DOI: 10.1007/s12541-015-0042-0

FEM Analysis for Laser Bending Process of DP980 Steel Sheet

Ya Jing Zhang[1], Jong-Bong Kim[2,#], Jung Han Song[3], Geun An Lee[3], Hye Jin Lee[4], and Nak Kyu Lee[4]

1 Graduate School of NID Fusion Technology, Seoul National University of Science and Technology, 232, Gongneung-ro, Nowon-gu, Seoul, 139-746, South Korea
2 Department of Mechanical Automotive Engineering, Seoul National University of Science and Technology, 232, Gongneung-ro, Nowon-gu, Seoul, 139-743, South Korea
3 Korea Institute of Industrial Technology, 156, Gaetbeol-ro, Yeonsu-gu, Incheon, 406-840, South Korea
4 Korea Institute of Industrial Technology, 143, Hanggaul-ro, Sangnok-gu, Ansan-si, Gyeonggi-do, 426-910, South Korea
Corresponding Author / E-mail: jbkim@seoultech.ac.kr, TEL: +82-2-970-6434, FAX: +82-2-979-7032

KEYWORDS: Laser bending, High strength steel, FEM analysis, Engineering parameter, Line energy, Scanning direction

Laser bending of metal sheet is a complex process that is achieved by introducing thermal stress into a metal sheet through irradiation using a defocused laser beam. In a single scanning process, it is important to know the effects of the engineering parameters on the final bending angle, such as the laser power, laser beam diameter, and scanning speed. Furthermore, it is important to investigate the effect of the scanning direction in a multiple scanning process. In this paper, FEM analyses for a laser bending process of DP980 high strength steel sheet under different laser powers, scanning speeds, line energies, and scanning directions are performed to analyze the effects of the engineering parameters and the scanning direction on the final bending angle. The results indicate that the final bending angle of a DP980 steel sheet increases in a linear increase fashion with the increase of the line energy in the single scanning process; it also increases when the scanning direction is changed time by time in the multiple scanning process.

Manuscript received: June 22, 2014 / Revised: October 5, 2014 / Accepted: November 8, 2014

1. Introduction

Laser bending is a flexible manufacturing process that was first proposed by Kitamura[1] in 1983. In this process, forming is achieved by introducing thermal stress into a metal sheet by controlled irradiation with a defocused laser beam, as shown in Fig. 1.[2] In the laser bending process, the metal sheet is clamped on one side on a CNC machine. When a laser beam of high power density is rapidly irradiated across the top surface of the metal sheet along a given path, the material absorbs a part of the laser energy on the top surface and the thermal energy is conducted into the material. The metal sheet expands in the heated zone and thermal stresses are produced by the restriction of the surrounding lower temperature material. During the cooling of the irradiation zone, the shrinkage of the materials causes tensile stress. As a result, the tensile stresses lead to bending of the metal sheet.

Laser bending process is applied to many manufacturing industry, such as plate bending, tube bending/forming, straightening of weld distortion, and thermal pre-stressing, as shown in Fig. 2. Recently, promising potential applications of laser bending have arisen, allowing rapid prototyping and shape correction in the automotive, aerospace, and shipbuilding industries. Another application of laser bending is precision adjustment of components in the microelectronics industries. In any laser bending process, due to the fact that thermal stresses are introduced into a metal sheet by irradiation rather than by external forces, the laser bending technique has certain advantages compared to the traditional forming processes, such as bending, drawing, stamping, and pressing. For example, reduction of manufacturing cost and time can be realized due to the fact that the forming process requires no dies or other sorts of tooling. Precise deformed shapes can be achieved due to the spring-back-free and non-contact forming characteristics of the process. Some special materials, such as those that are brittle, hard, or thick material can also be processed.[3]

In a laser bending process, due to the fact that the bending deformation is achieved using the thermal stress caused by the temperature gradient, it is important to learn about the relationship between the final bending angle and the engineering parameters of a given laser beam, such as the laser power and scanning speed. Some researchers have experimentally studied about the effects of the engineering parameters on the bending angle.[4-6] It is time-consuming and requires high costs to carry out the repetitive experiments when the material or the laser beam is changed. Other researchers have also studied the engineering parameters of laser beams and have predicted

