A double raster laser scanning strategy for rapid die-less bending of 3D shape

Daniyal Abolhasani\textsuperscript{a}, Seyed Mohammad Hossein Seyedkashi\textsuperscript{a}, Yong-Tae Kim\textsuperscript{b}, Mohammad Hoseinpour Gollo\textsuperscript{c}, Young Hoon Moon\textsuperscript{d,∗}

\textsuperscript{a} Department of Mechanical Engineering, University of Birjand, Birjand 97175-376, Iran
\textsuperscript{b} Department of Materials Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea
\textsuperscript{c} Department of Mechanical Engineering, Shahid Rajaee Teacher Training University (SRTTU), Lavizan, Tehran 16785-136, Iran
\textsuperscript{d} School of Mechanical Engineering, Pusan National University, Pusan 46241, Republic of Korea

Article history:
Received 25 June 2019
Accepted 16 August 2019
Available online 29 August 2019

Keywords:
Raster scanning
Laser forming
Curvature
Laser bending
Overlap
Heat transfer

Abstract

Double raster scanning approach to 3D laser forming was investigated to obtain a large deformation with one-step laser irradiation, avoiding repetitive scanning. The magnitude of the deformation during raster scanning was found to be strongly dependent on the overlapping between adjacent passes, which can be controlled by changing their spacing and the beam diameter. Therefore, 3D deformation during raster scanning has been analyzed at various overlap ratios, whose effect on the temperature and strain distribution were discussed. As the heat transfer mode significantly influences the uniformity of the bending process, the variations in bending angles with negative and positive overlapping ratios have also been investigated. The ratio of the longitudinal and lateral curvatures decreased with the increasing overlap ratio. Therefore, the effect of the lateral side is more important for specifying the final symmetry of the part, playing a critical role in bending with higher overlap ratios. In a rectangular part, deformation of the lateral side was found to be more difficult, showing strong dependence on the length of the scanning track, compared with the space of the adjacent passes. Through process characterization, the double raster scanning process has been well understood and proved to be a feasible approach to 3D laser forming of rectangular parts.

© 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Laser forming is a flexible manufacturing technique for rapid prototyping and adjustment of parts by controlled laser induced thermal stress. Important advantages of laser forming include a tool-less, flexible process amenable to automation and has the capability to form even brittle materi-
rials. During laser forming processes, a temperature gradient across the thickness of the heated zone results in a varying thermal expansion. Three key mechanisms have been proposed to explain the thermo-mechanical behavior during laser forming based on the geometrical and laser beam parameters: the temperature gradient mechanism (TGM), buckling mechanism (BM), and upsetting mechanism (UM) [1–3].

TGM is a common mechanism in laser forming and dominant when the laser beam diameter is smaller than the thickness of the metal plate. On the other hand, BM is dominant when the laser diameter is larger than the thickness of the plate. UM can be regarded as a part of BM because the conditions are similar; however, the material geometry increases in thickness and its section modulus changes.

Most of the laser applications, up till now, used different irradiation paths to achieve the desired forming results. Several scanning patterns were studied as shown in Fig. 1. The triangular pattern shown in Fig. 1(a) and rectangular pattern shown in Fig. 1(b) may result in uneven bending due to heat concentration in both sides of the scanning path. In order to achieve uniform deformation, a raster scanning pattern shown in Fig. 1(c) can be applied.

The spacing of adjacent passes was usually estimated to prevent excessive temperature accumulation [4–6]. Employing overlapped laser passes is a use of raster scanning motion strategy which includes adjacent linear scanning tracks [7]. The main idea behind the use of raster scanning motion for laser forming is based on the adjacent tracks being able to cause higher heat flux densities inside the metal. It should be noted that high heat flux densities—which are usually associated with local melting of the surface layer—can be utilized in laser surface melting. Vásquez-Ojeda [8] bent flat sheets in 2D forming with a certain radius of curvature by employing a line heat source of a raster-scanned laser beam, but with a negative overlap ratio and several irradiating steps. In fact, no discussion was found in previous studies about the process of determining the optimal distance between adjacent paths [5,8,9]. In particular, the overlapping effect in laser forming processes on the temperature field with respect to the resulting deformations has not been discussed with sufficient detail [10–12].

