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Revisiting image-based quality evaluation of laser cut edges

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Abstract. The optimization of laser cutting process parameters relies on productivity and obtained edge quality. Whereas maximizing cutting speed is a default procedure to increase the process performance, quality assessment of a cut edge is a non-trivial task. Both contact-based and image-based approaches can be used to quantify the quality of a cut surface. Since contact-based techniques are time-consuming and typically require expert knowledge, the development of simple and fast image-based approaches could improve the performance of sheet metal workshops. Due to the numerous quality characteristics that have to be considered, a significant challenge remains to establish a versatile approach for image-based quality evaluation. Within this paper, the quality assessment of laser cut edges by means of image processing techniques is analyzed. Additionally, the potential for employing visual evaluation to assess all quality indicators in a comprehensive measuring strategy is explored. Finally, the role of the presented approaches in shifting toward intelligent manufacturing is briefly discussed.

Introduction

In recent years, laser cutting productivity and thickness limitations have been shifted to higher values as a result of the increase in the available laser power, the development of novel optical components and the improvement of machine dynamics. When cutting thick plates, the quality assessment of a cut edge becomes more important since a large cut surface increases the variation of quality characteristics along the thickness. At the same time, whereas roughness and dross attachment are typically regarded in the literature as the main quality aspects [1, 2], the evaluation of cut edge quality in an industrial setting goes beyond measuring those characteristics. According to ISO 9013 [3], the main characteristics of an edge created by thermal cutting are perpendicularity (or angularity in bevel cutting), surface smoothness and dross attached to the lower edge of the cut surface. Measurements of roughness and perpendicularity are commonly performed by contact-based profilometry, while there is no standardized method for dross quantification. However, using such contact-based methods usually consumes considerable time and requires specific equipment and skilled operators to carry out, thus limiting extensive quality assessment within sheet metal workshops and preventing the collection of relevant production data. Such status restricts taking most of the benefits envisaged in the frame of Industry 4.0 that relies on the extensive use of data for continuous process improvement [4]. Therefore, the first step toward Industry 4.0 for quality evaluation of the cut edges is developing approaches with fewer possible human interactions with the process operations.

A few investigations have addressed the quality quantification of laser cutting parts using image-based strategies. Obtaining surface topography of laser cut edges using a focus-variation microscope and subsequent evaluation of the cut quality with areal surface roughness according to ISO 25178 [5] has been illustrated in [6]. An image-based technique to estimate the roughness of

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laser cutting samples has been described in [7]. In addition, an algorithm to predict the roughness of cutting edges by using an artificial neural network and applying image processing has been developed in [8]. A technique for quantitative identification of cut edge quality factors using an image analysis algorithm has been presented in [2]. An image processing algorithm to automatically evaluate the dross area in laser fusion cutting has been proposed in [9]. Despite numerous studies dedicated to measuring cut edge quality factors separately, there is no systematic approach to evaluate and quantify laser cutting quality considering all characteristics together.

In this work, quality evaluation of the laser cut edges employing an optical microscope with focus variation is investigated and compared with contact-based approaches. Moreover, a comprehensive method to measure all quality characteristics within a single measurement approach is proposed. Finally, a quality index is recommended to consider all quality factors with different weight parameters, which can be used further in the framework of Industry 4.0.

Roughness

One of the key factors determining the quality of a laser cut edge is roughness. According to ISO 9013, roughness of the cut edge should be evaluated as the arithmetic mean of the height between the peak and the valley over five sampling lengths (Rz5).

New techniques combining image processing and machine learning have been recently developed to estimate roughness [7, 8, 10]. But, as discussed in [11], these methods are extremely sensitive to lighting conditions and require a large database. Moreover, since roughness varies significantly along the plate thickness, especially for thick plates [9], the complex 3D geometry of the cut surface can hardly be represented by single line measurements. At the same time, contact-based profilometry does not provide enough information regarding dissimilarities in cut edges obtained by different processes. On the contrary, optical devices with focus variation can be used to extract full information about the surface topography of cut edges. This information may be further processed to quantify areal surface roughness and emphasize the difference between various laser cutting technologies.

