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Procedia CIRP 33 (2015) 533 – 538

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9th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '14

On the use of Areal Roughness Parameters to Assess Surface Quality in Laser Cutting of Stainless Steel with CO_2 and Fiber Sources

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Abstract

Laser cutting provides various advantages such as high flexibility in terms of process parameters and cut material type, as well as the possibility to obtain complex geometry in different dimensions with high precision. From industrial point of view, the two more competitive laser cutting technologies are based on the use of CO_2 and active fiber sources, which produce samples visually different, with non-uniform surface and different depth of the striations. The quality assessment between the two laser systems within the industry is commonly based on standard ISO 9013; that covers several aspects of quality, the most used are the surface roughness and edge perpendicularity; however 2D profilometers adopted for measures are not able to analyze the complex 3D surface topography of the cutting edge. As a result, despite the fact that the differences are visually appreciated, measured 2D roughness values of different CO_2 and fiber laser cutting conditions are very similar. Recently, a greater diffusion of 3D surface profilometry devices is present. These devices allow areal surface roughness parameters to be defined, which are potentially suitable to better quantify the laser cut quality. This work points out the use of a focus-variation microscopy to acquire 3D surfaces and evaluate analytically the surface quality of laser cut edges using areal surface roughness parameters. In particular, the purpose is to define a simple and repeatable method to identify the type of cutting process analyzed through the reconstruction of surface characteristics and quality of the cut-edge. As a case study, two stainless steel samples with the same geometry obtained with different laser sources, CO_2 and active, fiber is presented. For comparison purposes the cutting conditions were fixed to represent the state of the art of respective laser cutting technologies, which actually show distinct cutting edge characteristics.

Selection and peer-review under responsibility of the International Scientific Committee of “9th CIRP ICME Conference”

Keywords: Laser cutting; fiber laser; 3D surface topography; areal roughness

1. Introduction

Laser cutting of metals, like stainless steel, mild steel or aluminum, introduces many advantages over conventional mechanical technologies in terms of minimizing the cut-edge damages on material surface. Among them, there are the combination of high precision and fluency in carrying out complex geometries while keeping high quality of the cut-edge. Ensuring a correct control of the process parameters can result in very high performances in terms of quality or cutting speed. In particular the optimization of the parameters allows the production of a very small kerf, combined with a narrow heat-affected zone (HAZ) [1].

The fast development of solid-state lasers, such as active fiber ones, has stimulated the industrial background, making fiber technology very competitive respect the established CO_2 laser cutting process. The debates concerning the two technologies are very kindle especially around the quality of the cut-edge surface. Fiber lasers have two distinctive features concerning the cut of thick sheets: the apparent loss of the efficiency with the increase of the material thickness and on the other side the increase of the surface roughness for thick sheet (can be considered true for thickness above 4 mm) [2]. These differences can be explained considering the inclination angle of the cut front of laser fusion cutting. The expected inclination angles in medium and thick sheet fiber laser

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doi:10.1016/j.procir.2015.06.069

cutting are far away from optimum values at which the absorptivity reaches its maximum. Thus, the absorptivity of ferrous alloys to fiber laser radiation will be probably high for thin sheet metal cutting only. Instead, the theoretical absorptivity to CO_2 laser radiation is high and nearly constant over a broad range of sheet thicknesses. Therefore for a given sheet thickness the effective intensity of a CO_2 laser beam on the surface of the cut front can be higher than the intensity of a fiber laser beam, even in the case of greater focus radii of the CO_2 laser beam [3].

Characteristic defects of the cut-edge in laser cutting are dross, valleys and picks, macro-irregularities, striations and inclination of the kerf section [4]. Among these defects the striation pattern can be considered the most characterizing difference between the two laser cutting technologies. The coexistence of stable and unstable flows inside the kerf is important to understand the mechanism of striation generation, which originates from the instability of the side flow. These instabilities are the results of a combination of thermal instability of melting process and hydrodynamical instability due to the surface tension. [5]

In the paper in order to compare the two technologies, the quality of the cut-edge for the fusion cutting process of stainless steel (AISI 304) is analyzed. Two different cases will be considered: 6 mm that is a medium thickness and 10 mm, where due to the high thickness the difficulties of the cutting are more evident.