Regarding the actual development trends, the number of applications in the field of micro-component production and adjustment have further increased in the recent years. As the component dimensions are reduced to values that hinder mechanical handling, creating these very small samples by conventional sheet metal forming is difficult. However, if precise deformation—e.g., in the large values of curvature radii—are required, laser forming can be applied as an alternative process.

One-step laser forming is an important issue concerning time and cost, as well as microstructural changes and residual stresses. Furthermore, repetitive scanning beyond a specific value may increase the unwanted microstructural features in stainless steels [13]. Achieving the accurate production of small-dimension samples using this process is a key requirement. To the best knowledge of the authors, 3D laser forming strategies employed in various studies showed serious limitations regarding the sample size. Applying conventional strategies for forming small samples with curved shapes requires multi-pass irradiation across each path, or increased laser power [14,15]. There is a close relationship between bendability and the geometry of the sample during thermal processing [16]. The reduced bendability of small dimension samples can be attributed to the insufficient stress required for bending along a path perpendicular to the scanning direction and the thickness direction [17]. The application of a new strategy in 3D laser forming of smaller samples seems to be necessary, considering the required deformations to be achieved in a single step, without repetitive scanning. Therefore, in this study, 3D laser forming of a small dimension rectangular sample is conducted using a proposed strategy, which will be termed from now on as the “double raster scanning strategy”. This scanning strategy—considering various overlap ratios—is applied on the samples to achieve a doubly positive curved shape. This strategy promotes the idea of “one-step laser irradiation” with an increased controllability of the final shape using an optimal overlap ratio between the passes. The heat transfer mode and its influence on the bending angles, temperatures, strains, as well as deformation radii have also been discussed for various overlap ratios between the passes.

2. Experimental details

The laser source used in this work was an Ytterbium fiber laser (IPG YLR-200, IPG Photonics, Germany) with a maximum power of 200 W at 6 A and a wavelength of 1.07 μm. Different beam diameters were achieved by changing the vertical posi-
Fig. 2 – (a) Laser system. (b) Workpiece loaded on the steel pillar and base plate.

Fig. 3 – (a) Depiction of the desired shape. (b) Schematic of the sample with the proposed double raster scanning strategy. (c) Schematic diagram of the overlap zone profile.

tion of the base in the laser system shown in Fig. 2 (a). Flat, rectangular AISI 316 stainless steel samples with dimensions of $18 \times 22 \times 0.5\,\text{mm}$ were used. Before the experiments, the samples were cleaned with acetone and coated with graphite.

During the experiments, the samples were held on a cylindrical steel pillar with a diameter of $3\,\text{mm}$ and a base plate, as shown in Fig. 2 (b). As the material in contact with the specimens and pillar had a low thermal conductivity to inhibit
conduction, the steel pillar acted as a heat sink for the sample being formed and no additional cooling was used.

A schematic drawing of the target shape and the proposed scanning approach is illustrated in Fig. 3 (a) and (b), respectively. The length of the scanning track \(d\) and spacing of the adjacent paths \(g\)—shown in Fig. 3 (b)—play a key role in the final deformation and are discussed in section 5.2.5. To achieve smooth bending, the lines extended inwards from the edges, as less material shrinkage is needed there [18]. To realize a symmetric bending, scanning lines at the opposite sides of the sample are scanned sequentially. The critical buckling condition—which has been derived by Shi et al. [19]—was considered to determine the necessary laser power and scanning velocity. To generate a positive bending, the process started by one of the paths at the corners. It is assumed that the first paths would be laser formed by the TGM mechanism due to the high cooling rate caused by the significant heat convection losses. The assumed dominant mechanisms are shown in Fig. 3 (b). TGM causes positive bending. The bending process by the paths closer to the free edges of the sample plays a role of pre-bending for the bending process of the middle areas of sample. The parameter characterizing the overlap between passes is denominated “overlap ratio (OR)” and is defined by Eq. (1) [20]:

\[
OR = 1 - \left[ \frac{1}{D} \right]
\]

where \(l\) is the distance between the centers of the individual passes and \(D\) is the diameter of the beam spot, as shown in Fig. 3 (c). From this equation, it is evident that fully overlapped passes have an OR of 1. Furthermore, the OR will decrease with an increasing distance between passes. When \(OR < 0\), the passes do not overlap.

