CONVEX LASER FORMING WITH HIGH CERTAINTY

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ABSTRACT

Laser forming is a flexible sheet metal forming technique using laser induced thermal distortion to shape sheet metal without hard tooling or external forces. Concave laser forming can be readily achieved, while convex forming could be done under buckling mechanism but whether convex forming is actually obtained heavily depends on the initial strain/stress state of the sheet. A new laser-scanning scheme is postulated to obtain convex forming insensitive to the initial state. The postulate is validated by experimental and numerical results. How the parameters of the scanning scheme affect the certainty of the convex forming, and dependencies of bend angle on Fourier number, laser power, and dimensionless velocity are further investigated experimentally and numerically. The simulation results are in agreement with experimental observations. The numerical simulation model developed is also used to study the transient temperature, stress, and strain state and provide further insight to the process.

1. INTRODUCTION

Laser forming process uses laser induced thermal distortion to shape sheet metal without hard tooling or external forces. Majority of work on laser forming to date has been based on the so-called temperature gradient mechanism (TGM) proposed by Vollertsen (1994a). Under TGM, workpiece always bends concavely (i.e., bends towards the irradiated surface or towards the laser beam). Analytical and numerical modeling efforts have been made for TGM dominated laser forming process, which is fairly well understood (Vollertsen, 1994a; Vollertsen, et al., 1993; Hsiao, et al., 1997; and Alberti, et al., 1994 and 1997).

However, there are occasions in practical applications where convex forming is required. Fig. 1 shows examples where concave laser bending can not be applied due to impossible access by the laser beam. It has been shown that convex bending is possible under the buckling mechanism (BM), which is induced when the ratio of laser beam diameter to sheet thickness is small, resulting lower through-thickness temperature gradient. A local elastic buckling and plastic deformation takes place as a result of the thermal expansion more or less uniform throughout the sheet thickness (Arnet and Vollertsen, 1995).

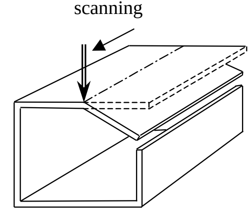


Fig. 1 Example requiring convex forming (dash lines indicating the shape before laser forming)

But understandably the direction of the buckling heavily depends on the initial stress and strain state of the sheet. For example, if a sheet is slightly bent, the buckling will take place in the bent direction. In fact, Arnet and Vollertsen (1995) conducted research on convex bending using slightly pre-bent sheets. They experimentally investigated dependency of bend angle on laser power, scanning velocity and beam diameter for steel (St14), AlMg3 and Cu at different values of thickness. They also conducted a well-known experiment, in which unbent but heavily constrained samples were used to demonstrate the existence of the buckling mechanism and the feasibility of convex bending under the condition. The sample is mechanically constrained at both ends instead of clamping on one side only. Holzer, et al. (1994) conducted a numerical simulation under a similar condition. Vollertsen, et al. (1995) proposed an analytical model for laser forming under the buckling mechanism. An expression for the final bending angle was obtained using the elementary theory of bending and a qualitative model proposed. The expression is $\alpha_b = [36\alpha_{th} k_f Ap / c_P \rho E v s^2]^{1/3}$, where α_{th} is the coefficient of thermal expansion, k_f the flow stress in the heated region, Ap the coupled laser power, c_p the specific heat of the material, ρ the density, E the modulus of elasticity, v the processing speed, s the sheet thickness. The model does not determine the direction of the buckling.

For industrial applications, pre-bending a flat sheet or to heavily constraining a sheet in order to effect convex bending is not economic for obvious reasons and sometimes impossible as seen in Fig. 1. It is postulated that if the starting point of the laser scanning is at a point other than one on a sheet edge, the direction of buckling will be certain, that is convex. In almost all laser forming work reported to date, laser forming starts from an edge of the sheet. The postulate is based on the fact that although the temperature difference between the top and bottom surface is small under the buckling mechanism, the flow stress is slightly lower and the tendency of thermal expansion is slightly higher at the top surface because of the slightly higher temperature there. The slight difference will be amplified by the heavier mechanical constrains introduced by the non-edge starting point which is completely surrounded by material. As the result, the amplified difference is sufficient to serve as a disturbance to induce buckling to take place in that direction. Once the buckling occurs in that direction, the rest of the forming process will be in that direction. The postulate is validated by the experimental and numerical results to be explained below.

