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Investigation of the Profile of Laser Bends with Variable Scan Distance

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Abstract

Laser forming is a process capable of bending sheet metal only with the laser beam and without a physical interaction with the part. The part is formed by small and local deformations by the laser beam and it is done in increments with each pass of the laser. This incremental forming makes it difficult to ensure a smooth deformation field, which can result in non-smooth components and difficulties in achieving the required tolerance of the bends. This work presents an experimental investigation of the effect of varying the scan distance, number of passes per scan line and number of scan lines on the profile of a v-bend. The v-bends were measured on both sides by a laser range scanner to determine the surface profile along the bend. To evaluate the quality of the v-bend and define the profile as discrete or continuous, the bend roundness was evaluated manually and automatically by a Least Squares Circles method and by using second order differentiation method. The effect of varying the scan distance was tested experimentally on five samples with 16 mm and five samples with 20 mm bend length. The parts were subsequently evaluated on both the inside and outside of the bend and the bend angle was measured. The results show good correlation between the manual inspection and the automatic examination. The results show that the overlapping of the laser beam paths is required to create a continuous smooth bend.

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Keywords: Laser forming; Sheet metal bending: Roundness error; Profile scanning

1. Introduction

Laser forming is an incremental forming method where the heat input from a laser is used for inducing a small deformation in a component. The deformation follows three different deformation mechanisms; the temperature gradient mechanism (TGM), the upsetting mechanism (UM) and the buckling mechanism (BM) [1,2]. The TGM is

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used for creating bends, the UM is used for creating plane contraction and the BM is an instability resulting in buckling. This work will concentrate on the TGM, as this is the dominant mechanism in creating bends in plates. The bend angle for each pass of the laser with TGM is typically around 1-3°. Creating a higher bend angle is possible using several passes of the laser, also denoted as multi-pass laser forming [3]. A bend with a higher arc length can be created by using parallel laser scan lines [4].

Despite many possibilities and promises of laser forming, there are still unresolved issues regarding prediction and process planning of laser forming [5]. Firstly, the inability to predict the bending behavior makes it difficult to plan the necessary process settings to achieve a target shape. Secondly, the process settings necessary to form a target shape are not unique. The planning process has been investigated by several authors [6–17], and some have adopted planning based on a database [11,13,17]. To achieve a target shape, the process settings are found by comparing the initial shape with the database. To limit the possible solutions, the paths of the laser are chosen to be independent of each other [13]. The independency of the laser paths means the distance between laser scans is set high. If there is no coupling between parallel laser scan paths, a continuous deformation field may be difficult to produce. If a discontinuous deformation field is produced, the shapes appear as in Fig. 1a, while a more continuous deformation field is required to create shapes as in Fig. 1b.

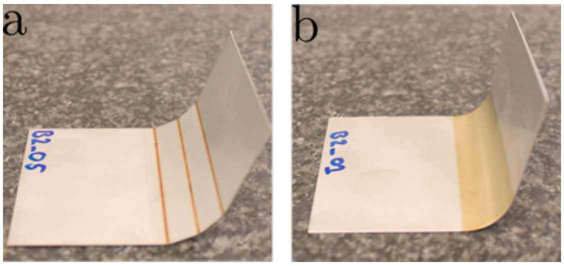

Fig. 1. A discontinuous bend (3x15-16) with three scan lines and 8 mm increment length; (b) A smooth bend (45x1-16) with 45 scan lines and 0.36 mm increment length.

This work investigates experimentally the influence of process settings on the shape of a v-bend profile and the bend angle. The shape is evaluated using the Least Squares Circle method [18] and the second order differentiation method. A dependency between the profile and the following process settings are presented: Number of laser scan lines made parallel with laser (number of scan lines), increment length between parallel laser scan lines (increment length) and number of passes per laser scan line (number of passes). The results show that laser beam overlapping of the parallel laser scan lines is necessary to achieve a smooth profile.