The radius of curvature of 3D formed samples was measured by commercially available software, Camera Measure™, as shown in Fig. 4.

3. Finite element simulations

Finite element (FE) simulations were performed with the commercial code ABAQUS™. Since the heat transfer and elastic/plastic deformation are symmetric about the vertical plane between the scanning lines at the opposite sides of the sample, only half of the sample is modeled by the numerical simulation [21]. As shown in Fig. 5 (a), a fixed constraint was added around the center of the symmetric line, representing the fixture used in the real experiments. In order to reduce the computational time associated with high precision, a mesh refinement test was performed to attain a suitable element size [22,23]. The whole specimen was meshed with nearly 54,500 eight-noded linear hexahedral elements of type C3D8RT, distributed uniformly in the whole region, as shown in Fig. 5 (b).

The thermal diffusion length (TDL) defined by Eq. (2) should be smaller than the element edge length to enhance accuracy of the analysis [24].

\[
TDL = \sqrt{\kappa t}
\]

where \(\kappa\) is the thermal diffusivity of the sheet material, \(t\) is the laser-material interaction time given by the ratio of the spot diameter and the velocity of the laser head: \(D/v\). The initial value of the time increment can be adjusted to satisfy this. Therefore, the initial value of time increment was \(7 \times 10^{-8} \text{s}\) and the thermal diffusion length for this time increment size, with respect to \(\kappa = 4.12 \times 10^{-6}\), was much smaller than the element edge length [8]. The temperature dependence of the specific heat and thermal conductivity were obtained from the supplier data and available literature [25].

For heat conduction within the workpiece, the thermal conductivity \(k\) (W/mK) was taken as temperature dependent values. The convection and radiation boundary conditions were set in terms of Eq. 3.

\[
q_{\text{total}} = q_{\text{con}} + q_{\text{rad}} = h(T - T_0) + \varepsilon \sigma (T - T_0)^4
\]

The heat transfer coefficient \(h\) was taken as 20 W/m²K, the surrounding temperature \(T_0\) was taken as 300K, \(T\) is the surface temperature during the laser heating processing, \(\varepsilon\) is the emissivity chosen as 0.8 and 0.32 for heated surface with graphite coating and uncoated domains, respectively, \(\sigma\) is the Stefan Boltzmann constant, \(5.6703 \times 10^{-8}\) (W/m² K⁴). The value of absolute zero on the temperature scale was set as
Fig. 6 – (a) Schematic of the relationship between bending variables and final radius of the curvature of sheet (R). (b) Schematic view of the final bending angle after each irradiation ($\alpha_i$), pre-bending angle ($\Delta \alpha_{i-1}$) and the bending angle caused by the heat flux ($\alpha$).

$0 \text{K} (-273 ^\circ \text{C})$. The thermal conductivity and specific heat were considered to be temperature-dependent.

The laser beam at the target surface was considered to have a Gaussian distribution in both X and Y-directions, which can be expressed as Eq. (4) [3]:

$$Q = \frac{2A P}{\pi R^2} \exp \left( - \frac{2 (x^2 + y^2)}{R^2} \right)$$

(4)

where $P$ is the laser power (w), $A$ the absorption coefficient, $R$ the laser beam radius (m), and $x$ and $y$ are the distance (m) of a point from the center of the laser beam. The absorption coefficient is given by Eq. (5):

$$A = \frac{4\pi i}{\lambda}$$

(5)

where $i$ is the imaginary part of the refractive index of the AISI 316 stainless steel at a laser wavelength of $\lambda = 1.07 \mu \text{m}$; although it is unknown for this material and $i = 4.5$ of iron was used [26]. To reduce computational costs, several adjoining tracks were selected for analysis through each simulation with critical process parameters to achieve a stable condition (steady/equilibrium state), in which constant peak surface temperatures are produced for most of the process duration—will be discussed in detail in section 5.2. After obtaining the steady-state conditions, the full simulation of each pass was neglected. In order to determine the radius of curvature in simulation tests the following approach is employed. With certain bending angle in each irradiating line and according to Fig. 6(a), a relation between final radius of the curvature of sheet (R), the initial length of the plate ($L_p$), the number of irradiating lines ($n$) and the bending angle in each irradiating pass ($\alpha_i$) is extracted as Eq. (6):

$$R = \frac{L_p}{\frac{n \times \alpha_i}{\pi}}$$

(6)

