Development of a irradiation strategy within a closed loop control system for the laser adjustment of deformation

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Abstract: By means of flexible forming processes in sheet metal manufacturing it is possible to produce parts of complex geometry within short manufacturing time. These procedures are suitable especially for prototyping or adjustment of deformation. Here formative procedures like laser forming are increasingly important, because they make the large-scale-like production of the prototypes with the required materials possible. High accuracy and reproducibility of the products is the precondition of the production. Due to the lack of a forming tool, complex geometries can hardly be manufactured within tolerances. To overcome this problem an automatic closed loop control system for the adjustment of deformations has been developed. An important element of the closed loop control system is the definition of a suitable irradiation strategy for laser forming. For the determination of the irradiation strategy a lot of influences must be taken into consideration from the field of material, geometry and laser. In this paper the improved closed loop control system and the development of an irradiation strategy for 4 mm deep buckles in an ALMgSi1 sheet will be represented. This system can be used e.g. in the automated adjustment of hail damage in car bodies or deformation by heat treatment.

Keywords: Closed loop control system, laser forming, adjustment, irradiation strategy

1. INTRODUCTION

The manufacture of complex sheet constructions is characterised by a great number of influence parameters. Heat treatment, shaping and mechanical machining lead to deformation of the finished product [1].

As a result, expensive adjustment operations are often manually carried out. To increase the economic efficiency and the productivity of the manufacturing process, automatic forming processes are necessary. A possible solution for this problem is laser bending. This laser forming process secures flexible forming through contactless operations. Flexibility and the abdication of forming tools make it possible to use laser forming in the sphere of Rapid Prototyping or for small batches [2, 3]. A great number of influences, variable properties of the semi-finished product and the lack of a forming tool can lead, however, to an unsatisfactory repeatability and inaccuracy [4, 5, 6]. Therefore, a closed loop control system is necessary.

2. LASER FORMING

Laser beam bending is based on plastic deformation of the heated area. The laser beam heats the material locally and thus introduces thermal stresses. As a result, the flow limit is achieved. The ambient material prevents lateral expansion. That leads to local compressive stresses [7]. When cooling, this area shrinks and the corresponding stresses deform the workpiece. Depending on geometry and irradiation strategy this basic mechanism leads to different forming mechanisms. The two fundamental mechanisms are represented in Fig. 1.

If the difference in temperature in the warming period between the irradiated and unirradiated side is great, the material is bent towards the beam when cooling down. This effective mechanism is called temperature gradient mechanism [8].

An irradiation strategy which ensures a uniform warming of the irradiated area with a small difference in temperature between the irradiated and unirradiated surface is chosen for the upsetting and buckling mechanism. According to the geometry

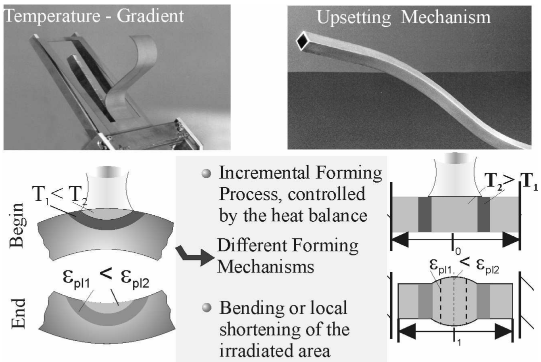

Fig. 1 Mechanism of laser forming.

of the irradiation trajectory, shortening (upsetting) and crippling (buckling mechanism) of the sheet take place [9].

The flexibility of this process is influenced by many individual parameters which determine the achievable deformation. They can be divided into three different groups: the material parameters, laser system parameters and parameters of the part geometry. Heat conductivity, density, heat capacity, coefficient of thermal expansion, surface quality, inherent stress condition, state structure as well as yield stress are mentioned in the range of material parameters.

Laser parameters like laser power, path feed rate beam diameter and laser operational mode (pulse mode or continuous wave (cw) mode) are especially important. The forming mechanism is determined by them, for they cause the development of the temperature field within the interactive area.