Fig. 1 shows the surface condition and measured roughness using a profilometer and optical microscope with focus variation for 15 mm cut edges of stainless steel and mild steel created by the fusion and flame cutting processes, respectively. Contact-based (Fig. 1a, b) and optical (Fig. 1c, d) measurements have been performed for the same measuring area using a Mitutoyo Formtracer CS-3200 profilometer and a Keyence VHX-6000 microscope, respectively. To measure the roughness over an area using a profilometer, the edge of the sample can be divided into several sections, for which roughness is evaluated independently and then averaged (Fig. 1a, b). As a result, the average roughness of the cut edge, as well as the worst roughness, can be extracted. The profile roughness is calculated employing a Gaussian filter with λc and λs equal to 2.5 mm and 8 μm respectively. Computed average roughness can be considered as a value to represent the overall surface conditions of the cut edge. In this case, ignoring some areas between the measuring lines would be inevitable. However, increasing the number of measuring lines to cover the area as much as possible would significantly increase the measurement time.

In contrast to line measurements, the whole edge surface is considered by means of surface topography, thus eliminating the possibility of disregarding potentially important edge areas. Different roughness parameters can be used to quantify surface roughness using optical measurements. The maximum height of the surface (Sz) is sensitive to individual peaks and valleys which may not be significant for the whole surface characterization [12]. To evaluate the surface roughness, a Gaussian filter with λs and λc equal to 20 μm and 2.5 mm is applied. According to Fig. 1, both surfaces have comparable roughness conditions in terms of average Ra and Rz5, whereas it is not evident for Sz. As a result, Sz cannot be considered a reliable value implying areal surface roughness. Another areal roughness parameter is the arithmetic mean height (Sa),

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defined as the arithmetic mean of the absolute value of the height within an evaluation area. It provides a more representable value for a surface and a better criterium for comparison between different surfaces since it is less sensitive to individual peaks and valleys.

As seen in Fig. 1, a comparison between contact-based profilometry and surface topography using an optical microscope with focus variation illustrates that optical evaluation provides more absolute information for different surfaces and a roughness value (Sa) for the whole area, considering all peaks and valleys.