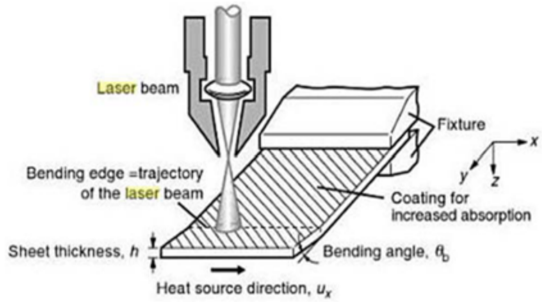


Fig. 1 Schematic of laser bending process

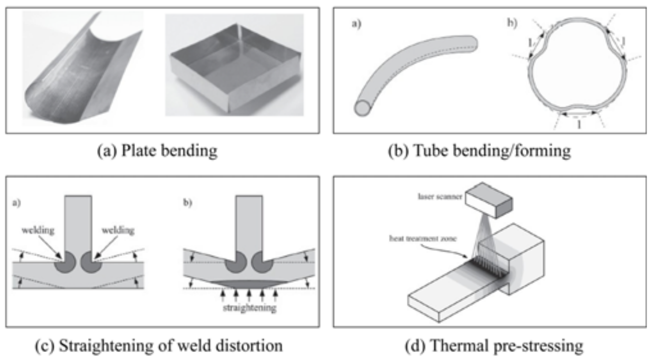


Fig. 2 Applications of laser bending process

the final bending angle using the finite element method.[7-11] However, most of the previous researchers have focused on those materials with good deformability at ambient temperature, such as mild steel, titanium, aluminum, and so on. In this study, using both finite element analysis and experiments, a kind of high strength steel DP980 (dual phase 980), which is getting starting to be widely used in the automotive industry, was selected in order to allow a study of the bending characteristics under different laser powers and scanning speeds of laser beam using both finite element analysis and experiment.

Furthermore, due to the fact that bending deformation is realized by scanning the metal sheet repeatedly for many times, not only one time, using the laser beam, it is necessary to investigate the effect of the scanning strategy, for example, the scanning direction of each iteration of the process, in order to improve the processing efficiency. However, there have been very few studies that have referred to the effect of scanning direction in multiple scanning processes. In this study, we performed finite element analyses for different scanning directions in a two-time scan and a three-time scan in order to investigate the effect of scanning direction on the final bending angle of DP980 steel sheet.

2. Material and Finite Element Analysis Model

2.1 DP980 steel

DP980 (dual phase 980 steel) is a kind of high strength steel that is gaining more and more favor in the automotive industry in recent years due to its high yield strength and light weight. Using this material to manufacture a car body can help to satisfy safety requirements and

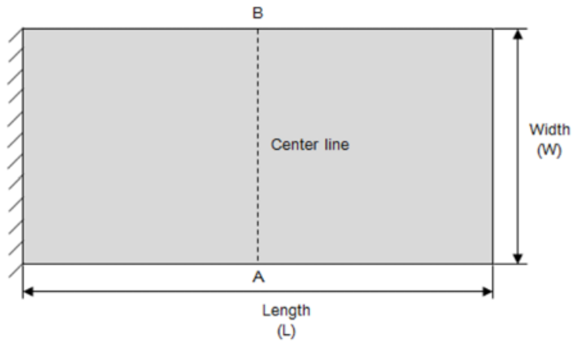


Fig. 3 Scanning path description of laser beam

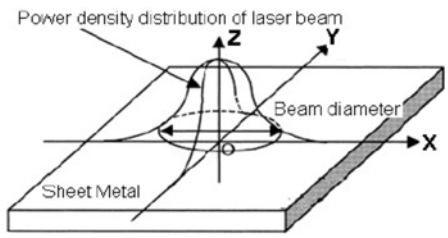


Fig. 4 Idealized Gaussian heat flux distribution

allow high fuel efficiency to be obtained at the same time. However, the property of high strength brings more difficulties to manufacturing process than would be the case with other materials. For instance, it is difficult to deform a high strength material; also, spring back is large under the traditional forming process. As is well known, one of the final goals of the laser bending process is to make a target shape from a flat metal sheet. Thus, the bending characteristics of steels such as the difficult-to-deform DP980 steel in the laser bending process should be investigated before design the scanning strategy. With the investigated bending characteristics, it is possible to find the best scanning strategy to improve the bending quality. The basic specimen is a DP980 metal sheet with a length of 100 mm, width of 50 mm and thickness of 1.4 mm.