Table 1. Definition of the samples characteristics

Characteristics	Specifications
Material	AISI 304
Thickness	6/10 mm
Dimensions	45x45 cm^2
Technologies	CO_2/fiber

All samples were cut with process parameters and technologies at the state of the art of the industrial knowledge and for this reason can be considered representative for both processes.

The effect of fusion cutting combined with different laser sources generates characteristic effect on the material and samples appear visually different (Fig. 1). In particular, CO_2 laser ensures uniform surfaces (very low presence of valleys or picks) combined with the production of regions with different roughness on the cut edge. Instead the characteristic thick/medium section of cut surface appears with lower roughness at the upper part and increased roughness at the bottom part of the cut surface, appearing with a net separation between the zones and lower uniformity [6]. Considering the 6 mm thick sheets, the industrial practice accepts the cut quality of CO_2 to be better than the fiber laser. On the other hand, neither of the technologies stand out to show better quality in the case of 10 mm thickness.

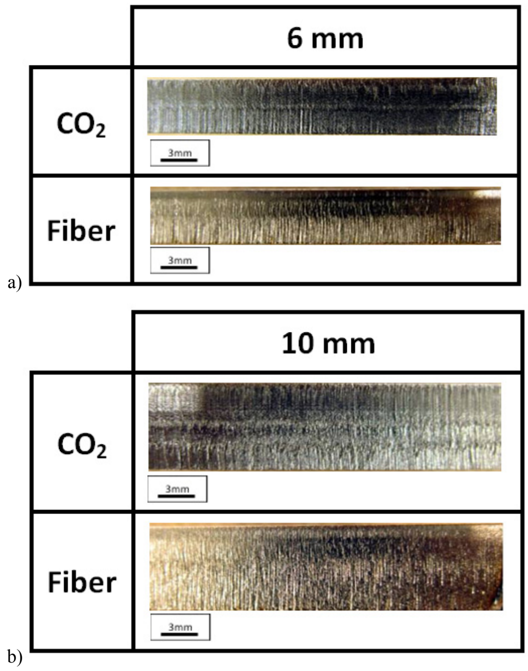

Fig. 1. Photographs of AISI 304 cut surfaces obtained with CO_2 and fiber laser: a) thickness 6 mm; b) thickness 10mm.

These considerations constitute the bases of the measurements as the visual analysis of the samples should be supported by a quantitative evaluation.

The evaluation of thermal cut-edge quality usually follows the indications of the standard UNI ISO 9013 about roughness and perpendicularity measures. However, standards suggest only a 2D analysis along a line of the surfaces and do not consider a complex 3D surface topography. This deficiency is underlined by the results; they are very similar and not able to reproduce the visual difference between the two technologies. In order to overcome this problem and to better quantify the laser cut quality, a 3D surface profilometry was employed, which could calculate areal surface roughness parameters.

Nomenclature

R_a	arithmetical average of surface heights [µm]
R_{z5}	mean height from fifth highest peak to fifth lowest valley [µm]
S_a	average areal roughness [µm]
S_{10z}	mean height from tithe highest peak to tithe lowest valley [µm]
T	thickness of the sample [mm]
λ_c	cut-off length [mm]
λ_{cx}	cut-off length on thickness direction [mm]
λ_{cy}	cut-off length on cutting direction [mm]

2. Experimental set up

2.1. Experimental equipment

A linear surface profilometer (Perthometer Concept MAHR PGK–MAHR PCMESS7024357) with tip and arm probe II was used for the roughness measures. The system was equipped with with2 µm diameter tip (MFW-250) and an arm with 50 µm range (6851805). In this case the cut-off wavelength value for roughness measurements was 0.8 mm.

For what concerns the 3D surface profilometry, a focus variation microscopy system (AliconaInfiniteFocus Real3D) was used with the specifications contained in Table 2.

Table 2. Specifications for the Focus-Variation parameters.