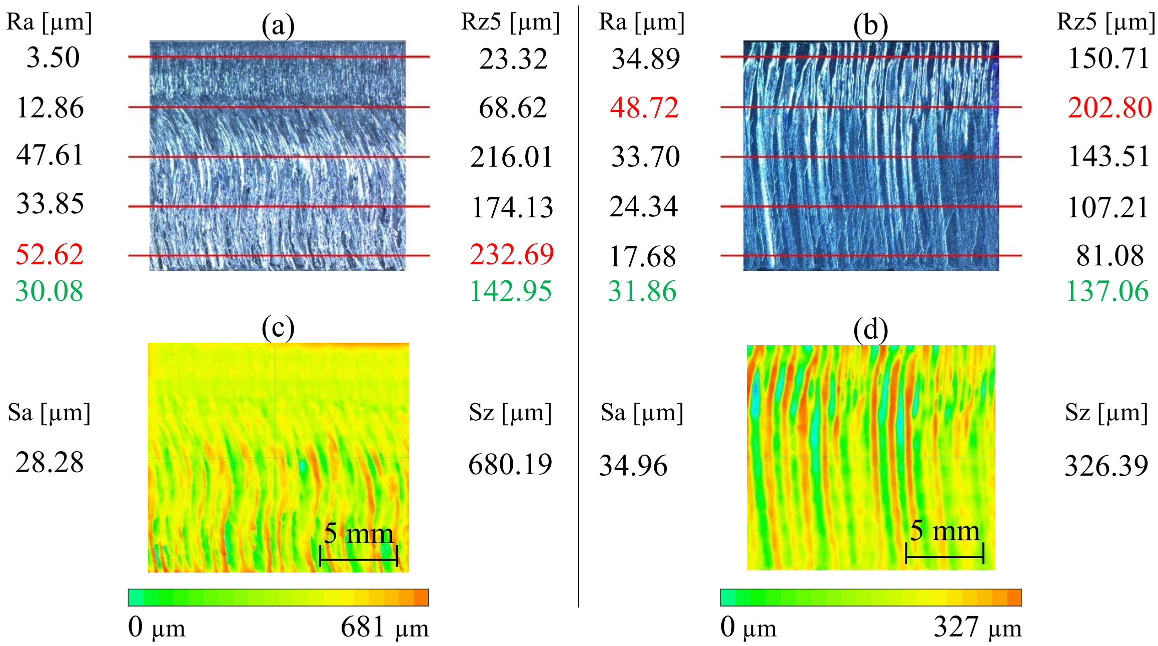

Fig. 1. An example of roughness measurements: (a) and (b) contact-based measurements for fusion and flame cut edge, respectively; (c) and (d) optical measurements for fusion and flame cut edge, respectively. Red and green color values present the worst and average roughness of the cut edge, respectively.

Fig. 2 shows a comparison of different surface conditions created by laser fusion cutting. Table 1 summarizes the measured surface parameters employing both contact-based and optical techniques for the samples presented in Fig. 2. The roughness distribution is more uniform on the surface in Fig. 2a, while the rougher region is near the bottom edge of the surface in Fig. 2b. Despite a higher value for the worst roughness on the surface in Fig. 2b using profilometry, the average roughness is lower. Considering areal roughness, Sz is affected by isolated peaks and valleys which can be seen by comparing the surfaces of Fig. 2b and Fig. 2c. Based on visual observation, the surface in Fig. 2c is rougher than the surface in Fig. 2b, but both have comparable values for Sz. Among all roughness parameters in Table 1, Sa considers the whole cut edge area and can be a more robust indicator of surface conditions.

Although contact-based profilometers provide more accurate measurements in a specific location, the obtained areal roughness values using optical measurements are more reliable due to considering all details of a region of interest. However, when roughness measurement aims to define the post-process requirement, other feature parameters (for instance, S10z) can be used to shift the importance towards extreme peaks and valleys.

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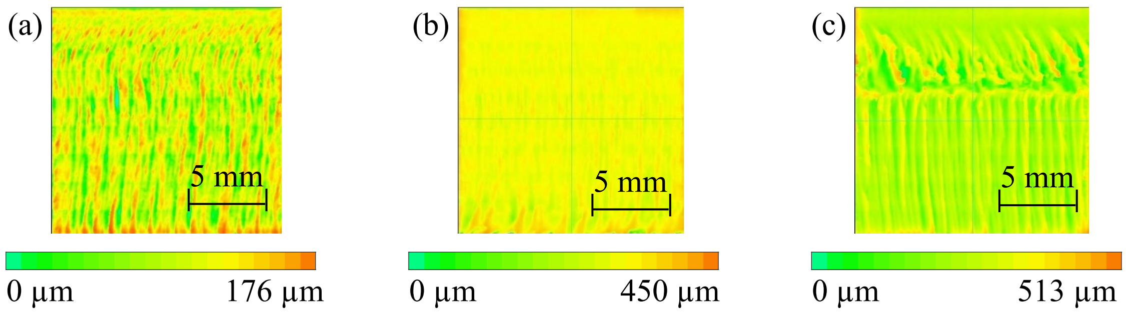

Fig. 2. Topography measurements: (a) homogeneous surface roughness; (b) non-homogeneous surface roughness; (c) rough surface.

Table 1. Measured roughness parameters using both contact-based and optical approaches for surfaces presented in Fig. 2.