2.2 Finite element analysis model

The FEM (Finite Element Method) is a computer-based analysis method used to solve engineering problems, for instance, structural, thermal, fluid flow, magnetic, and so on, in bodies of user-defined geometry. Both structural and thermal problems are involved in the laser bending process. It is an effective method to simulate the forming process, shorten the design cycle, and improve the quality of products. In this study, the commercial software ABAQUS v6.10-1 is employed to perform the coupled temp-displacement analyses. An idealized Gaussian heat flux is implemented to the user subroutine DFLUX of ABAQUS which can be used to define a non-uniform distributed flux as a function of position, time, temperature, element number, integration point number, etc. in a heat transfer or mass diffusion analysis.[12]

Scanning is carried out along the center line of the top surface in the width direction, as shown in Fig. 3; the idealized Gaussian heat flux distribution is shown in Fig. 4,[6] which can be described using Eq. (1):

$$I = \frac{2AP}{\pi R^2}\exp\left(-\frac{2r^2}{R^2}\right) \quad (1)$$

Where; I is the intensity of the incident heat flux at the material surface, A is the absorptivity of laser energy, P is the laser power; R is the beam radius, and r is the distance from the center of the laser beam. In order to find the effects of the engineering parameters, we focused on a single scanning analysis in which the effects of laser power, scanning speed, and line energy were investigated.

3. Analysis Results for Single Scanning

For the FEM simulations, the DP980 steel sheet is designed as a shell model due to the large size ratio of the sheet length to its thickness. All degree of freedom of the left edge of specimen is fixed. For the top and bottom surface, convection heat transfer boundary condition is imposed. The shell surface is defined as the top surface of the specimen. There are 5 integration points from top to bottom surface in the thickness direction at which temperature, stress, and strain are calculated. Therefore, the temperature gradient in thickness direction can be analyzed. Element type of the sheet is selected to be S4RT. The diameter of the laser beam is 5.2 mm, with a power of 1.0 Kw and a scanning speed of 2.0 m/min. The single scanning direction is from point A to B, as shown in Fig. 3.

3.1 Effect of laser power and scanning speed

The deformed shape and stress distribution of the DP980 sheet after one-time scanning by the laser beam and cooling for 1.0 min is shown in Fig. 5. The deformation is magnified 10 times for clarity. We can see that the DP980 sheet bent towards the laser beam; the average bending angle is 1.27°. In order to verify the FEM analysis, an experiment under the same processing conditions was performed, as shown in Fig. 6(a). Fig. 6(b) shows the experimental results. The average bending angle, measured using a protractor, was 1.23°. In the finite element analysis, both spring back owing to self-weight and heat transfer from the work-piece to the clamp are neglected which may lead to a small difference between finite element analysis result and experimental result. From these results, however, it can be seen that the analysis results are in good agreement with the experimental results. Thus, we can conclude that the FEM analysis results are valid for the analysis of the laser bending process.

Fig. 7 shows the temperature histories at the center point and the final bending angles obtained from the analysis. In order to investigate the effect of the laser power, analysis is carried out for the laser power of 0.75 Kw. The other process conditions are the same with them of Fig. 7. Fig. 8 shows the temperature histories at the center point and the final bending angles under the laser power of 0.75 Kw. In Fig. 8, it can be seen that both the temperature and the final bending angle are smaller than those shown in Fig. 7. This means that when the laser power increases, both the temperature and the final bending angle increase. This is because the heat flux flowing into the material at the unit time increases as the laser power increases. The increased heat flux leads to a high peak temperature and high temperature gradient, such that, the final bending angle increases.

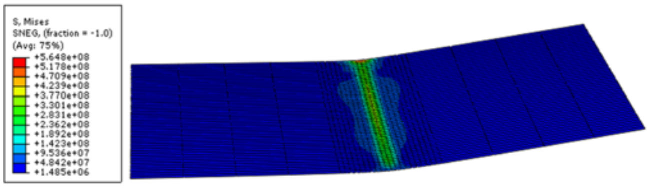
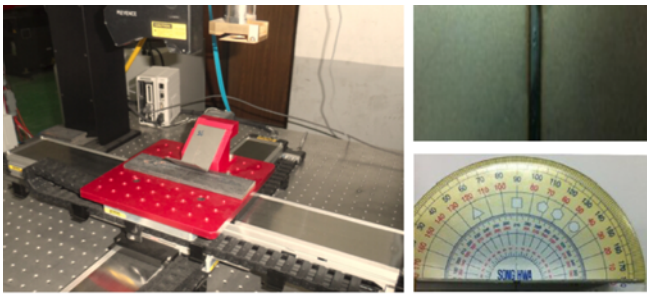
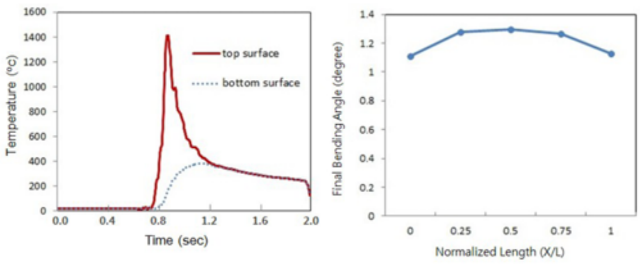