Characteristics	Dimensions
Magnification	x10
Exposure time [µs]	100
Vertical resolution [µm]	0.836
Lateral resolution [µm]	3.014

2.2. Experimental procedure

The experimental procedure covered the use of linear and 3D surface characterization equipment in comparison. Roughness measures on smooth surfaces, free from oxide and far from macroscopic errors had been performed, as well as indicated in standards ISO 9013:2002 (E), and ISO 4287:1997 (E), on specific rules for the preparation of surface edge. The results are listed in Fig 1. Focus variation microscopy was the employed method to capture 3D images of the laser cut edges. The technique of focus variation has been included in the recent standard EN ISO 25178.

For each laser cut sample, an area of 40xT $mm^2$was processed (where T is the sample thickness). The acquisitions contain information along two directions: cutting direction (y axes) and sample thickness (x axes). One of the most critical points in the surface topography measurements is the determination of the applied filter cut-off length. The information coming from the surface could be filtered selecting an appropriate cut-off length. The applied filter could be different along x or y directions.

International standards specify the selection of the cut-off length starting from precise surface parameters; in the analyzed case, the problem is more complex because the analytical parameter is the quality of the cut-edge and a numerical indicator cannot quantify it. Selection of an appropriate λ_c is important because surface roughness parameters are affected by this value. In fact the numerical values of the parameters are extracted from the filtered profiles. In order to make more readable the results and to focus on the surface features of interest, usually measurements of surface roughness require the removal of the waviness portion from the measured profile. However more waviness features are included in the surface roughness profiles when a longer cut-off length is used in filtering [7]. For this reason becomes very important identify the right cut-off length for the measures.

For very low value of λ_c, microscope acquires lower wavelengths (like a sort of low passing filter) and surface appears practically flat without roughness. Instead for higher values (high passing filter) all the wavelengths pass through the filter and microscope acquires not only information on roughness but also part of the waviness (modulation of the surface).

3. Analysis of 2D and 3D surface roughness parameters

First point focuses on the visual analysis of the samples with reference to Fig. 1: behaviors and appearances of the samples depend on cutting technologies and material thicknesses. The quality of the cut-edge in the case of medium thickness 6 mm of stainless steel is similar for both laser sources: samples appear in general smooth and homogeneous. On the lower part of the cut by fiber laser sample, the surface is rougher. However in the case of high thickness 10 mm sample the situation is different. Considering the CO_2 technology, surface appears less homogenous with many different zones generally smooth but a central part very coarse. For what concerns the fiber laser source, the problem is the same respect the previous case: surface is almost homogeneous but with striations in the lower section.

Fig.2 reports the result coming from the standard measures of roughness. R_{z5} and R_a at T/3 and at 2T/3 from the cut edge were collected. Five quality classes characteristic of R_{z5}, reported also in the graph at Fig. 2, are identified by the standard UNI ISO 9013. Roughness is evaluated also at 2T/3 from the top of the surface, in a region where there are more striations, but far away from macro-damages.

In the light of the 2D surface roughness measurements calculation using the related standards, the following points can be inferred:

- Ra and R_{z5} are strictly dependent on the position of the measurement. This observation is underlined by the values obtained at 1/3 and 2/3 of the thickness. Linear procedure is not optimized to describe an entire surface because each zone of the plane is characterized by a different value of roughness.
- The measurement length is very short according to the standard and consequently the profile acquired is representative of just a small portion of the cut surface.
- The standards impose measurement to be taken along a line far away from the macro-damages. Such defects, such as deep incisions are process characteristics and contain information regarding the differences in the cut quality. These characteristics are neglected in the measurement.
- The results often contradict with the visual inspections and common practice knowledge. For instance R_a and R_{z5} measured at 2T/3 height shows poorer quality on CO_2 laser cut edge, which is the opposite of the observed reality.

For all these reasons, linear measurements and values of R_a or R_{z5} cannot be considered reliable for the evaluation of cutting quality.