2. Experimental method

An experimental setup was created to ensure that the laser forming experiments on the industrial sheets could be conducted at the laser laboratory at Aalborg University. The experimental setup is shown in Fig. 2, and the equipment is presented in Table 1. The experiments were performed with the laser beam angle perpendicular to the workpiece. The constant process parameters can be seen in Table 1 and a description of the geometrical settings can be seen in Fig. 2. The purpose of the experiments was to determine how the process variables of number of scan lines, number of passes and increment length, influence the bend profile of the workpiece, illustrated in Fig. 3. The variable process settings were chosen to ensure that all samples were made with 45 laser scans. The increment length was calculated by eq. 1 and for this experimental setup the bend length of 16 and 20 mm were applied. A label, e.g. 45x1-16, is used for denoting the sample with 45 scan lines “x” 1 pass per scan line “-“ bending length of 16 mm. The combinations of process settings used in the performed experiments are shown in Table 2.

$$Increment\ length = \frac{Bending\ length}{Number\ of\ scan\ lines - 1} \tag{1}$$

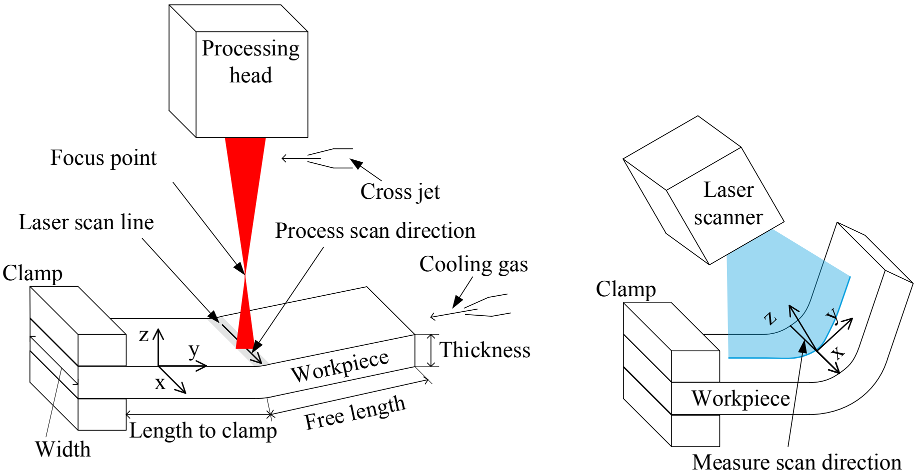

Fig. 2. Left: A schematic of the laser forming process and workpiece where the material for all the sheets was AISI 304 / EN 1.4301. The thickness is 0.5mm, width is 50 mm, length to clamp is 30 mm and free length is 25 mm. The first scan path was performed at this location and the following ones are placed towards the clamp. The laser scan path was perpendicular to the rolling direction of the sheet. Right: A schematic of the laser scanner process of the inside side of the workpiece where the scan was performed along the x-axis. An outside scan of the formed workpiece was performed by mirroring the laser scanner setup in the xy-plane.

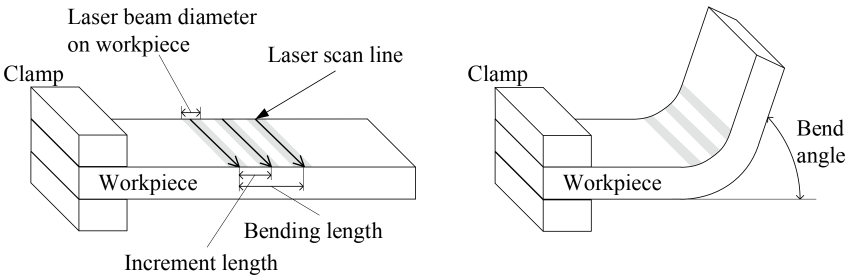

Fig. 3. Left: The workpiece with the planned laser scan lines, in this case three. Right: The workpiece after processing with a bend profile.

Table 1. Equipment, equipment parameters and process parameters used for all experiments.

Equipment	Manufacture	Equipment parameters	Value	Unit	Process parameters	Value	Unit
Laser	IPG YLS-3000 SM	Focal length	470	mm	Laser power	620	W
Processing head	HighYag (modified)	Collimated beam diameter	11.05	mm	Scan speed	6000	mm/min
XY-positioning	Q-sys	Beam parameter product	1.6	mm × mrad	Laser beam diameter on workpiece	3	mm
		Wavelength	1076	nm	Offset from focal point position	128	mm
		Cooling gas	Air		Dwell time	15	second

Table 2. Process settings used in the experiments with the resulting incremental length [mm].

Number of scan lines / Bending length [mm]	3	5	9	15	45
16	8	4	2	1.14	0.36
20	10	5	2,5	1.43	0.45

The measurement setup can be seen in Fig. 2, to the right. The used equipment can be seen in Table 3.