Fig. 5 Deformed shape and Von-Mises stress distribution (Deformation scale factor = 10)



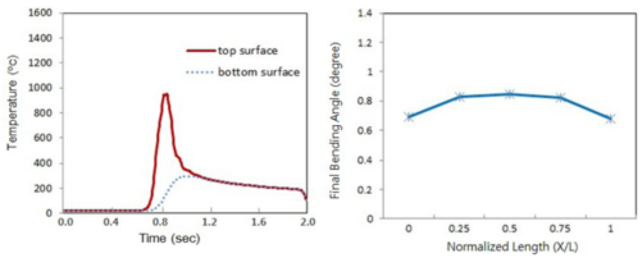
(a) (b)

Fig. 6 (a) Experimental equipment and (b) bending angle measurement



(a) Temperature (b) Final bending angle

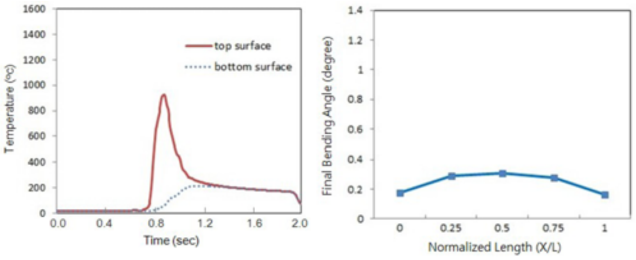
Fig. 7 Temperature histories at the center point and final bending angle (P=1.0 Kw, v=2.0 m/min)



(a) Temperature (b) Final bending angle

Fig. 8 Temperature histories at the center point and final bending angle (P=0.75 Kw, v= 2.0m/min)

In order to investigate the effect of the laser scanning speed, analysis is carried out for the scanning speed of 5 m/min. The other process conditions are the same with them of Fig. 7. The result of this analysis is shown in Fig. 9. By comparing the results of Figs. 9 and 7, it can be seen that both the temperature and final bending angle in Fig.



(a) Temperature (b) Final bending angle

Fig. 9 Temperature histories at the center point and final bending angle (P=1.0 Kw, v=5.0 m/min)

9 are smaller than those in Fig. 7. That's to say, when the laser scanning speed increases, both the temperature and the final bending angle decrease. The reason for this is thought to be the fact that when the laser scanning speed increases, the duration of the heat flux into the material becomes shorter and the temperature peak value and the temperature gradient are both reduced. Therefore, the final bending angle decreases. Furthermore, it can be seen from Figs. 7(b), 8(b) or 9(b) that bending angle at the edge is smaller than that at the center which is because the heat transfer exists between edge of the work-piece and ambient air. The temperature difference between the top and bottom surface at the edge is smaller than that at the center, which means the thermal stress is smaller at the edge than at the center. So that the bending angle at the edge is smaller than at the center. This phenomenon is termed edge effect.[14]

3.2 Effect of line energy

As mentioned in the previous section, the final bending angle increases with the increase of the laser power and with the decrease of the scanning speed. However, in an experiment, it is difficult to control both the laser power and the scanning speed simultaneously to obtain a required bending angle. Thus, the concept of line energy[2] is proposed; line energy is defined as the ratio of the laser power (W) times the absorptivity (%) to the scanning speed (m/sec). It is necessary to investigate the relationship between the final bending angle and the line energy.

If we name the cases in Figs. 7, 8, and 9 case 1, case 2, and case 3, respectively, the line energies of these three cases can be calculated using the following Eqs. (2)~(4).

$$E_{L,case1} = \frac{PA}{v} = \frac{1000 \times 0.6 \times 60}{2 \times 10^3} = 18(J/mm) \tag{2}$$

$$E_{L,case2} = \frac{PA}{v} = \frac{750 \times 0.6 \times 60}{2 \times 10^3} = 13.5(J/mm) \tag{3}$$

$$E_{L,case3} = \frac{PA}{v} = \frac{1000 \times 0.6 \times 60}{5 \times 10^3} = 7.2(J/mm) \tag{4}$$

Here, the absorptivity A was set at 0.6.[13] It was found that the line energy of case 1 is the largest (18 J/mm) and that that of case 3 is the smallest (7.2 J/mm). The final bending angle comparison among these three cases can be seen in Fig. 10, in which it can be seen that the final bending angle in case 1 is the largest (1.27°) and that that in case 3 is the smallest (0.24°); this means that the final bending angle increases with the increase of the line energy.