Sheet thickness, length of irradiated path, width of bend leg and curvature are noted as geometry parameters. The irradiation strategy applied in this case is of particular importance. [9]. Deformations in the curvature can be adjusted, for example, through multiple irradiation of the same area or neighboring positions. Another example is the laser forming of a spherical dome carried out by radial irradiation pattern and concentric lines (Fig. 2) [10]. However, the multitude of influence parameters, varying properties of semi-finished goods in conjunction, the complex multiple irradiation strategy with the lack of a forming tool technology lead to an insufficient reproducibility and accuracy of the parts.

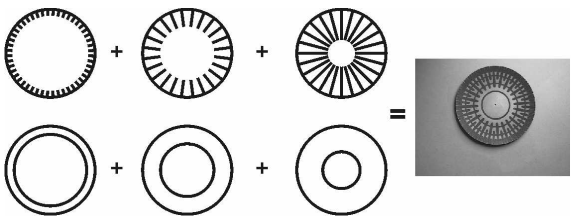

Fig. 2 Irradiation strategy for laser forming of a spherical dome.

3. CLOSED LOOP CONTROL SYSTEM

A closed loop system which controls the laser process online has been developed so as to solve the problem of the reproducibility of the resulting forming. It consists of a so-called preprocessor and the actual closed loop system (Fig. 4), which will be specified afterwards. An optical 3D sensor which digitzes the workpiece between manufacturing steps is employed. The comparison of the actual geometry with the nominal one provides information about the geometry deviation. Based on this nominal/actual comparison the irradiation strategy for the correction of the deviation by means of laser radiation can be developed.

The preprocessor analyses the target geometry which is either presented as 3D-point cloud resulting from scanning a physical model or as CAD-Model. CAD models are imported in VDAFS-Format (Verband der Deutschen Automobilindustrie Flächen Schnittstelle), a standardized CAD interface for the exchange of free-form surfaces [11]. This format is used by the German automotive industry to define surface models, e.g. car bodies. In this description free form geometries are specified as pieced polynomial curves and tensor product surfaces over the monom base:

$$X(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} u^i v^j A_{i,j} \quad \text{with} \qquad (1)$$

$$u, v \in IR, A_{i,j} \in IR^3, n, i, m, j \in IN$$

with u^i and v^j are polynomials of the order $i \le n$ and $j \le m$ respectively. Tensor product surfaces are defined over a rectangular parameter domain. For a more detailed description see [12].

During the closed loop the workpiece is repeatedly digitized by the 3D-sensor. With respect to the large amount of data, a complete surface reconstruction is avoided. The nominal/actual value comparison acquired in this case is based on the comparison of manufacturing features. The features can be margin contours which are present in automobile parts by clearances (e.g. fuel tank gap), the margin itself or the bending angle (Fig. 3). These features have to be extracted via pattern recognition both out of the sensor point cloud and out of the CAD point cloud by an appropriate rapid feature extraction algorithm. For more details see [13, 14].

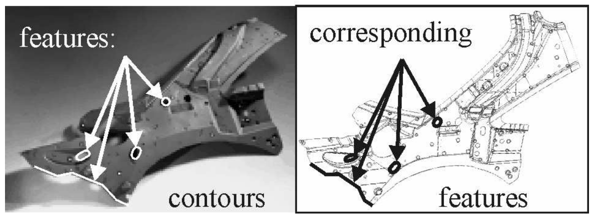

Fig. 3 Influence parameters in 3D-laser forming.

To obtain a fast control the closed loop is partitioned hierarchically into coarse and fine correction (Fig. 4). For both steps suitable optimization algorithms have been developed. In this context, coarse correction is the correction of bending angles and fine correction is the removal of small deviations e.g. buckles and dents. Both correction steps rely on the above-mentioned features.

Prior to the actual determination of geometrical deviations the position deviation has to be determined. The position deviation is defined as the difference in position between the CAD model in the CAD coordinate system and the actual part in the sensor coordinate system.

Within the coarse correction the nominal/actual value comparison can be done on the basis of a rough match of the positions, which is reached by a fast feature dependent coarse registration. This registration fits the two parts to each other by using the 3-points-to-3-points algorithm and three corresponding contour features in the CAD-model as well as in the actual point cloud [15]. This optimization algorithm results in a rotation and translation, which transforms the two point clouds roughly together. Now the geometrical deviation is defined by the difference of bending angles. Based on the difference and the bending angle reached so far the irradiation strategy is determined with regard to the different process parameters. Since laser beam bending achieves only small transformations, the actual geometry is again digitized and the control cycle is reapplied. After the correction of the coarse deviations all bending angles are within tolerances.