Table 3. Equipment and equipment specifications used for measurements.

Equipment	Manufacture	Scan specification	Axis	Measurement interval	Working range [mm]	Resolution [µm]
Laser scanner	Wenglor MLWL131	Scan length	x	0.05 mm between scan lines		
Robot	KUKA KR60-3	Scan width	y	2048 points per scan line	30...52	17…26
		Scan height	z		70...130	2…4.9

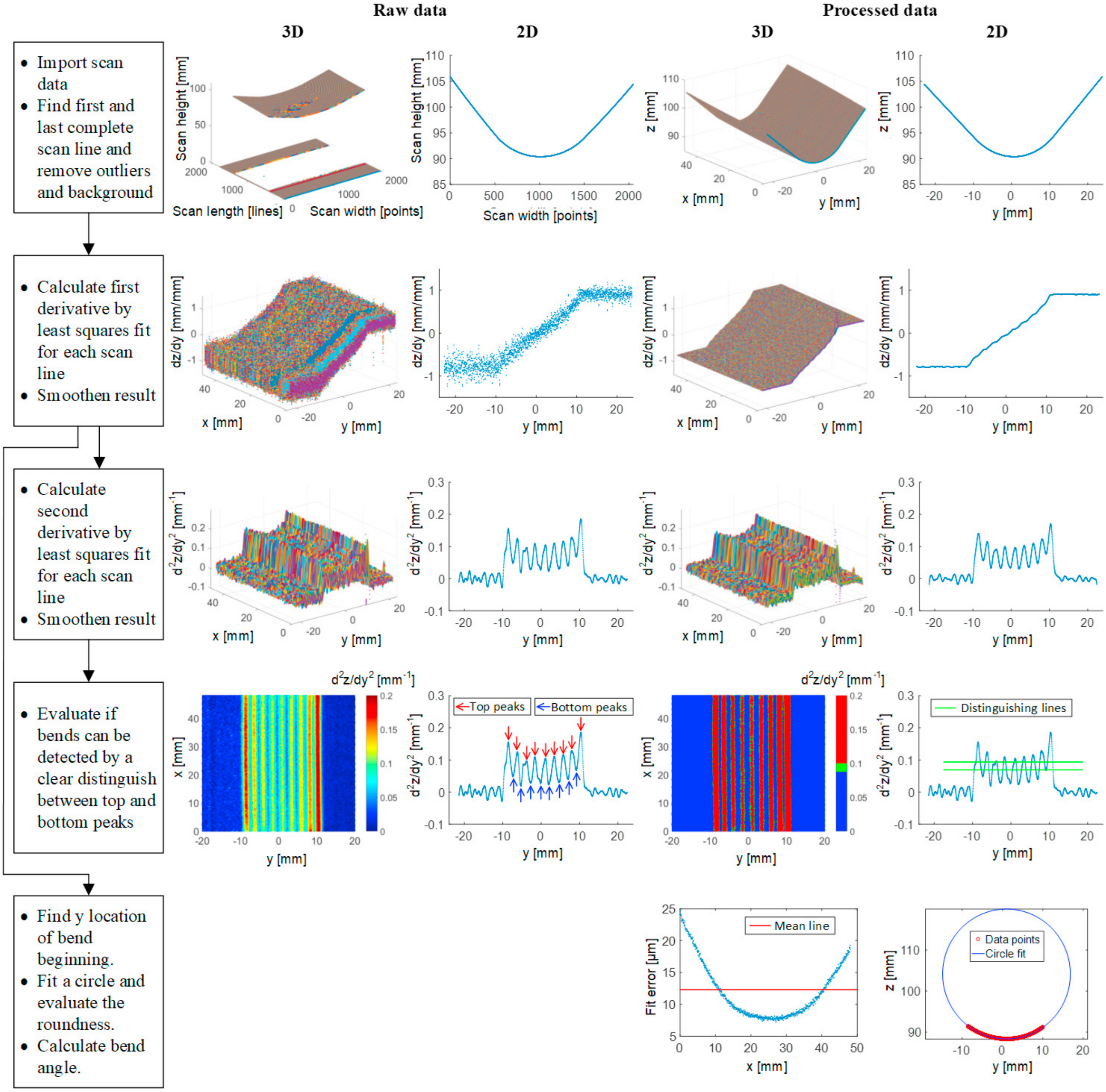

Fig. 4. Sequence of the scanning data processing and evaluation. The experiment with label 9x5-20 outside is used as illustration and the 2D line shown is taken from a scan line at x = 36 mm.