Parameter	Fig. 2a	Fig. 2b	Fig. 2c	Measurement type
Average Rz5 [µm]	87.25	62.45	174.59	Contact-based
Worst Rz5 [µm]	105.29	114.91	295.93	
Average Ra [µm]	15.49	11.48	36.33	
Worst Ra [µm]	18.87	23.79	66.64	
Sa [µm]	13.83	14.38	39.07	Optical
Sz [µm]	175.01	449.65	512.86	

By correlating the cutting process parameters with the areal roughness of the cut edge, roughness prediction could be realized with machine learning algorithms, for instance, by using one of the already proposed techniques [7, 8, 13]. This approach could be further extended to be used for modeling the surface topography of the cut edge depending on the process parameters [14].

Dross attachment

Melting drops that are not able to escape during the laser cutting process, lead to the formation of dross on the bottom side of the cutting edge. Although the perfect cut edge is a dross-free surface, the attachment of dross might become inevitable, especially in the case of fusion cutting of thick plates [9]. Moreover, there is no clear definition for the acceptable amount of dross. Therefore, it is necessary to measure dross as a quality factor and accordingly determine the post-processing requirements based on industrial demands. Different techniques based on image processing have been proposed to measure the average dross height [15, 16]. Employing these methods, the cut edge is divided into a few sections and the maximum dross height is determined in each area. Then, the average dross height along the entire cut edge can be calculated. However, dross area can also be measured instead of dross height [9].

Fig. 3 shows two cut surfaces with different amounts of dross and compares both dross height and dross area measurements. Whereas the measured dross height is only increased by 34 % changing from the surface in Fig. 3a to Fig. 3b, the measured dross area is increased by 115 %. Therefore, dross area measurements provide a more reliable value of the dross amount compared to the height measurement approach. The principle of the algorithm for measuring the dross area has been thoroughly explained in [9]. Although the measuring length can be divided into different areas to provide an average value when considering dross height, the algorithm for measuring dross area is more robust. The latter method measures the amount of dross considering two dimensions while the other approach is based on a one-dimensional measurement. All in all, when

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the total amount of dross is the goal of measuring, the dross area assessment is more accurate. However, both approaches can be considered when defining post-processing requirements.

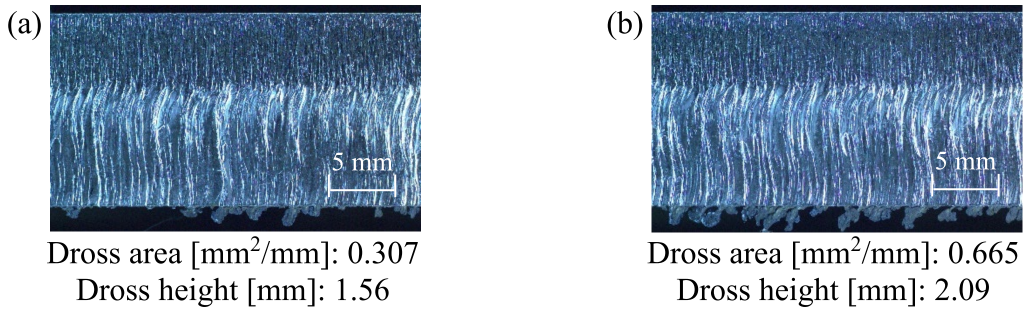

Fig. 3. Dross measurements using two different approaches for two surfaces with (a) non-homogeneous dross and (b) homogeneous dross.

Perpendicularity

According to ISO 9013, the perpendicularity of the cut surface is the distance between two parallel straight lines with a right angle to the reference surface in which the cut edge profile is enclosed [3]. The above-mentioned definition is shown in Fig. 4b, where *Δa* is the reduced cut face to allow for melting of the top and lower cut edge, *a* is the area for evaluating the perpendicularity, and *u* is the perpendicularity tolerance.