Now the deviations in shape of buckles and dents require the fine correction. For this reason an exact matching of the two point clouds is necessary. Again the geometrical deviation consists of difference in position and the actual deviation in shape. The coarse registration described above is used as an initial state for the fine registration. Thus, a fast determination of the accurate deviation in position is possible. During the fine registration the parts are exactly fit onto each other by applying the ICP-algorithm (Iterative-Closest-Point Algorithm) to their features. The ICP-algorithm estimates the optimal transformation that aligns the model features and the data features, minimizing the distance between the shapes. The application of the transformation to one of the data sets fits the two point clouds together. The two point clouds are now divided into a sufficiently close grid. Afterwards the different grid elements can be compared and consequently the deviation in shape can be determined.

After determination of the form a suitable irradiation strategy for the automated adjustment must be found. The irradiation strategy for the coarse correction (adjustment of bending angles) has been presented in [13].

Thus, this paper especially focuses on the development of an irradiation strategy for the efficient adjustment of the fine deviation given in the shape of buckles and dents. The examined AlMgSi1-sheet metal parts parts have a mechanically pressed-in deformation in the form of circular, 4 mm deep buckles. To find a suitable irradiation strategy it was necessary to vary both laser-depending and geometrical parameters.

paths have been investigated. First of all, via experimentally adjusted parametermodifications the necessary energy amount for the required deformation was identified and then the geometrical change was analysed. By the combination of different settings of the influence factors special strategies have been worked out for the determination of the parameters. Some preliminary tests were necessary for the development of a suitable irradiation strategy.

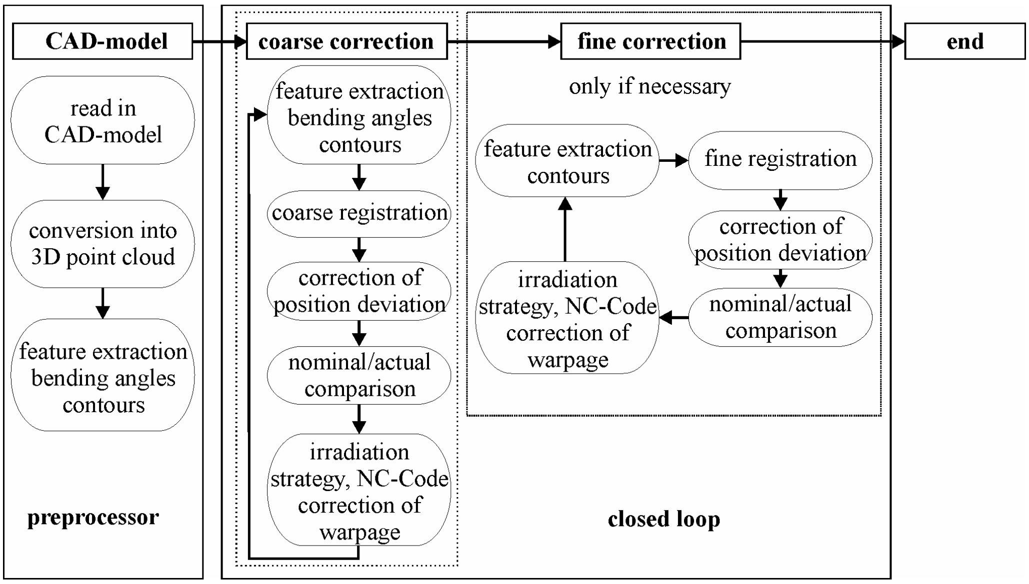

Fig. 4 Principle of the closed loop control system.