2. EXPERIMENTS

The specimen size is 80×80 mm. Two values of thickness, i.e., 0.61 and 0.89 mm are examined. Instead of starting laser scanning at an edge (i.e., X_s=0 in Fig. 2a), a non-zero value of X_s is used for the reasons stated before. A scan starts from a point X_s mm away from the left edge rightward till reaching the right edge. To complete the scan, the scan resumes at a point X_s mm away from the right edge leftward till reaching the left edge. The overlap in scanning is primarily to reduce the so-called edge effect (Bao & Yao, 1999).

In addition, to obtain a BM-dominated laser forming process, it is essential that the ratio of beam diameter to sheet thickness is high. The parameters used in the experiments are shown in Table 1.

Table 1 Experimental parameters for convex laser forming (Sheet size: 80x80 mm)

No.	Power (W)	Velocity (mm/s)	Diameter (mm)	Thick. (mm)
1	900	30	12.0~14.8	0.89
2	900	20~58.3	14.8	0.89
3	700	18.3~50	14.8	0.89
4	600~1010	30	14.8	0.89
5	807~1345	36.7	14.8	0.89
6	600~1200	36.7	14.8	0.61

Except for some experiments in the first group, the diameter/thickness ratio is at least equal to 14.8/0.89=16.6, which ensures the forming process will be dominated by the buckling mechanism. Typical samples so formed are shown in Fig. 2b. The reduced diameter in the first group is to obtain conditions under which concave bending takes place.

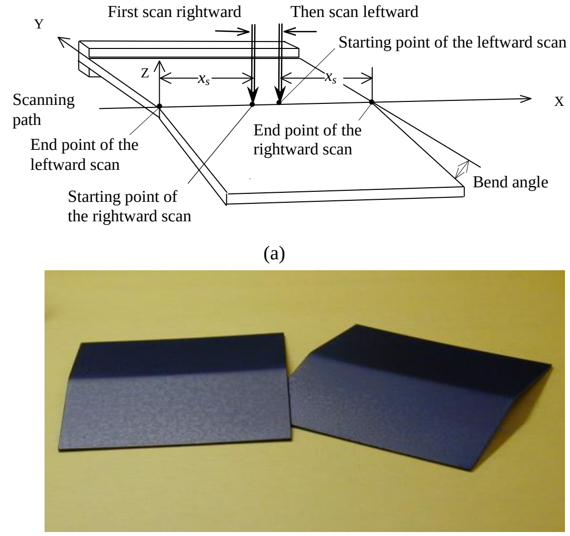


Fig. 2 (a) Scanning scheme for convex laser forming, (b) Samples formed convexly using the scanning scheme

The material is low carbon steel, AISI 1010. The samples were first cleaned using propanol and then coated with graphite to increase coupling of laser power. During forming, the samples were clamped at one side. A coordinate measuring machine was used to measure deformation at different positions along the scanning path. An average bending angle and curvature of the scanning edge were calculated based on the measurement for each sample. The sheet metal was scanned with a PRC1500 CO_2 laser system with the maximum power of 1.5 kW. The power density has a Gaussian distribution (TEM_{00}). The diameter of the laser beam is defined as the diameter at which the power density becomes $1/e^2$ of the maximum power value.

3. THEORETICAL ASPECTS

For an isotropic material, the relationship between stress σ_{ij} and strain ε_{ij} including the influence of temperature can be written in terms of tensor as

$$\varepsilon_{ij} = \frac{1}{E}[(1+\nu)\sigma_{ij} - \nu\delta_{ij}\sigma_{kk}] + \delta_{ij}\alpha\Delta T \qquad (1)$$

where E is the modulus of elasticity, ν the Poisson's ratio, δ_{ij} the Kronecker delta, α the coefficient of thermal expansion, and ΔT the temperature change.

The deflections of the buckled plate is obtained by buckling equation (Thornton, *et al.*, 1994)

$$\Delta\Delta w = \frac{1}{k}\left(N_x^* \frac{\partial^2 w}{\partial x^2} + 2N_{xy}^* \frac{\partial^2 w}{\partial x \partial y} + N_y^* \frac{\partial^2 w}{\partial y^2} \right)$$

$$k = \frac{Eh^3}{12(1-\nu^2)} \quad (2)$$

where w is the deflection of the plate in the Z direction, h is the thickness of the plate, k is the bending stiffness of the plate, E is the modulus of elasticity, α is the coefficient of thermal expansion, ν is Poisson's ratio, and Δ is potential operator $\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$. N^*_x, N^*_y, *and* N^*_{xy} are stress resultants, which are given by multiplying the stresses by the plate thickness.