The deformation prediction based on Eq. (5) shows the same trend for all the passes, however somewhat overestimates experimental or simulation measurements. In reality, by applying several adjoining irradiation lines, bending angle in each irradiating pass ($\alpha_i$) forms during and even before a laser beam reaches a pass and is non-uniform along the longitudinal direction of the sheet. In other words, the sheet longitudinal deformation is associated with the pre-post-bending effect. The pre-bending effect is more dominant than the post-bending effect in creating the final deformation. Thus the proposed approach by Cheng et al. [27] taking into account the pre-bending effect for small segments of a single scanning path and then derivation of an $\Delta \alpha$ expression for the pre-bending angle, is considered in this work for several adjoining scan tracks. $\alpha_i$, the bending angle after each irradiation, can
be obtained directly through the simulations. Also it can be expressed as:

$$\alpha_i = \alpha + \Delta \alpha_{i-1}$$  \hspace{1cm} (7)

where $\Delta \alpha_{i-1}$ is the pre-bending angle in recently scanned track (i-th track), caused by previous scanned track ($(i-1)$-th track) and $\alpha$ is the bending angle caused by heat flux which is considered to be constant during steady-state condition shown in Fig. 6 (b). $\Delta \alpha_{i-1}$ could be extracted as Eq. (8) [27].

$$\Delta \alpha_{i-1} = \frac{1}{4} \alpha_{i-1}$$  \hspace{1cm} (8)

where $\alpha_{i-1}$ is the total bending angle created in previous scanning. Therefore, the bending angle after each irradiation, $\alpha_i$ is

$$\alpha_i = \alpha + \frac{1}{4} \alpha_{i-1}$$  \hspace{1cm} (9)

The radius of longitudinal curvature in each simulation test were calculated with the use of simulation observations of several passes at steady-state conditions and then followed by the calculation of Eq. (5) and Eq. (6) to estimate the final deformation radius.

4. Validation of model

In order to evaluate the model capability to predict the deformation during forming, the temperature distribution during a single scan pass on the plate and 2D deformation have been investigated. The verification performed on the forming of the AISI 316 plate of $200 \times 200 \times 0.5$ mm, laser power $P = 150$ W, at forming velocity $v = 3.82$ mm/s. The laser beam diameter was set to 1 mm. For the simulation, the laser parameters were kept the same as experiment. The absorption coefficient obtained by Eq. (5) was little changed around the first value and is assumed to be 42%. For the experimental case the hole of 1.5 mm diameter was drilled in coincidence with the middle of
the forming path shown in Fig. 7(a) and a thermocouple (model OKE-130CD) was placed in the hole. In Fig. 7(b) and (c) the experimentally measured transient temperature distribution and bending angle are compared to the computed results from the simulation model. Also the 2D bent samples are shown in Fig. 7(d). The value of 0.75 of the time-axis in Fig. 7(b) coincides with the time point when the laser passes the thermocouple. By this figure the maximum measured temperature was 612 K and the predicted 648 K, that is, a deviation of ~5.8% is observed, indicating a very good correlation. A major factor affecting the temperature distribution, the thermal conductivity probably has the smaller value in the experiment compared with the model considered. This may be the reason for which the estimation of maximum temperature and the temperature decrease in cooling step, differed relatively less as compared to that of numerical simulation.

5. Results and discussion

To characterize the raster scanning approach for 3D laser forming, essential simulation results are presented to show the process transiency and necessary operational parameters of the proposed pattern to attain steady-state conditions during the experiments. Subsequently, the experimental and numerical results are discussed.

5.1. Process analysis of raster scanning

To investigate the effect of the overlap ratio, different combinations of parameters are selected, as shown in Table 1. While varying two parameters, such as spacing of adjacent passes and beam diameter, the rest of the laser forming parameters were maintained constant. These parameters were selected to achieve an effective shaping of the metal, while avoiding significant surface burning and material damage. Accordingly, laser power and scanning velocity were set to 150 W and 3.82 mm/s, while the minimum time interval between two adjacent passes was almost 2 s, which is required for scanning opposite lines of the sample by the laser head motion.