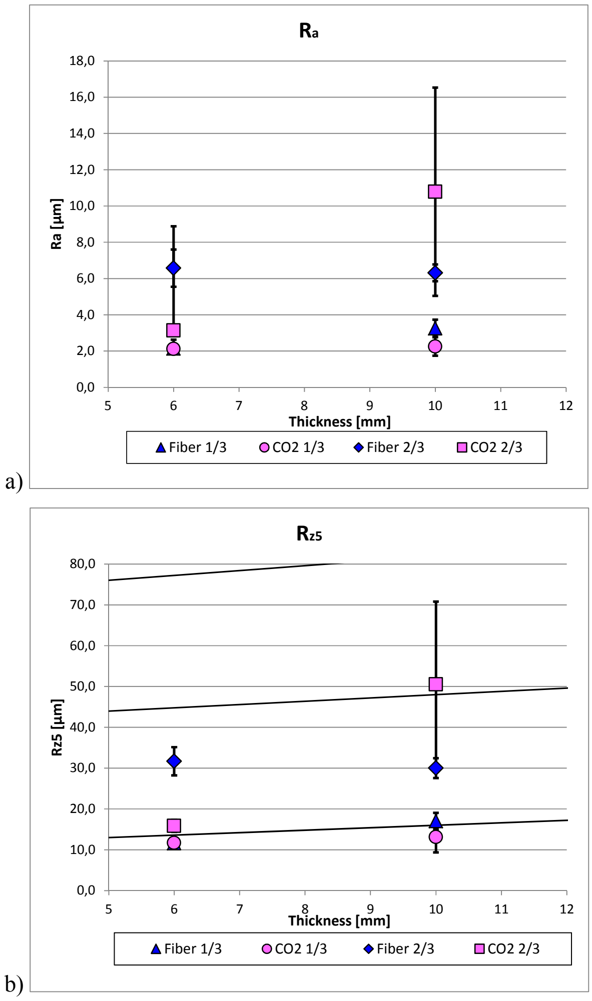

Fig.2. Summary of a) R_a and b) R_{z5} for the analyzed stainless steel samples.

The digital acquisition of 3D surface data with focus variation microscopy allowed flexibility in terms of calculation of roughness parameters and application of filter parameters. Through preliminary analysis it was seen that the cut off length (λ_c) was a key parameter in realizing surface defects on the reconstruction of the acquired surface. The cut-off length acts as the threshold for a low-pass filter for the roughness profile, *i.e.* surface features with repetition periods longer than λ_c are excluded in the roughness profile. Imposed by the standard the cut-off length is a fixed parameter on both axes and has a value of 0.8 mm. Accordingly, the defects present on the cut–edge surface, especially striations were studied underlining as a function of λ_c. Preliminary tests with the same value of λ_c on both directions were performed, but the obtained scans are not visually representative for surface condition of the samples. Moreover it was observed that different cut-off lengths on the different axes resulted to enhance the image representation. As a matter of fact, physically different phenomena occur along the thickness (y) and cutting (x) directions. A range regarding the limit levels was determined through the preliminary experiments.

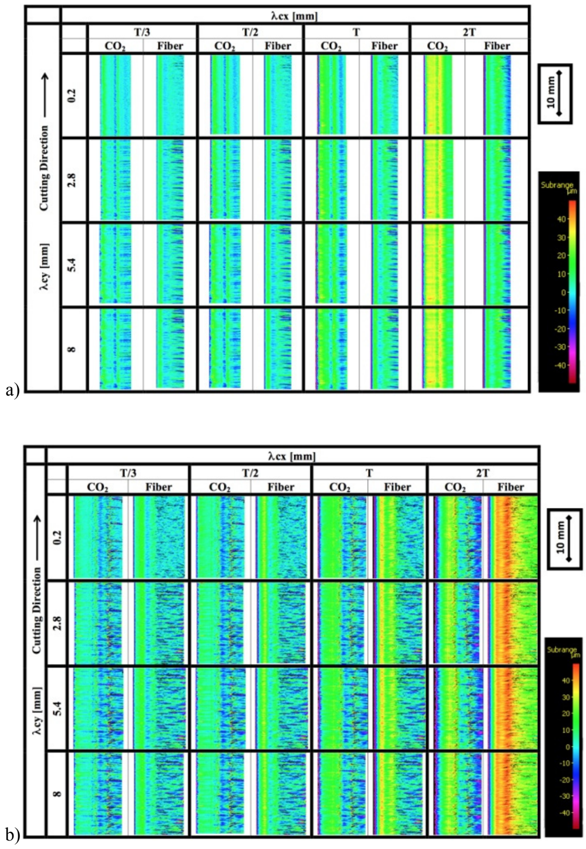

Fig. 3. Roughness profiles of the CO_2 and fiber laser cut edges for all the combinations of λ_{cx} and λ_{cy}. a) 6 mm b) 10 mm.