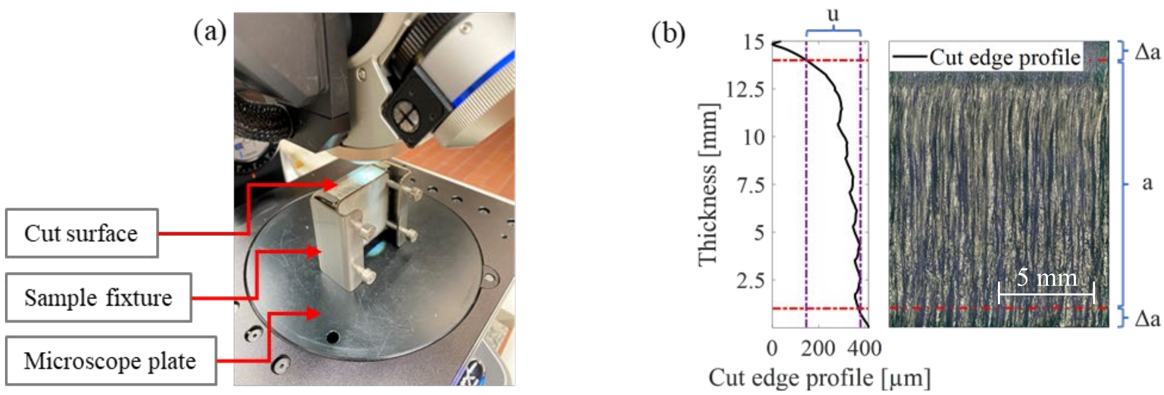

Fig. 4. Perpendicularity evaluation using the proposed image-based technique: (a) the setup used to avoid slope correction; (b) the average cut edge profile of the entire measuring area.

To evaluate perpendicularity, an image-based approach is proposed rather than complex contact-based measurements. The principle of this technique is similar to the roughness measurement using an optical microscope with focus variation. However, the reference surface should be located perpendicular to the microscope plate (Fig. 4a) to avoid slope correction after scanning the cut surface. A sample fixture can be used for the latter purpose as seen in Fig. 4a. After scanning the cut edge using a microscope, the 3D surface geometry can be captured in a JPEG image. Furthermore, this data can also be exported in a matrix representing the height of each point on the cut surface. The rows of the matrix are in the cutting direction and the columns are in the thickness direction. Afterward, instead of evaluating the perpendicularity in different vertical locations along the cut length, the average of the cut edge profile is calculated. Considering laser cutting as a stable process, the striation patterns are repeated periodically along the cutting length [16, 17]. Therefore, the average cut edge profile can be measured to ignore the possible

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extreme areas which have resulted from irregularities in the dynamic flow of the molten material in the cutting process. However, another statistical analysis is possible on the matrix to achieve the minimum and maximum height, standard deviation, etc.

To extract the average cut edge profile, the matrix is transformed into a column vector where each component is the average of the associated row in the matrix. Then, the average cut edge profile is extracted based on the previously calculated column vector. Furthermore, the perpendicularity tolerance (u) can be evaluated within the a area. Fig. 4b shows the average cut edge profile of the evaluated surface. By means of this approach, Δa can be determined for different thicknesses using [3]. Within the a area, the distance of the two parallel lines, in which the cut edge profile is inscribed, can be calculated and defined as the perpendicularity of the cut edge.

Quality index

Since the quality evaluation is affected by different factors, a multicriteria quality index is proposed instead of assessing surface characteristics separately. Although merging cutting performance parameters, including cutting speed, has been explored in the literature [16, 18], there is no recommendation for the quality index for laser cutting. As a result, a quality index (Eq. 1) has been developed considering roughness, dross area and perpendicularity with changeable weight parameters ($\mathrm{a} + \mathrm{b} + \mathrm{c} = 1$).

$$\mathrm{QI} = \mathrm{a}\frac{\mathrm{R}_m}{\mathrm{R}_t} + \mathrm{b}\frac{\mathrm{DA}_m}{\mathrm{DA}_t} + \mathrm{c}\frac{\mathrm{U}_m}{\mathrm{U}_t} \tag{1}$$

where R is roughness, DA is dross area and U is perpendicularity. Indices “m” and “t” refer to the measured and tolerance (and or reference) values respectively for the particular parameter. Tolerances for roughness and perpendicularity can be adjusted in accordance with the levels specified in [3] when QI is used as a rejection criterion. However, QI might also be taken as a target value. In this situation, the optimum results from laser cutting with the recommended process settings for each individual machine can be used as a reference.

