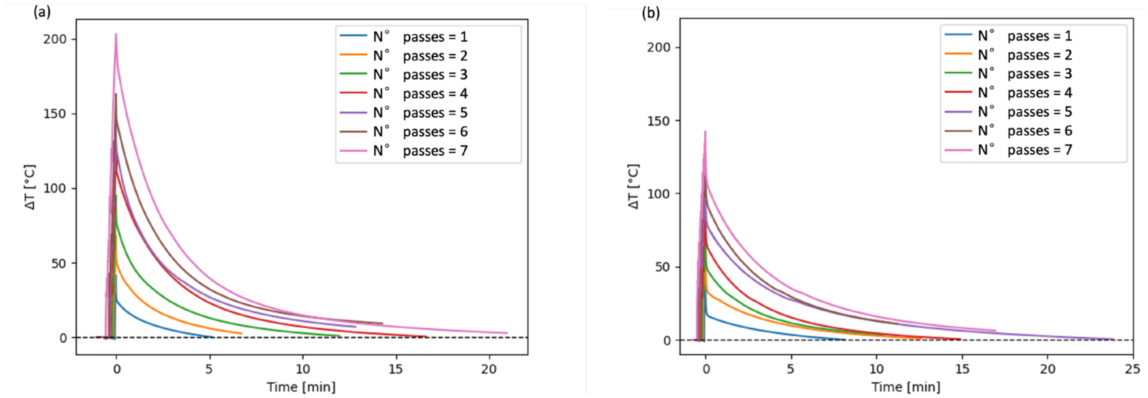

Fig. 5: Cooling behavior at different values of pre-heating passages for 10 mm (a) and 15 mm (b) material thickness.

The exponential function results to be a simple but effective solution for the fitting of the cooling temporal behavior ($R^2_{adj} = 0.998$) and the relation giving the waiting time (WT) necessary for the material to cool down below the critical temperature is computed as a function of the initial base material temperature. Exploiting the obtained relationships, it is now possible to give an estimate of the cooling ratio of the material:
For 10 mm thickness, considering a temperature difference $\Delta T\ >\ \Delta T_{critical}$, the resulting time is:

$$WT_{10mm} = 0{,}237 + 2{,}929 \cdot \ln\left(\frac{\Delta T - 5{,}635}{174{,}962}\right) \tag{1}$$

while, for 15 mm thickness:

$$WT_{15mm} = 0{,}361 + 4{,}152 \cdot \ln\left(\frac{\Delta T - 6{,}217}{97{,}940}\right) \tag{2}$$

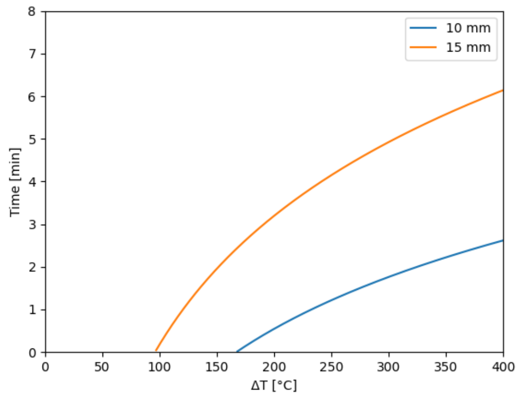

Fig. 6: Waiting time relationship for 10 mm and 15 mm material thickness as a function of the base material temperature.

It is possible to notice from Figure 6 that as the material thickness increase, the critical temperature and cooling ration both decreases. This means that increasing the material thickness leads to a less efficient waiting time mitigation strategy.

3.3. Mitigating defect formation via modification of the process parameters

The cut quality roughness profile (R_z) measurements as a function of variable process parameters previously introduced (laser power P, cutting speed V, gas pressure Pr, and focal position F), are represented in Figures 7 and 8 for 10 mm and 15 mm material thicknesses respectively. The base material temperature is equal to the critical one.

From the ANOVA analysis on the 10 mm thickness, only cutting speed V (Figure 6a), and gas pressure Pr (Figure 6b) parameters result to have a positive impact on cutting quality, reducing the roughness profile of the cut samples, while laser power P and focal position F does not have any significant effect.

So, reducing the gas pressure down to $Pr = 0.5\, bar$ or increasing the cutting speed up to $V = 2500\, mm/min$, it is possible to improve the roughness profile and obtain a cutting quality comparable to the nominal case obtained at ambient temperature for 10 mm mild steel thickness.