4. DEVELOPMENT OF AN IRRADIATION STRATEGY

4.1 Test facility and researched materials

The required experiments for the analysis have been carried out with a 4 kW ND:YAG laser. An aluminum alloy is used as a material. Due to its low density of 2.71g/cmm^3 aluminum is a frequently used design material. As a lightweight construction material, aluminum is applied within the automobile and aerospace industry. The irradiated samples are precipitation hardened AlMgSi1-parts (T6, artificial aging) 350 x 250 mm in size and with 2 mm sheet thickness. During the artificial aging aluminum alloys are quenched in water after a solution annealing in salt bathes or annealing furnaces at a temperature of 600°C (±10°C) close to the melting point. The precipitation heat treatment lasts from 4 to 48 hours at temperatures of 100°C - 200°C. In this way the strength can be increased. This material is applied e.g. in the C-pillar of the DaimlerChrysler CLK Coupe.

The buckles had a diameter of 45 mm and an initial depth of 4 mm. To increase the absorption coefficient up to 80% the parts are covered with a graphit film [16]. Prior as well as after the irradiation the sheets are measured by a coordinate measuring machine in order to draw a conclusion based on the geometry of the buckles. The coordinate measuring machine used in this case is a surface measuring instrument Perthometer from the Mahr GmbH company. To determine an irradiation strategy the laser-depending factors of influence have been varied. These are laser power, feed rate, beam diameter, pulse width, cooling interval and operational mode. Furthermore, the dependencies of the machining result on the geometry-depending influencing factors like the number of irradiations or the distance between the generated irradiation

4.2 Preliminary tests

Some preliminary tests were carried out to determine a suitable parameter range. Thus, it is possible to draw general conclusions concerning laser power, pulse width, number of irradiation points, cooling interval between the irradiations and the interaction of single parameters. As a result of the preliminary tests, a cross-irradiation has proved to be a suitable strategy in the pulse mode. Thereby the symmetrical stress condition is obtained during the processing. In case of this irradiation form, four points lying on the same path and forming a cross are combined to make up an irradiation unit. (Fig. 5). The irradiaion sequence is given by Fig. 5 a-d . Since this irradiation has proved to be suitable for the resulting geometry, it is used in further experiments. Furthermore, the preliminary tests showed that a laser power P_L varying from 3.5 kW to 4 kW is necessary to achieve good forming results. A beam diameter of $d_L \geq 10$ mm is necessary to obtain a smooth surface. During the irradiation in the pulse mode the pulse width is $\tau \geq$ 0,125s.

Different parameters are varied in the following tests in oder to obtain a suitable irradiation strategy. Due to the mutal interaction of these, several parameters are varied at the same time in the experiments. First of all, the irradiation by cw-mode was researched.

4.2.1 Strategy 1: cw-mode: circular path with different laser power rating and different path feed rate

In this strategy the cw-mode is tested to find a suitable irradiation. For that purpose 8 paths are generated and located inside the buckle. The marginal path is placed on the circumference. The paths are equally spaced. Different laser power ratings are analyzed with a beam diameter of d_L= 10 mm, a

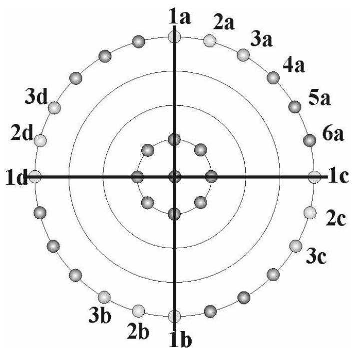

Fig. 5 Cross-irradiation.

path feed rate of 0,1 m/s and a cooling interval of 60s. The laser power is varying from 3 kW to 4 kW.

Result: With respect to the surface quality the best forming (deformation induced by the scanning strategy) is given with a laser power of 3,5 kW. Nevertheless, the surface is melted.

Due of the surface melting, the path feed rate is tested. The 5 outer paths are processed with a path feed rate of v_1. Thereby v_1 is always smaller than v_2 of the other paths in order to prevent the melting of the surface. The laser power applied to the inner paths is also varied.

Result: In spite of the different laser power melting of the surface occurs. To reduce the thermal damaging of the sheet the laser power is strongly decreased in the middle. As a result of the small energy input, the total forming is highly reduced. The maximum reduction of the buckle without melting the surface is 1,8 mm. This cannot be prevented by multiple irradiations. Another result is the high warpage all over the sheet due to the heat treatment. By reason of bad results the cw-mode is no longer analyzed.

Therefore the pulse-mode is tested in the next strategy.