The principle of evaluating the laser bended workpieces is illustrated in Fig. 4. The scan data are filtered using a mean filter before the second order derivative is used for calculating the curvature. The difference between the raw data and the filtered data can be seen in Fig. 4. The density of 2048 points per scan line and the scan height resolution, see Table 3, makes the derivatives noisy. Because of the high number of point per scan line compared to the curvature of the bends to detect, a mean filter to smoothen the data was applied without destroying the curvature of the bends.

In order to evaluate the roundness of the v-bends and quantify if the bend is continuous the following methods are applied:

- Manual inspection by vision and touching.
- Second order differentiation method, see Fig. 4. Based on the second derivative of the data for each measured scan line the bottom and top peaks were detected. If a clear difference could be distinguished the bend was classified as discreet.
- Least squares circle fitting method, see Fig. 4. Based on the first derivative of the date for each measured scan line the start and end of the bend were detected. A circle was fitted by the least square circle fitting method for the data between the start and end of the bend and a fit error was computed. A threshold of the average fit error was determined to 12 µm. The bend was classified as discreet when the values were above this threshold.

3. Results and discussion

In the following section, the obtained profiles of the laser forming experiments are evaluated. A picture of the samples can be seen in Fig 5.

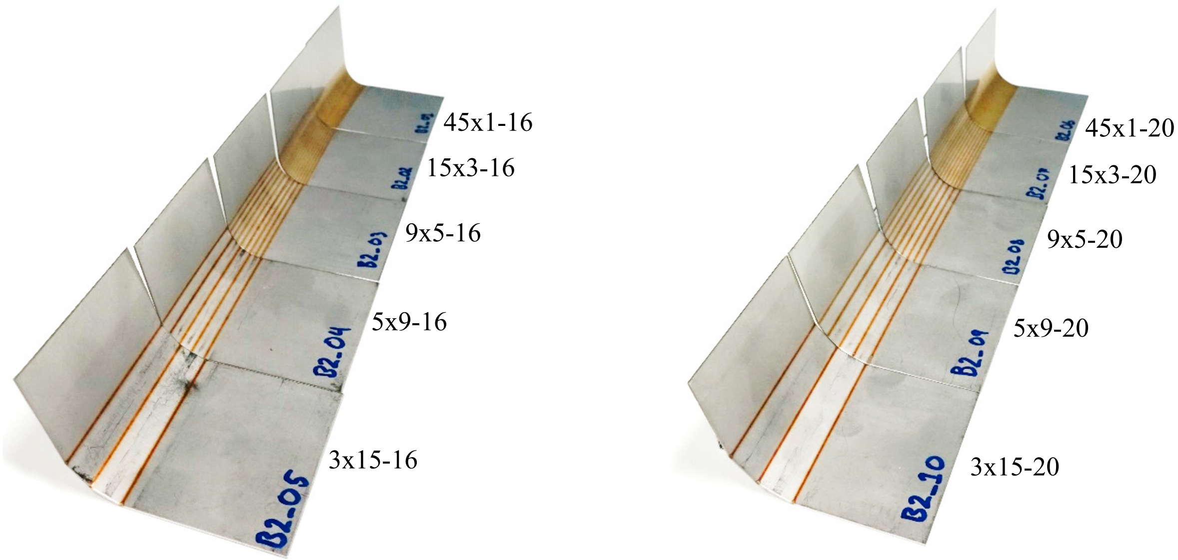

Fig. 5. Picture of the samples with experiment label. The numbering of the samples is explained in section 2.

All samples were made with the same total laser heat input; however, the samples show a trend where the samples with less number of passes had a lower bend angle, see Fig. 5 and Table 4 and 5. This is believed to be a result of the reduced bend angle per laser scan pass described by [19]. Each time the laser scan line is incremented in parallel, new virgin material is affected, furthermore the increment in parallel also ensures that the laser diameter is less distorted [19].

Table 4 and 5 show the results of the manual and automatic evaluations of the profiles.

Table 4. Evaluation of the results for the parts with 16 mm bend length.