The following von Kármán's equation describes the thermal post-buckling problem.

$$\Delta\Delta F = -E\alpha\Delta T + E\left[\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2 - \frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}\right] \quad (3)$$

where F is the stress function and T the temperature field.

The plastic buckling of a plate is governed by

$$\left(1-\frac{3}{4}\lambda\frac{N_x^2}{\overline{N}^2}\right)\frac{\partial^4 w}{\partial x^4} + 2\left(1-\frac{3}{2}\lambda\frac{N_x N_y}{\overline{N}^2}\right)\times$$
$$\times\frac{\partial^4 w}{\partial x^2 \partial^2 y} + \left(1-\frac{3}{4}\lambda\frac{N_y^2}{\overline{N}^2}\right)\frac{\partial^4 w}{\partial y^4} + \quad (4)$$
$$+\frac{N_x}{\overline{D}}\frac{\partial^2 w}{\partial x^2} + \frac{N_y}{\overline{D}}\frac{\partial^2 w}{\partial y^2} + 2\frac{N_{xy}}{\overline{D}}\frac{\partial^2 w}{\partial x \partial y} = 0$$
$$\overline{D} = \frac{E_s s^3}{9}, \lambda = 1 - \frac{E_t}{E_s}$$

where $E_s = \frac{\overline{\sigma}}{\overline{\varepsilon}}$ is the secant modulus, $\overline{\sigma}$ the effective stress, $\overline{\varepsilon}$ the effective strain, $\overline{N} = \overline{\sigma}s$, and E_t the tangent modulus.

These equations describe the behavior of the buckling deformation involved in this study. Analytical solutions for the laser forming processes will be difficult to obtain without significant simplifications. Instead, numerical simulation is conducted.

4. NUMERICAL SIMULATION

The assumptions made for the numerical modeling are as followings. Workpiece materials are isotropic. The rate of deformation is the sum of the elastic strain rate, plastic strain rate, and thermal strain rate. The heating and deformation in the laser forming is symmetrical about the laser-scanning path and the symmetric plane is assumed adiabatic. Heat generated by plastic deformation is negligible because it is small as compared with heat input by laser beam. Therefore a sequential thermal-mechanical analysis will suffice. Laser forming process is so controlled that the maximum temperature in the workpiece is lower than melting temperature of sample material. No cooling of gas or water jet is followed after laser scanning.

The boundary conditions are described follow. Heat flux generated by laser beam is only applied to top surface with a non-uniform distribution. Free heat convection with air occurs on the all surfaces except the symmetric plane: $q = h\ (T - T_0)$, where h is the heat transfer coefficient, and $T_0 = T_0\ (x, t)$ the surrounding temperature. Radiation takes place on the same surfaces: $q = A\ ((T - T_Z)^4 - (T_0 - T_Z)^4)$, where A is the radiation constant, and T_Z the absolute zero on the temperature scale used. The initial temperature is set as 300K. On the symmetric plane, no displacement in the Y direction occurs throughout the laser forming process.

The numerical simulation is conducted using code ABAQUS. Three-dimensional heat-transfer elements with eight nodes DC3D8 is used for thermal analysis, and continuum stress/displacement elements with the same dimension and number of nodes C3D8 for structure analysis. Heat flux is determined by the maximum intensity in the center of laser beam with Gaussian distribution (TEM_{00}) and the distance of calculating point from the laser-beam center. That depends on laser beam power, absorption coefficient, beam diameter, scanning velocity, and the distance. A FORTRAN program is developed to define the magnitude of the heat flux generated by laser beam for specific positions on the top surface of the workpiece as a user subroutine. Von Mises criterion is used as the yield criterion in the simulation. Temperature-dependent work hardening of the material due to plastic deformation is considered. Strain-rate and temperature effects on flow stress are taken into account (Li and Yao, 1999a)

5. RESULTS AND DISCUSSION

5.1 Supporting evidence for the postulate

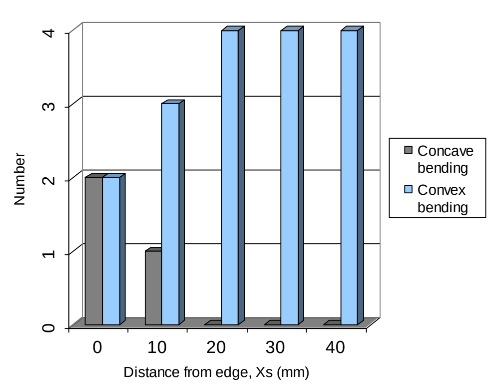


Fig. 3 Histogram of bending direction vs. distance from edge, X_s (power:900W, velocity:30mm/s, beam diameter:14.8mm)