4.2.2 Strategy 2: Pulse mode: Sequence of paths

As a result of the bad forming and surface in the cw-mode, the pulse mode is tested. In this strategy the effects of different irradiation sequences of the points are researched. In order to prevent melting only four paths are generated at equal distances. The marginal path is placed on the circumference. Altogether 81 points are irradiated: 32 on the outer paths, 16 on the interior paths as well as the central point. The points are uniformly arranged on the paths. Thereby the cross-irradiation found by the preliminary tests is retained unchanged. Due to the preliminary tests the laser power is 4 kW, the beam diameter is 10 mm and the cooling interval is 0,15s. The points on the marginal path are irradiated in the first tests. Thereby the points in the right upper quadrant are being used as starting points for the cross-irradiation until all points are irradiated. Afterwards, the next paths are processed and finally the center point is irradiated. Altogether up to 3 irradiation cycles (every point is irradiated thrice; multiple irradiation) take place. Within the next experiments the irradiation points on one path are divided into several passes. In variation 1 e.g. only half of the points of all paths is irradiated during the first pass so that all the points are irradiated after the second pass. Other variations divide the number of points of one path into two halves, which are irradiated e.g. back-to-back.

Result: Altogether a better forming result can be achieved by pulse-mode. The maximum reduction of the buckle without melting the surface is >2 mm. Therefore, in the next strategies the pulse irradiation is chosen. Another positive result of the experiments is the segmenting of the irradiation points into two passes. This strategy is used in addition to the irradiation which is carried out in one pass. Furthermore, a much better forming result can be achieved by upgrading of the irradiation (more points) density. The number of points is directly correlated with the other parameters to prevent melting and to achieve a good forming result. Thus in the next strategy the number of the points is increased and the sequences of the irradiated points as well as the cooling interval are analysed.

4.2.3 Strategy 3: Pulse mode: Sequence of irradiated points with different cooling intervals.

As mentioned above the pulse strategy is chosen due to the good results. Since the former strategy has not achieved the desired forming, the number of irradiated points is increased up to 205 points. In this connection the number of paths is increased to 8 paths. The points are again equally spaced on these 8 paths. Hereby the first 5 paths each have 32 points, the 6. path has 24, the 7. path has 12 points, the 8. path 8 has points and the last one is the center point.

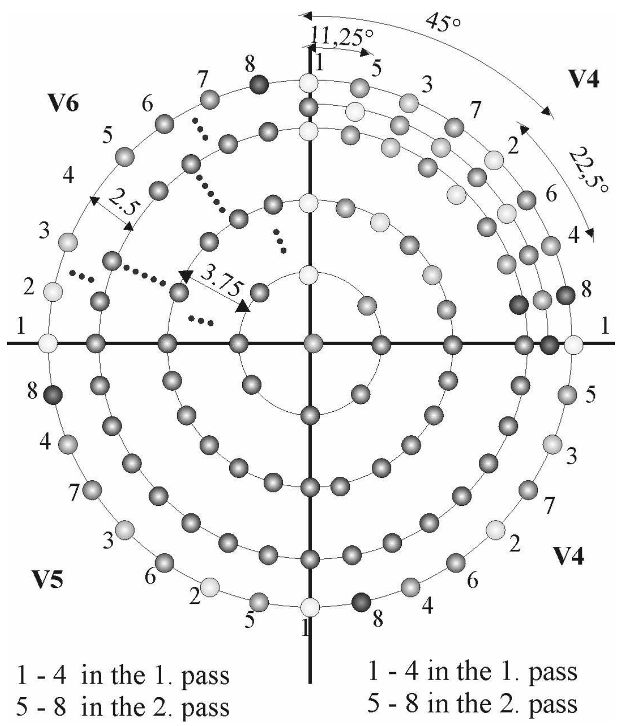

Fig. 6 Different sequences of points.

In former tests the forming of the middle and outer paths is lower than in the center of the buckle. Therefore, the distance between the outer paths is reduced. The distance between the first 6 paths is 2,5 mm and between the other ones it is 3,75 mm. The cross-irradiation of the preliminary tests is retained. On the one hand, points directly adjoining each other are chosen as starting points for the cross-irradiation (Fig.6). On the other hand, the points are subdivided into two passes (Strategy 1). The cooling interval varies between 0s and 60s. In this strategy we especially focus on the variation of the sequence of the starting points concerning one path. The following section explains 3 variations of sequences in detail.