	Bend angle [°]	Manual inspection	Second order differentiation method	Least squares circle fitting method average fit error [µm]
45x1-16 inside	80.0	Smooth	Smooth	9.75
45x1-16 outside	80.1	Smooth	Smooth	9.45
15x3-16 inside	80.9	Smooth	Smooth	7.72
15x3-16 outside	81.1	Smooth	Smooth	7.11
9x5-16 inside	80.2	Smooth	Smooth	4.89
9x5-16 outside	80.1	Discreet	Discreet	5.18
5x9-16 inside	76.3	Discreet	Discreet	14.20
5x9-16 outside	76.5	Discreet	Discreet	18.71
3x15-16 inside	71.9	Discreet	Discreet	74.16
3x15-16 outside	72.0	Discreet	Discreet	81.30

The results show a good correlation between the manual inspection and the curvature plots shown in Fig. 6 and 7. A clear variation in the curvature for the 3 and 5 parallel scan lines is shown for the bend length of both 16 and 20 mm. This suggests that the bend profiles are perceived as discreet, which is also evident in the manual inspection. An analysis of Fig. 5 also reveals this. These samples contain no overlapping of the laser beam with an incremental length of 4 and 8 mm for the 16 mm bend length and 5 and 10 mm for the 20 mm bend for the 5 and 3 parallel scan lines respectively, see Table 2. The incremental lengths are above the laser beam diameter and this ensures that no overlapping has occurred between parallel scan lines.

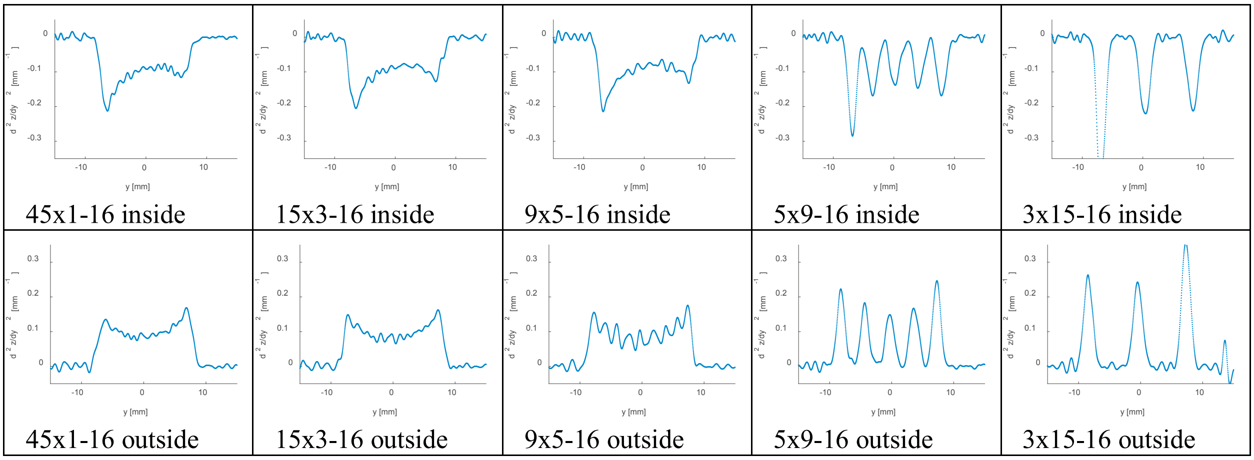

Fig. 6. Smoothened second order derivative plot of the parts with 16 mm bend length.

The 9x5-16 and 9x5-20 are both edge cases, with incremental lengths of 2 and 2.5 mm respectively, that may be accepted under some circumstances. The samples with a smaller incremental length are all accepted for both the manual inspection and the curvature. The largest incremental length is the 15x3-20 with an incremental length of 1.43 mm, or approximately half the diameter of the laser. This suggests that using less than half the laser diameter may be a useful rule of thumb to ensure smooth profiles using laser forming.

Another observation is the difference in results depending on the inside and outside of the bend; this is due to the thickness of the plate. This means that which side is measured becomes relevant for the results. As the plate is formed during bending, the inside bend is compressed, while the outside is stretched. Therefore, if the outside is acceptable, the inside will usually be as well. An argument for using the inside instead of the outside may be made on a component specific basis. The smoothness evaluation of the 16 and 20 mm bending length by a least squares circle fit method shows a clear tendency that a large fit error exists for the bends with three parallel scan lines. However, the method is unable to discern the edge case at 9x5-16 and 9x5-20, even resulting in a lower error for the 9x5-16 compared to 15x3-16 and 45x1-16 for both inside and outside.