Fig. 3 is a histogram of bending direction for different distance from edge, X_s. At each distance, four samples were laser formed. When X_s=0, i.e., scanning from an edge, the bending direction is uncertain, two samples were bent concavely and two convexly. This is consistent with published results, that is, in a BM-dominated laser forming process, buckling will occur but the direction of the buckling is uncertain and heavily depends on the initial stress/strain state. A small disturbance in favor of a particular direction will easily induce the buckling towards that direction. When X_s increases, i.e., the starting point of the scanning moving away from the edge, the bending becomes predominantly convex. When the starting point approaches the middle of the plate, that is, X_s approaches 40 mm, the bending is always convex. This clearly confirms the postulate made earlier, that is, in a BM-dominated laser forming process there is a slight difference in temperature/thermal expansion between the top and bottom surfaces, the difference is significantly amplified by the added mechanical constraints when the starting point of the scanning moves away from an edge. As a result, material at the starting point starts to buckle convexly. Once the starting point has even a small convex bending, the rest of the forming process will understandably follow its lead. More discussions will be given later in the paper when transient simulation results are discussed. For the rest of the experiments and all simulation studies, X_s=25 mm.

5.2 Effect of Fourier number

The Fourier number, F_o, is defined as $F_o = \frac{\alpha_d d}{s^2 v}$, where α_d is the thermal diffusivity, d the beam diameter, s the sheet thickness, v the scanning velocity. It has been known that a TGM dominated laser forming process has a smaller Fourier number, while a BM dominated process a larger F_o. Shown in Fig. 4 are bending angles at both convex and concave directions when the Fourier number F_o varies from about 6.25 to 7.75. The variation in F_o is obtained by varying the laser beam diameter from 12 to 14.8 mm while keeping other parameters unchanged (the first group in Table 1). It can be seen that corresponding to small values of the Fourier number, concave bending, represented by a positive value, always occurs even X_s=25 mm.

When F_o increases, the direction of bending becomes uncertain. As seen, for F_o =6.6 to 6.8, the bending is sometimes convex (represented by negative bending angles) and sometimes concave. Beyond the critical region, convex bending always takes place for the reasons already stated earlier. It has been known that the Fourier number can be used as the criterion to determine whether a laser forming process is TGM or BM dominant. Fig. 4 shows F_o can be reliably used as a criterion to predict concave and convex bending under the new scanning scheme used (e.g, non-zero X_s). The switch between concave and convex forming will be further discussed with the simulation results late in the paper.

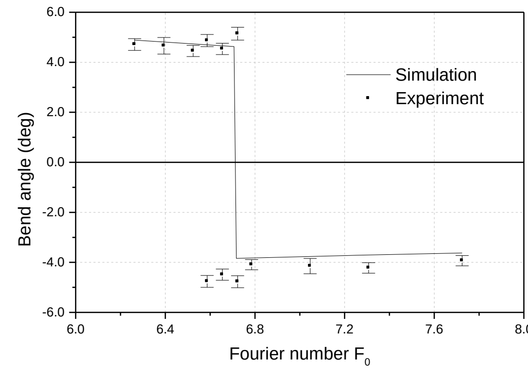
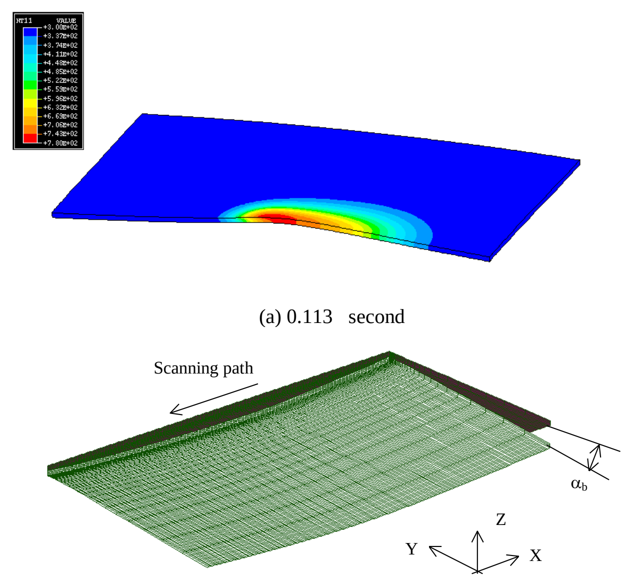