In variation V4 (Fig. 6) the spacing between the first two starting points is 45°. The next starting point is placed between the two points. The following starting point is at a spacing of 45° from the last one. The points are divided into two halves and performed in two passes.

In variation V5 (Fig. 6) the spacing between the starting points is 22.5°. Thus, the number of points is divided into two halves. They are irradiated in two passes.

In variation V6 (Fig. 6) the starting points directly adjoin each other. The points are irradiated in one pass.

A laser power of 4 kW, a beam diameter of 10 mm and a pulse width of 0,15s are used for the irradiations.

Result: These variants lead to a good forming. The maximum reduction of the buckle is about 2,7 mm (variation 4). The reduction is approximately equal in all variants. However, a wavy, melted surface appears in each variant.

The results demonstrate the necessity of a cooling interval between 30s and 60s, depending on the sequence. It is obvious that the sequence of irradiated points directly correlates with the increase/ decrease of the cooling interval. The increasing of the cooling interval when irradiating starting points which directly adjoin each other (variation V6, Fig.6) leads to the same forming result as the other irradiation sequences with lower cooling intervals (variation V4,V5, Fig.6). Thus, the forming results of the sequences V4, V5 and V6 are approximately equal due to the different sequence and cooling interval. Anyway, the forming does not have the desired result. It leads to a partly melted and wavy surface and to warpage all over the sheet, which cannot be prevented by higher cooling intervals. As a result of this, different clamping is tested to achieve the desired forming.

4.2.4 Strategy 4: Different clamping

As a result of the residual deformation as well as the partly melted and wavy surface a different clamping is tested. This ensures a better heat dissipation as present in larger workpieces. Therefore the samples are clamped between two copper sheets. A hole of 75 mm in diameter is cut out in the center of each sheet (Fig. 7). This leads to a faster cooling. Thus, increasing the energy is possible without the simultaneous occurrence of melting. The irradiation is carried out through the increasing of the pulse width to 1,75s. The cooling interval of an irradiation unit (cross-irradiation) is 30s. The laser power is 4 kW, the beam diameter is 10 mm. With respect to the former strategy variation V4 is used for the irradiation.

Result: With variation V4 the buckle depth can be reduced to 0,2 mm. However, a complete removal of the buckle is not possible in this case. The surface remains lightly wavy, but melting does not occur. Thus, in the next strategy the number of irradiated points is increased. To test the influence of stresses by the prior mechanical pressed in buckles some sheets are temper annealed.

4.2.5 Strategy 5: Examination of the effects of mechanically introduced stresses

Since the deformation and the wavy surface is not totally removed by the last strategy, 3 paths with 32 irradiation points each are added in the outer part of the buckle. So, the number of irradiated points is raised to 301 per buckle. Although the number of irradiation points is increased, still variation V4 is applied to the old paths (two passes altogether) and afterwards to the additionally 3paths (also two passes altogether). Therefore, a total of 4 irradiation passes is necessary to irradiate

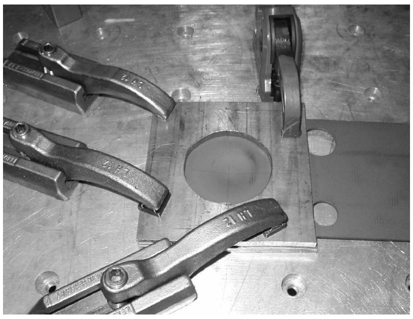

Fig.7 Clamping.

each point exactly one once.

Another aspect investigated in the experiments and summarized as strategy 5 represents the influence of the stresses introduced to the workpiece by molding the buckles into the sheet. To remove these effects some of the samples were annealed. Through annealing at 400°C a complete thermal softening of the workpiece is achieved and afterwards a new grain structure is built. Through this recrystallization process all mechanically introduced stresses are removed. Thus, information about the effects of the irradiation on the workpiece without prior mechanical treatment can be gained. After the workpiece annealing all observed deformation after the irradiation is caused by the irradiation and is not effected by the history of the workpiece.

Each point is irradiated for 1.75s with 10 mm beam diameter and 4 kW laser power. A rest period of 30 s is introduced between the different irradiated groups.