The time interval between passes could be obtained from the following reasons. Fig. 8 shows the final temperature for each case taken at different interval times. Only short and close interval times (2, 5, and 8 s) were investigated. This avoids the yield stress being increased by high cooling steps [28]. Short interval times can be suitable for metals with high strength, or for laser forming aiming at avoiding repetitive scanning. As shown in Fig. 8, the maximum temperature predicted is seen to be more affected by the intensity distribution of the laser beam for various overlap ratios, especially in the cases with higher ORs (OR of 0 with a 0.5 mm beam diameter, OR of 0.30, 0.50 and 0.62) because of the sharper slope at the end of the plot, but not considerably with change in the inter-pass delay. This can be explained as follows: during the laser forming process with the proposed pattern, the increase in interval time within a short range could reduce only the starting temperature of each scanning pass. However, while moving along a heat line, the temperature enhanced significantly, reaching higher levels. This could be attributed to the heat remaining from previous opposite scan lines at the middle area of the sample. Therefore, the time interval of 2 s was selected for minimum cooling time between the passes. This time is sufficient for the material to prevent excessive temperature accumulation and to attain almost identical peak surface temperature by each simulation.

The TGM was investigated through the BM dominant condition. Fig. 9(a) shows that the lateral side of the sample undergoes counter-bending during the primary scanning and the sample bends in the direction away from the laser. Additional thermal expansion occurs by the consecutive scans and additional plastic tension is generated on the top surface. After each irradiated pass, the material expands again in the upper layers. However, with the maintained heating, the bending moment of the samples at the earlier scan lines opposes the counter-bending. Hence, during the temperature fall period, the material around these lines contracts in the upper layers and plastic compression causes local shortening of the upper layers of the sample. The samples, therefore, bend towards the laser beam, as shown in Fig. 9(b). In these figures, the deformation direction is shown by the plot symbols. A similar trend was observed in most of the cases. Consequently, the TGM condition (a primary negative bending followed by a positive one) could be achieved by the beam diameter enlarging the sheet thickness during the primary scans. This phenomenon takes into account the Bauschinger effect as well, since the material undergoes two opposite loading processes during the heating and the subsequent cooling step, as shown in Fig. 9.

<table>
<thead>
<tr>
<th>Table 1 – Different parameter combinations for obtaining various OR.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>F</td>
</tr>
<tr>
<td>G</td>
</tr>
<tr>
<td>H</td>
</tr>
</tbody>
</table>

Fig. 8 – Final temperature obtained from the simulations (D: beam diameter).

Fig. 9 – Final temperature obtained from the simulations (D: beam diameter).
This plays a significant role in the area with high bending rigidity.

As already reported, the critical parameters were obtained for shaping the workpieces under nearly constant peak surface temperature along the most number of passes with each simulation. Case H in Table 1—with the highest overlap ratio of 0.62—represents the worst case, regarding the temperature distribution, as it indicates a steady-state of heat transfer during the process and the equilibrium is reached after several passes. Fig. 10 (a) and (b) show the deformation during laser forming and the corresponding temperature distributions for several laser-scanning passes and required processing time.

There is a difference between the predicted peak temperatures for the first three scans. However, by increasing the number of heating lines—after three consecutive scans with 2 s intervals between the individual scans—the difference decreases, despite the heating being maintained. This suggests that the effect of heat transfer from the irradiated lines becomes constant. Although a low thermal gradient is presented, bending developed in two directions, as shown in the Fig. 10 (a), due to the generation of out of the plane deformations caused by the constraints of the non-treated surrounding material, which is typical for material with a low thermal conductivity, such as austenitic stainless steel [11].

The points on the trailing lines of laser scan paths experience higher temperatures while the points near the shorter edge lower temperatures, demonstrating the higher cooling rate of the passes close to the short edge.