Fig. 4 Bend angle vs. Fourier number F_0 (power: 900W, velocity: 30mm/s, dimension: 80×80×0.89mm, diameter: 12-14.8mm)

5.3 Simulation validation



(a) 0.113 second

(b) 1000 second

Fig. 5 (a) Deformed shape with temperature contour (deformed magnification 5X). (b) Comparison between undeformed sample (top) and deformed one (bottom) (deformed magnification 3.5X).(showing half plate due to symmetry, power=800W, velocity: 30mm/s, beam diameter: 14.8mm, workpiece size: 80×80×0.89mm)

Simulation results of bending direction and angle are superposed on experimental ones in Fig. 4. Good agreement can be seen. Unlike experimental results, the simulation gives a much clear cut in switching from the concave and convex bending when the Fourier number increases because the uncertainties existing in the experiments do not exist in simulation. A typical result of thermal-mechanical simulation of convex laser forming is shown in Fig. 5. Fig. 5(a) shows temperature distribution and deformation when a laser beam is scanning through the workpiece. Only half of the plate is shown due to symmetry. Please note the deformation is magnified to show the workpiece bends convexly in the early stage of the forming process. Fig. 5(b) shows a formed sheet that has undergone natural cooling for a few minutes. Comparing it with the undeformed sheet shown in the same figure, it is obvious that it is convexly bent. It can also be seen that the bending edge is curved (although magnified) and this is because the X-axis plastic contraction near the top surface is larger than that near the bottom surface (Bao and Yao, 1999).

Shown in Fig. 6 are comparisons between numerical and experimental results of bending angle vs. power and non-dimensional parameter v_n. v_n is defined as vs/α_d. The physical meaning of v_n is the ratio of through-thickness unheated part of the sheet to thickness. For obvious reasons, the bending angle becomes more negative with laser power increase, and less negative with velocity increase. Figs 4 and 6 together show that the simulation results are fairly consistent with the experimental measurements.

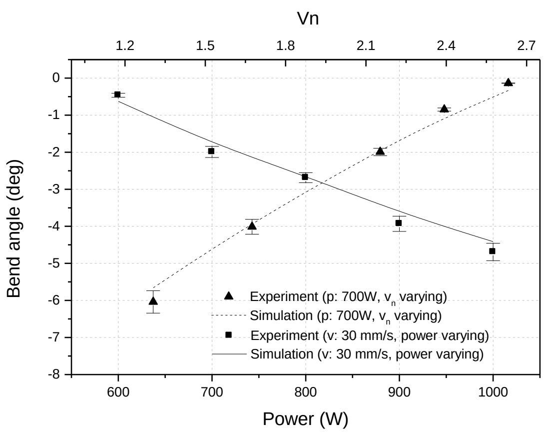
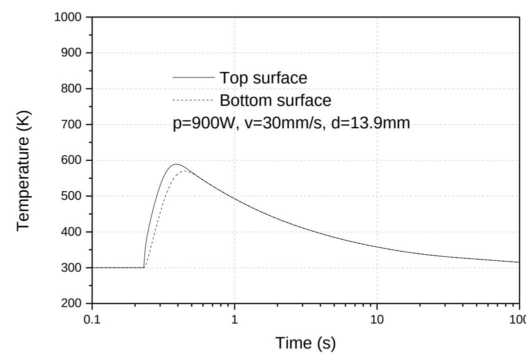


Fig. 6 Numerical and experimental results of variation of bend angle with power p and dimensionless velocity v_n (beam diameter: 14.8mm, workpiece size: 80×80×0.89mm)

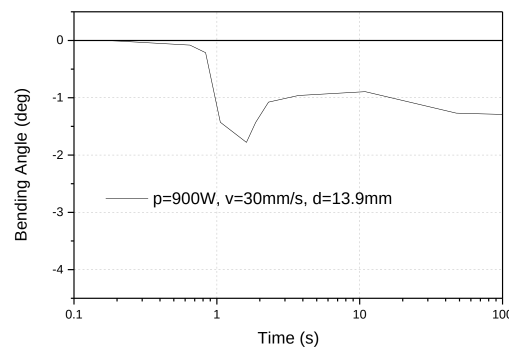
5.4 More discussions on convex forming mechanism

In order to obtain further insights why the convex forming is always obtained when the starting point of laser scanning moves from an edge to a point closer to the center of the sheet, the transient plots from simulation are shown in Fig. 7. The plots are for the starting point X_s=25 mm. At time=0 sec, the scan begins at the starting point rightward, proceeds till it passes the right edge, and waits there for a few minutes for the sheet to cool down before completing the scan rightward (Fig. 2a). Shown in Fig. 7 is time history of the first 100 seconds.