Result: As a result, the surface quality is much better than the one resulting from the experiments for strategy 4. The annealing has no effect on the resulting geometry. The deformation is almost perfectly removed for the annealed sheets as well as for the other sheets. The only observable effect of the annealing step was a slightly more even surface for the annealed samples. As another result, the buckle is almost reduced (0,1 mm rest). The residual deformation is a material accumulation. This is a result of the mechanical pressing of the buckles by means of a sharp-edged punch. This material defect can not be removed by laser forming or temper annealing.

4.3 Result and further work

Currently experimental work is carried out to bring forward these results towards non-circular buckles (Fig. 8). In these experimentations we vary not only the geometry but also the depth e.g. from 4 mm to 2 mm. The smallest width of the deformation in some examples is about 10 mm. Thus, it is possible to use the results for other, smaller geometries. Within the experiments well-known parameters like laser power, beam diameter, clamping etc., new irradiation geometries like pulsed tangential and radial lines (Fig. 2) or other not described asymmetrical irradiation strategies are investigated.

Summarizing all experimental results, it can be seen that the irradiation of certain paths with a constant beam does not remove the buckles as intended. Instead, the work piece surface is destroyed. Thus, adjustment strategies using pulsed laser beams are more successful. In these experiments the pulsed laser power is very high (up to 4 kW). In order to receive a smooth surface a very large beam diameter ($\geq$10 mm) is chosen. In all experiments even for the asymmetrical deformations the cross-irradiation is proved to be very essential. Furthermore, investigations have shown that it is very important to have an appropriate heat drain to avoid melting of the surface. In addition there must be cooling intervals between irradiation to avoid the damage of the surface. Sometimes the appearance of warpage all over the sheet is possible. The number of points per path necessarily depends on the deformation.

As described at the beginning of the paper and documented in [15], the detection of warpage by means of feature-based geometry comparison within a closed loop control system is possible. The detected deviations in bending angles can be adjusted by laser forming as it is shown in [7,13,14,]. Through the systematic experiments described in section 4 and the testing of the results at asymmetrical deformations some general rules for the definition of irradiation strategies for the correction of warpage by laser forming can be formulated:

- pulsed irradiation seems superior to constant beam strategies
- cross-irradiation seems a very successful strategy
- in these experiments high laser power connected with a large beam radius are essential
- several passes (segmenting the points of one path) connected with cooling intervals and a suitable clamper are essential for a fast heat dissipation which cannot be replaced by longer cooling intervals

If all mentioned parameters are co-ordinated with each other, a correction shown in Fig. 8 is possible. The resulting surface shown on the right hand side shows the marks from introducing the buckle. As mentioned above, this material defect can not be removed by laser forming or recrystallization.

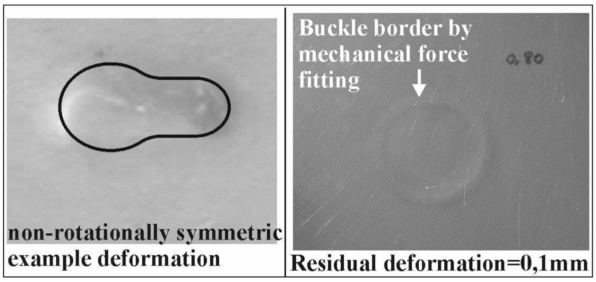

Fig. 8: Example buckle (right) and result of the optimized irradiation strategy (V4)

The grain structure is scanned by means of a light-optical microscope to detect the influence of the irradiation. As a result the grain structure of the workpiece is not visibly affected by the process.

5. SUMMARY AND OUTLOOK

To satisfy the need for an automated adjustment process increasing the economic efficiency and productivity of today's manufacture, a closed loop system for the application of laser beam bending has been introduced. Experimental results leading to some rules for the definition of irradiation strategies have been presented. Therefore irradiation strategies for circular buckles can now be defined after little experimental work to adapt process and irradiation strategy parameters.

Furthermore a model based methodology for the automated definition of irradiation strategies employing knowledge bases and finite element simulation will be researched in future projects. This will enable the use of laser beam bending not only to adjust deviated workpieces at the end of a manufacturing process but also to actually manufacture workpieces in small batches.

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