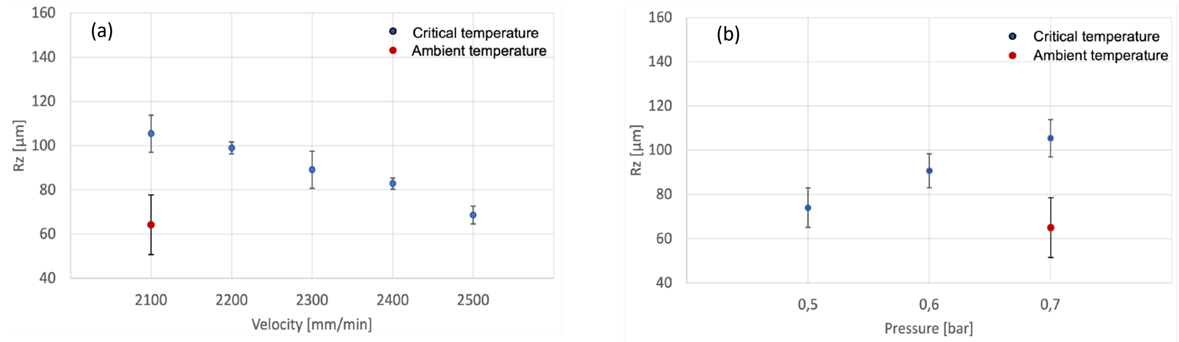

Fig. 7: Roughness peak profile (R_z) at the critical base material temperature as a function of (a) cutting speed V and (b) gas pressure Pr for 10 mm material thickness. The mean value is represented, together with ±σ error bar.

For the 15 mm case, the only significant factor results to be the focal position F (Figure 8), while the cutting speed V, gas pressure Pr, and laser power P, does not have any significant effect on improving cut quality.

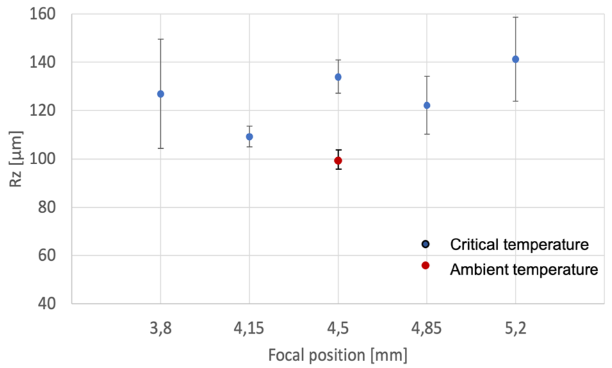

Fig. 8: Roughness peak profile (R_z) at the critical base material temperature as a function of focal position F for 15 mm material thickness. The mean value is represented, together with ±σ error bar.

As a new finding in this study, it has been verified that the mitigation strategy based on the modification of laser process parameters leads to an enhancement in the overall quality of the laser cutting process in terms of roughness profile (R_z) for different thicknesses of mild steel material.

4. Conclusions

In the present work, the cut quality degradation due to heat accumulation is investigated through a methodological framework to relate it to the workpiece temperature, and the critical conditions for the cutting of mild steel sheets of different thicknesses are identified. Then, two mitigation strategies are investigated for reducing defect formation.

The main outcomes and original contributions of the work can be listed as follows:

- A novel preheating strategy providing thermal energy to the material in order to control its temperature increment has been developed, tested and validated.
- The degradation of the cut quality in terms of roughness profile R_z has been investigated and related to the workpiece temperature. Moreover, the critical temperature for the cutting of mild steel sheets of two different thicknesses has been identified. For high material thickness, the critical temperature has a lower value with respect to the thinner ones.
- A waiting time mitigation strategy has been developed and the material cooling ratio has been estimated. Moreover, as the material thickness increase, the critical temperature and cooling ration both decreases. This means that increasing the material thickness leads to a less efficient waiting time mitigation strategy.
- Finally, it has been verified that the mitigation strategy based on the modification of laser process parameters leads to an enhancement in the overall quality of the laser cutting process in terms of roughness profile (R_z) for different thicknesses of mild steel material.

Acknowledgments

The authors gratefully acknowledge the BLM Group for supporting the research activities. The authors would like to thank the Italian Ministry for University and Research (MUR) for supporting the research via the National Plan for Recovery and Resilience (PNRR).

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