Table 5. Evaluation of the results for the parts with 20 mm bend length.

	Bend angle [°]	Manual inspection	Second order differentiation method	Least squares circle fitting method average fit error [μm]
45x1-20 inside	88.0	Smooth	Smooth	11.07
45x1-20 outside	86.9	Smooth	Smooth	9.02
15x3-20 inside	84.5	Smooth	Smooth	11.40
15x3-20 outside	84.7	Smooth	Smooth	10.68
9x5-20 inside	80.2	Smooth	Discreet	13.31
9x5-20 outside	80.4	Discreet	Discreet	12.10
5x9-20 inside	75.0	Discreet	Discreet	27.47
5x9-20 outside	75.3	Discreet	Discreet	32.46
3x15-20 inside	75.0	Discreet	Discreet	139.35
3x15-20 outside	75.3	Discreet	Discreet	138.89

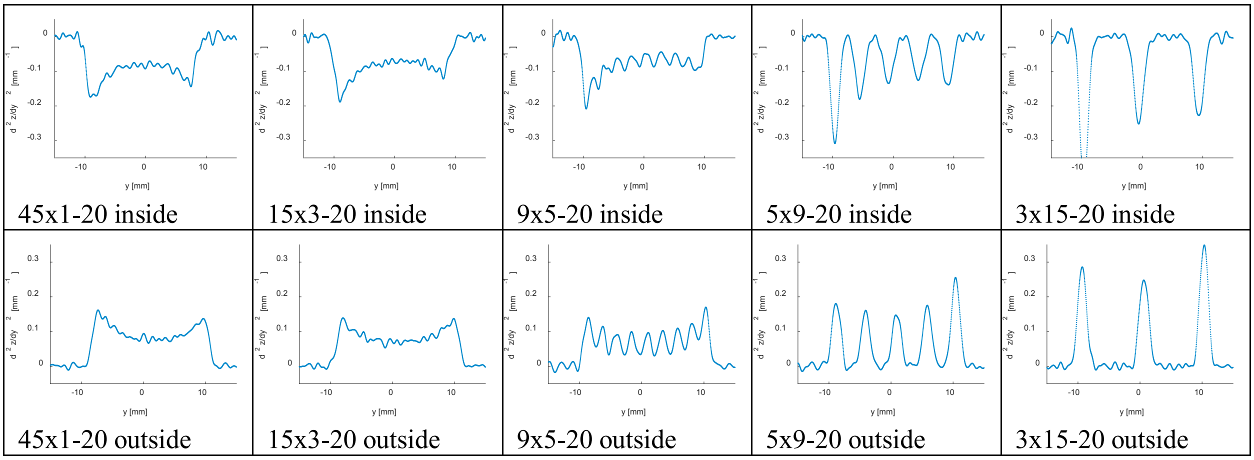

Fig. 7. Smoothened second order derivative plot of the parts with 20 mm bend length.

4. Conclusion

Several samples with the same number of total scan lines but varying incremental length and number of passes were made and analyzed. The aim was to detect and classify when the bend goes from a continuous to a discrete bend profile. A good correlation between the manual and vision-based curvature inspection methods was observed. The least squares circle fitting method was found to disagree with the manual inspection in the edge cases but was able to detect when the discontinuity became substantial. The results suggest that the curvature is best classified with automatic inspection.

Using an incremental length between parallel laser scan lines of less than half the laser diameter appears as a useful rule of thumb for ensuring smooth bend profiles. Furthermore, the results show that the process settings with number of passes and a small incremental length can be used for increasing the total bend angle. For the 16 mm bend angle the angle was almost kept constant for one, three and five passes per scan line whereas for the 20 mm bend angle this tendency was not so clear. This could indicate that the bending deformation rate will decrease after a certain number of passes on the same scan line. The unclear result confirms that the prediction of the process is difficult, which was also reported by other research.

From the evaluation of the automatic methods to detect if a smooth profile is achieved it is observed that for the cases where a threshold for the least squares circle method fit can be set around 12 µm there is a general agreement in distinguishing the continuous and discrete profiles.

The knowledge gained from this study shows that the geometrical quality of the bending profiles can be achieved, but the prediction of the process is difficult, and it is important in order to apply this technology in robust industrial solutions.

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