In particular, the cut off frequency on the thickness axis could be linked to the material thickness (T), which allowed parameterization for measurements involving different thicknesses. Thus, λ_{cx} varied with the levels T/3, T/2, T and 2T.

The cut-off length λ_{cy} along the cutting direction varied from 0.2 mm, which was found to be the minimum significant value that represents the largest cut-off value needed to detect the striations of the surface, up to 8 mm. Investigated ranges are summarized in Table 3.

Table 3. Parameters range in the sensitivity analysis on roughness profile.

Variable Parameters	Range [mm]
λ_{cx} : Cut-off length on thickness direction	T/3-T/2-T-2T
λ_{cy} : Cut-off length on cutting direction	0.2-2.8-5.4-8.0

Fig 3 reports the color map representations the roughness profiles for all the combinations of cut-off lengths tested in both thicknesses and laser cutting technologies. The visual inspection on the maps confirms a strong influence of the cut-off length combinations on the surface topography. As a matter of fact, the surface representations corresponding to the intersection between λ_{cx}=T/3-T/2 and λ_{cy}=5.4-8.0 mm ranges are the ones that better reproduce the real condition of the cut edge surface. In the other combinations, the information

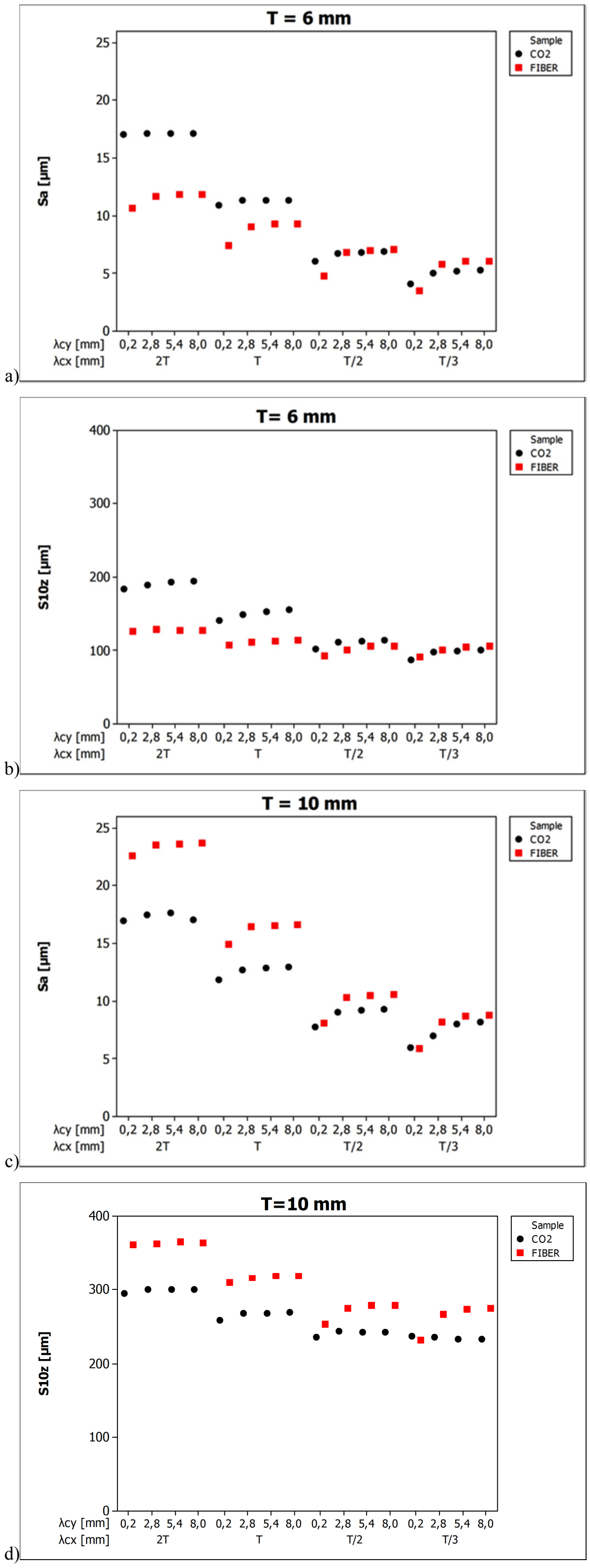

Fig.4. Values of Sa and S10z in relation with the cut-off lengths: a) S_a for 6mm b) S_{10z} for 6mm c) S_a for 10mm d) S_{10z} for 10mm.

contained in the color map is incomplete as most importantly striations are filtered out and not recognizable.

Fig. 4 reports the values of S_a and S_{10z} for different cut sheet thicknesses. Each plot is organized to compare directly each combination of λ_{cx} and λ_{cy} for both technologies. The graphs show that the values are strongly influenced by the cut off length. It can be seen that λ_{cx} has a stronger effect on the results, which is coherent with the color maps obtained seen in Fig 3.However, the parameters are not robust as the difference between the measured values change as a function of the cut-off lengths. Accordingly, the best technology, which should be identified with a lower number of S_a and S_{10z}, inverts as a function of the cut-off lengths. The measurements do not coincide with the quality measures determined in the visual inspection. As a matter of fact, if the analysis should be focused on the region determined in the qualitative analysis over the color maps (λ_{cx}=T/3-T/2 and λ_{cy}=5.4-8.0 mm), where 3D data successfully represents the quality of the visual inspection, no significant difference is observed in numerical values. This points out that the average roughness parameters such as S_a and S_{10z} do