According to Fig. 10 (b), a common phenomenon in the laser forming process is observed: the laser energy deposited during the short transient period at the start and end of the laser scan is different from that deposited during the rest of the scan. This is called the “transient effect”, which is caused by the varying speed of the laser head at the starting point of the scan. The rest of the scan track is carried out in a quasi-stable state, although the peak temperatures at the starting point and end of the pass are higher than that of the quasi-stable state. The transient effect can be exerted in the simulation by selecting a scanning line that starts from a point on the edge. These temperature variations occurred on a small segment of the scanning length. Therefore, in this study, the elimination of the transient effect by the increase of the scanning length
was neglected. The ultimate temperature value of this laser formed sample was about 1630 K. Numerical results under other conditions showed similar trends, however, with different obtained peak temperatures.

The experiments were repeated at least two times and the final values of the experimental runs were calculated by taking the average from the two or three samples. The deformation results are presented and discussed in the next section.

5.2. 3D bending during raster scanning

5.2.1. Deformation measurement

Temperature distribution contours (unit: K) and longitudinal displacement contours (unit: m) with an OR of 0.50 are shown in Fig. 11. Temperature distribution contours indicate a uniform transformation of the temperature along the area marked as 0.
Fig. 11 – (a), (b), (c) Temperature distribution contours (unit: K); and (d), (e), (f) longitudinal displacements (unit: m) for the 1st, 5th, 10th passes, respectively.

Standard errors of experimental measurement were calculated using uncertainty analysis with MS Excel. Formula to find the mean ($X$) of a population with $N$ members is:

$$X = \frac{1}{N} \sum_{i=1}^{N} x_i$$

(10)

And formula to estimate standard deviation ($S_D$) of the entire population data is:

$$S_D = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2}$$

(11)

The standard error of the mean designated as $S_E$ is then calculated by:

$$S_E = \frac{S_D}{\sqrt{N}}$$

(12)

Fig. 12 (a) and (b) show uncertainty components for both longitudinal and lateral curvatures of the samples. Fig. 12 (c) and (d) also show the variation of the numerical (by Eq. 6) and experimental longitudinal and experimental lateral curvatures of the deformed samples ($C_{\text{longitudinal}}, C_{\text{lateral}}$, respectively) with the related overlap ratio and calculated error bars. In Fig. 12 (c) the curvatures obtained by the simulations present small deviations compared to the experimentally measured curvatures. This can be attributed to pre-bending and strain hardening effect in real condition. The deformation increased non-uniformly with the increasing overlap ratio. At lower overlap ratios, the deformation was smaller, despite the beam diameters held nearly identical as for the positive conditions. This shows that the overlap ratio significantly influences the magnitude of the deformation. As demonstrated by these figures, the radii of curvatures are not identical in the two directions. Fig. 12 (e) shows the ratio of the longitudinal curvature and the lateral curvature as function of the overlap ratio from the experiments. This ratio determines the symmetry through two deformed sides. Significant changes from or towards the value of 1 means a change of the symmetry. As the ratio departs from 1, the symmetry of the deformed sample decreases even if the total bending may be high, and vice versa. It is seen that the ratio decreases with the increase in overlap. This means that the effect of the lateral side is more important for specifying the final symmetry of the sample, which plays a critical role in bending with high overlap ratios.

5.2.2. Characterization of bending with heat transfer
To find the portion of the bending produced by each heat transfer state, the forming processes were investigated. The numerically obtained diagram of the bending angle after ten passes is shown in Fig. 13 for selected samples. Fig. 13 (a) shows that the bending angles for case A increase at a roughly constant rate. This reveals that with a negative overlapping process, all scan passes act approximately as in the equilibrium-state. From experimental observations, the final bending angle along the longitudinal direction was 21.71° for case A and 54.67° for case G shown in Fig. 14. The bending angles can be accurately approximated by linear functions up
to ten adjacent scans. Considering the symmetry of the part about the X and Y axes, from Fig. 13 (b), it was found that about 20% of the completely bent longitudinal side (including 4 × 2 passes) is in a non-equilibrium-state of heat transfer, and about 80% (32 middle passes) is in an equilibrium-state of the process. This may cause a non-accurate approximation of the measured radius. The symmetry of the two deformed sides of the sample may also be affected through the non-uniformity of the heat transfer and subsequent deformation.
5.2.3. Investigation of temperature gradient as the driving force for deformation