Table 2 lists the selected references, measured values and weight parameters for different quality factors for a 15 mm thick stainless steel surface processed with an industrial fiber laser cutting machine. Since cutting results are not comparable with each other when employing different machines due to different process parameters and conditions, the references in Table 2 have been defined based on the optimal values obtained during laser cutting with nominal process parameters on a particular machine.

In this work, due to the priorities in industrial applications, weight parameters were selected using the following condition (Eq. 2):

$$\begin{aligned} &\mathrm{a} = 0.35, \mathrm{b} = 0.35, \text{and } \mathrm{c} = 0.30 \ \text{ if } \mathrm{DA}_m \leq \text{Threshold} \\ &\mathrm{a} = 0.55, \mathrm{b} = 0.05, \text{and } \mathrm{c} = 0.40 \ \text{ if } \mathrm{DA}_m > \text{Threshold} \end{aligned} \tag{2}$$

Considering the threshold, the post-process requirements can be defined to remove the dross. If dross is less than the threshold, post-processing is not required and the importance of dross is much higher. The opposite is expected when the dross area is higher than the threshold. However, this statement does not lead to increasing the quality index value for a cut edge with an amount of dross lower than the threshold. Since there is no standard value for this threshold, a value of 0.05 mm^2/mm could be considered based on the recommendation of industrial users and experienced operators [18].

Table 2. Measured data, tolerances and weight parameters for one sample.

	R [µm]	**DA [mm^2/mm]**	**U [mm]**
Measured (m)	28.28	0.347	0.356
Reference (t)	13.83	0.147	0.235
Weight parameters (a,b,c)	0.55	0.05	0.40

By replacing the parameters from Eq. 1 with variables from Table 2, the calculated quality index is 1.85. The smaller the quality index, the higher the quality of the cut surface.

All quality parameters required in the proposed quality index can be evaluated using one optical microscope with focus variation, where a sample with a sufficient length of the cut edge is positioned in a fixture to ensure that the reference surface of the sample is perpendicular to the microscope plate. After scanning the cut surface using the microscope with focus variation, the extracted surface topography can be used to quantify areal roughness (with slope correction), dross and perpendicularity.

The time for scanning the surface is dependent on the scanning area, magnification, and the number of focus variations at each point. However, this time can be equal to the roughness measurement using the contact-based approach illustrated in Fig. 1. Finally, the calculated quality index can be used as the objective function for an optimal selection of process parameters.

Conclusion

The measurement of different quality characteristics of laser cut edges through image-based methods has been discussed in this contribution. The proposed techniques can provide a more robust and faster quality assessment compared to conventional contact-based approaches. For instance, measuring areal roughness gives more detailed information about surface topography and can be used to clarify cut surfaces produced through different technologies. Perpendicularity evaluation using an optical microscope with focus variation provides more reliable values compared to contact-based approaches since it considers the whole cut edge surface.

Image-based approaches can also be used to evaluate other quality factors, such as cutting kerf and heat-affected zone. This study, however, took into account the three main characteristics based on current standards.

The proposed quality index can be used as the objective function for training machine learning algorithms for process parameter optimization based on overall quality requirements. Compared to contact-based measurements, the approach proposed in this paper allows faster and more automatic collection of quality information, enabling the use of larger data sets for the training of the required machine learning algorithms for process parameter optimization. Whereas the proposed techniques are applied for offline measurements, further studies can be dedicated to the development of online methods which can be used for real-time optimization.

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