not fully represent the surface conditions, even though they are areal roughness parameter. Although, the 3D surface data adequately represents the difference in cut kerf quality, the applied surface parameter shades the difference. This is the consequence of aggregation of the whole surface to an averaging parameter. Therefore, the choice of adequate surface roughness parameters and their combinations is required for a complete analysis and comparison.

4. Conclusions

In this paper, the differences between two laser cutting technologies, in terms of the cut-edge quality, have been investigated. In particular the reliability of the standard roughness measurements and the possibilities arising from the use of new 3D topography measurement technologies have been addressed. The following conclusions can be drawn by this paper:

- R_a and R_{z5} are not representative of the quality of the cut surface because of the high dependence of the linear roughness from the position of the measurements along the thickness.
- On areal surface roughness measurements the use separate cut-off lengths on cutting and thickness directions (λ_{cx} and λ_{cy}) is more appropriate.
- The final representation of the surface roughness profile is highly dependent on λ_{cx} and λ_{cy}. The cut off length have different effects on the surface roughness evaluation as the sensitivity analysis underlines. For adequate representation of the surface defects, especially striations, the best conditions coincide with a λ_{cx} between T/3 and T/2, combined with a λ_{cy} between 5.4 mm and 8 mm.
- For areal roughness evaluation, parameters S_a and S_{10z} have been chosen. They are the corresponding translation on the area of the ones used in linear standard measurements.

- S_a and S_{10z} show a highly dependence over the cut-off length, especially to the λ_{cx}. The parameters are not robust and do not express the differences observed in the visual inspection.

In summary, this preliminary work showed a possible protocol for analyzing laser cut kerf, especially to compare two contemporary technologies CO_2 and fiber. The protocol is capable of representing the cut kerf visually and maintains the most important quality aspect, surface striations in the measurement data. However, for completion of the measurement chain other surface parameters and their combinations need to be analyzed to find the suitable quantitative parameter. The protocol requires validation of its robustness over replications of the cuts, different materials and thicknesses. Future works will be dedicated in this direction.

Acknowledgements

The authors gratefully acknowledge the support from the BLM Group.

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