Further numerical simulations were conducted to investigate the effect of the thickness temperature gradient on the deformation. The temperature gradient is defined by Eq. (13):

\[ TG = \frac{(T_{\text{top}} - T_{\text{bottom}})}{S} \]  

(13)

where \( T_{\text{top}} \) is the temperature of a point on the top surface on the scanning path, \( T_{\text{bottom}} \) is the temperature of a point on the bottom surface with the same X and Y coordinates, and S is the sample thickness [13]. Fig. 15 shows the variation of temperature gradients as function of the overlap ratio. This figure reveals that the thermal gradient through the thickness direction in case E is larger than those of other samples, indicating a large heat sink effect. It resulted in a relatively large deformation, as observed in Fig. 12. The magnitude of the longitudinal deformation for this sample was lower than that of cases with positive ORs, as is shown in Fig. 12 (a). Considering the maximum temperatures plot in Fig. 6 and the melting point of AISI 316 stainless steel (1713 K), only this sample is affected by surface melting. Thus, its relatively low longitudinal deformation can be the result of high thermal expansion and the subsequent thickening of the material cross section [2]. The decrease of the effect of the inherent constraints—which is the cold surrounding material—will result in a reduced deformation in the longitudinal direction. Despite the melting phenomena, it may result in a large shrunken zone and a plastic compression at the top surface due to the high cooling rate. Hence, a larger deformation occurs, as more plasticized material is available to overcome the increasing thermal expansion and thickening of the sample compared with the cases where the overlap ratio was \(-1, -0.66, -0.25\) and \(0\), respectively (with \( D = 1 \text{ mm} \)).
Fig. 16 - (a) Strain components on a plane perpendicular to the scan passes. (b) In-plane strains (PE11 and PE33) and (c) out-of-plane strain (PE22) variations along the line X = 3 mm according to the coordinate system shown in Fig. 3 (b).
According to Fig. 12 (b), this case (OR = 0, D = 0.5 mm) exhibits the largest lateral deformation. The reason can be explained as follows: it is seen that the maximum temperature of the top surface of the samples drops when the overlap ratio exceeds 0 with D = 0.5 mm, as is shown in Fig. 8, while the space of adjacent passes is constant (Table 1). This can be attributed to the increased beam diameter. The reduced maximum temperature in the cases with positive ORs can be responsible for the reduced lateral deformation for overlap ratios exceeding 0. This is due to the fact that a larger temperature dissipation in the top layer provides a larger heat sink and a more prominent in-plane shrinkage in the shorter direction (lateral side) of the rectangular samples [9,27]. In other words, the drastic increase of the heat sink increases the heat loss from the superheated target, resulting in a higher cooling rate at the top surface associated with the compressive strain under cooling, and in turn, an increased lateral bending in the sample with a non-laser-treated area in its middle portion (see Fig. 3 (b)). For case H, in spite of the lower TG-in contrast with cases F and G—it is assumed that the large size of the heat-affected zone including in-plane shrinkage is responsible for the enhanced deformation, as shown in Fig. 12.

5.2.4. Strain fields exploration
The strain components, including PE11 and PE33 as in-plane components, and the out-of-plane strain PE22, are shown in Fig. 16 (a). The in-plane component was calculated by taking the average value of PE11 and PE33 at the top and bottom surfaces. The out-of-plane variations have also been analyzed at the same locations as the in-plane strains. Since the strain fields perpendicular to the scan passes is of important factor in laser forming [5], thus Fig. 16 (b) and (c) show the plastic strains for several overlap ratios after ten simulated tracks along the path perpendicular to the middle area of scanning passes.

In these figures, only selected plots are shown for better clarity. Both the average of the in-plane strains and the out-of-plane strain variations are seen to be sharply increasing with the increase of the distance from the lateral edge. This could be caused by the heat conduction from the previously heated areas being influenced by the higher plastic strains developed by the higher temperatures. As the laser passes move toward the center, the strains slightly decrease due to the temperature fluctuations. However, this trend diminishes and the rest of the forming process becomes more apparent, reaching a constant level of strain variations as the temperature alteration along the longitudinal direction (Y-direction) remains nearly constant, as shown in Fig. 10 (b).