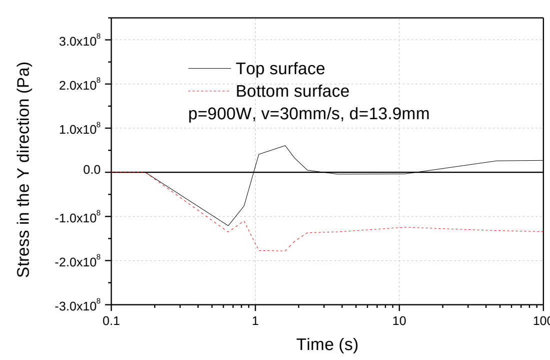
Fig. 7a confirms that, although small, there is a temperature difference between the top and bottom surface under the process condition, which is known to induce the buckling mechanism (BM). As a result, there is slightly more thermal expansion at the top surface than that at the bottom surface, resulting a small negative bending angle (convex bending) as seen from Fig. 7b. The small convex bending angle in turn causes a slightly more compressive stress at the bottom than that at the top as seen from Fig. 7c. This trend continues till about t=0.7 sec. At the point of time, the convex bending angle has grown just big enough to make the buckling happen of course in the same direction, which is the convex direction. This is evident in the dramatic increase in the negative bending angle with a fraction of second (from about 0.7 to 1.1 sec as seen from Fig. 7b). As a result, the compressive stress at the top surface also abruptly reverses its sign to become tensile (Fig. 7c).



(a)



(b)



(c)

Fig. 7 Typical time history of (a) temperature, (b) bend angle, and (c) Y-axis stress at the starting point, X_s=25mm (p=900W, v=30mm/s, d=13.9mm, workpiece 80×80×0.89mm)

It should be pointed out that the initial small convex bending angle exists in laser forming under almost any condition. This includes TGM-dominated processes. This also includes BM-dominated processes in which the starting point of the laser scan is from an edge of the workpiece. In the TGM-dominated processes, the small convex bending angle is quickly reversed to a large concave bending angle because the significant shortening at the top-surface caused by significant temperature gradient through the thickness serves as a strong pulling force during cooling. In the BM-dominated processes in which the starting point of the laser scan is from an edge of the workpiece, the initial small convex bending angle may lead to either directions. This is because the mechanical constraints near the edge are less. As a result, the inducing effect of the initial convex bending angle can be easily overturned by other forms of small disturbances, such as unevenness of the sheet and surface condition.

But this is not the case for the conditions used in this paper. Once an initial small convex bending angle is formed, it is very hard, if not impossible, to reverse because of the heavier mechanical constraints surrounding the starting point. As a result, the buckling can only take place in the same direction as the initial direction, that is, convex direction.

6. CONCLUSIONS

A new scanning scheme is postulated, in which laser scanning starts from a location near the middle of workpiece instead of normally from an edge of the workpiece. Using the scanning scheme, convex forming is realized with high certainty unlike the case of scanning from the edge where either concave or convex forming could take place. The postulate is based on the analysis that the added mechanical constraints by moving the starting point from an edge to the middle will amplify and sustain the initial convex deformation, which exists in both concave and convex forming. The postulate is successfully validated by experimental and numerical results. With the method, neither pre-bending nor additional external mechanical constraints are needed in order to effect convex laser forming. The underlying physical phenomena, including temperature, stress, and strain field near the starting point, are comparatively investigated to give better understanding of the effect of the new and conventional scanning schemes. Even with the new scanning scheme, the condition for buckling mechanism to dominate still needs to be satisfied. Otherwise, convex forming may not be reliably obtained or not be obtainable at all. In this connection, the Fourier number F_o can still be used as a threshold between the concave and convex deformation, like it has been used in laser forming to date to distinguish between TGM and BM dominated forming processes.

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