With negative overlap conditions, the strain gradient between the top and bottom surfaces along the longitudinal direction diminishes towards the center of the sample, thus the deformation magnitude becomes smaller. For positively overlapped samples, where the laser beam diameter is close to the negatives, a smaller drop in the strain gradient increases the 3D deformation more significantly than in the rest of the samples. The reason is the higher quantity of heat created in the upper layers producing a buckling effect [29]. Moreover, since in these samples, the temperature distribution is larger, the reduction of through-pass yield stresses during the heating process is assumed to be considered for explaining larger deformations. Thus, for metals such as steels, which exhibit relatively low stacking fault energy, the proposed pattern could activate more slip systems by accommodating a high density of dislocations during high deformation, leading to large strains. The difference in beam diameters with various ORs influences the variation of the obtained results, as they may cause the plastic strain to develop differently along the thickness direction. The strain components in positive OR samples showed a similar trend, i.e., a greater difference between the strains at the top and bottom surfaces leads to a greater deformation, suggesting the occurrence of buckling. However, in the negative OR samples (besides 0 with 1 mm beam diameter), UM is the most probable dominant mechanism present during the process, so it can be regarded for high precision forming.

Fig. 17 – Deformed curvatures as a function of (a) length of the scan track, and (b) spacing of adjacent passes.
5.2.5. Relationship between bending radii and scan track parameters
The effect of the parameters $d$ and $g$ shown in Fig. 3 (b) on the bending radii are presented in Fig. 17. Fig. 17 (a) shows numerically obtained results from a path at the middle area, considering the variation of the deformation through five segments of the scanning path. Fig. 17 (b) was obtained by taking the average of the deformation values shown in Fig. 12. According to Fig. 17 (a), there is an optimum value for the length of the heating line for obtaining the maximum longitudinal deformation. Developing a line of heating, the shrinkage occurs in the direction perpendicular to the line, and the deformation increases accordingly. Over a certain value, however, the accumulated temperature may cause a thickness increase, and hence, the longitudinal deformation decreases. Large temperature dissipation in the top layer causes a lateral increase of the deformed sample at the same rate. From Fig. 17 (b), this lateral deformation is in the range of $0.01 < R < 0.015$. Therefore, it is not significantly dependent on the spacing of adjacent passes. It can be concluded that the length of the scanning lines has a prominent effect on the lateral deformation, as was seen by larger scale of the lateral plot in Fig. 17 (a) compared to that of Fig. 17 (b).

In this figure, the decreased deformation with the increase of the spacing of adjacent passes can be attributed to a smaller temperature accumulation associated with the lower temperature gradient. Through process characterization, the double raster scanning process has been well understood and estimated to be a more feasible approach to rapid 3D laser forming of fine rectangular sheets.

6. Conclusions
A raster scanning approach to 3D laser forming of 316 stainless steel has been characterized in this study and the following conclusions were obtained:

1. Raster scanning caused a large magnitude of temperature dissipated at the top of the surface resulting in a significant deformation by one-step laser irradiation during 3D laser formation of a rectangular sample. The deformation curvatures and bending angles of the sample edges were strongly affected by changes in the overlap ratio between passes.
2. The increase in overlap ratio was associated with the increase of the temperature gradient, which in turn, caused a larger deformation mainly in the lateral dimension. The effect of the lateral side was found to be more significant for specifying the final symmetry of the part, playing a critical role during bending with higher overlap ratios.
3. The heat transfer mode reached an equilibrium state during raster scanning, although the areas with equilibrium and non-equilibrium states varied under negative and positive overlap conditions.
4. A larger heat sink effect—which is the result of a larger temperature dissipation in the top layer—enhanced the strain components and magnitude of the lateral deformation.
5. The increase of the length of the scan track over a certain value adversely affected the longitudinal deformation. This could be attributed to thickness increment caused by an excessive accumulation of temperatures at the middle areas of the samples. In the rectangular sample, the deformation of the lateral side was found to be more dependent on the length of scan track, compared with the spacing of the adjacent passes.

Conflict of interest
The authors declare no conflicts of interest.

Acknowledgments
This work was supported by the National Research Foundation of Korea (NRF) grant, funded by the Korean government (Ministry of Science and ICT) (no. 2012R1A5A1048294). The authors wish to acknowledge Mr. Seo Dong Myeong in Pusan National University for his highly appreciated help.

References