Table 1 Bending angles obtained with various line energies

Laser power (Kw)	Scanning speed (m/min)	Line energy (J/mm)	Bending angle (°)
0.75	2	13.5	0.78
	3.5	7.74	0.25
	5	5.4	0
1	2	18	1.27
	3.5	10.26	0.53
	5	7.2	0.24
1.25	2	22.5	melt
	3.5	12.84	0.72
	5	9	0.41

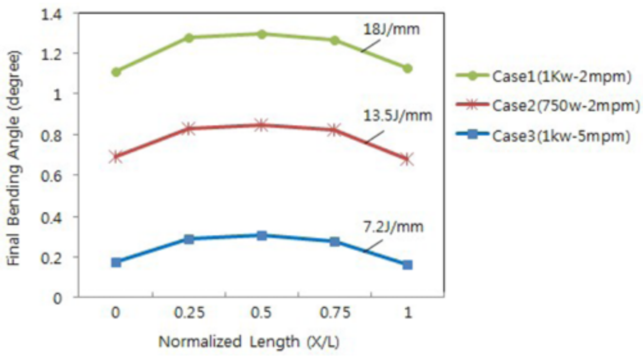


Fig. 10 Final bending angle comparison of case 1, case 2 and case 3

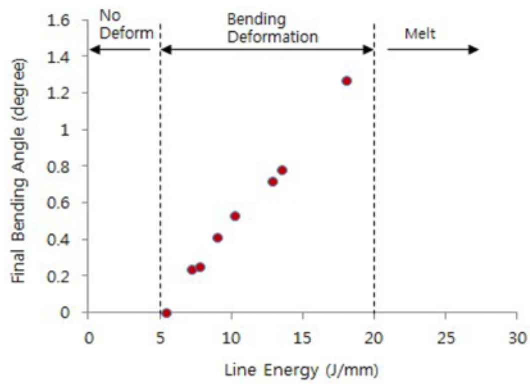


Fig. 11 Relationship between bending angle and line energy

In order to confirm this conclusion, we performed a series of additional simulations with various line energies. The laser power was kept in the range of 0.75~1.25 Kw; the scanning speed was 2~5 m/min. All of the conditions and results are listed in Table 1; the relationship between the bending angle and the line energy can be seen in Fig. 11. From Fig. 11, it can be seen that the threshold line energy is about 5 J/mm, which means that no deformation occurs if the line energy is below 5 J/mm. Furthermore, when the line energy is above 20 J/mm, the sheet surface melts, meaning that bending deformation is impossible. Bending deformation occurs in the range of 5~20 J/mm, in which an almost linear increase of bending angle is found and the largest bending angle after a single scanning of the laser beam laser

Table 2 Analysis cases for two-time scanning

	First scanning direction	Second scanning direction
Case 1	A → B	A → B
Case 2	A → B	B → A

Table 3 Analysis cases for three-time scanning

	First scanning direction	Second scanning direction	Third scanning direction
Case 1	A → B	A → B	A → B
Case 2	A → B	B → A	A → B

beam is about 1.27°. According to these results, an appropriate laser power and scanning speed can be selected to obtain the required bending angle in an actual experiment.

4. Multiple Scanning Analysis

In the traditional laser bending process, the metal sheet is scanned repeatedly by the laser beam in a single-direction, for example, from point A to point B (see Fig. 3). However, we wanted to know the effect of scanning direction on the bending angle. So, the analyses are carried out for different scanning path for both of the two-time and three-time scanning as shown in Tables 2 and 3.

The material employed in these analyses was still DP980 steel sheets with dimensions of 100 mm*50 mm*1.4 mm. The power of the laser beam was 1 Kw, the laser beam diameter was 5.2 mm and the scanning speed was 2 m/min.

4.1 Two-time scanning analysis

In the two-time scanning analysis, two cases of different scanning directions were subjected to the analysis. One was scanning from point A to point B for both of the two scannings. The other was scanning from point A to point B for the first scanning and from point B to point A for the second scanning, as indicated in Table 2.

Fig. 12 shows the final bending angles for the different scanning directions in the two-time scanning analysis. The average bending angles in case 2 was 2.048°, which is about 4.0% larger than that in case 1 (1.97°). Fig. 13 shows the time histories of temperature for the different scanning directions in the two-time scanning analysis. In both cases, the metal sheet is irradiated by the laser beam for 2 seconds and cooled for 60 seconds during every scanning process. Here, in order to see the difference between case 1 and case 2 clearly, the curve of case 2 was delayed by 0.06 seconds. It was found that the temperature distributions were almost the same for the two cases. The reason is thought to be that the sheet sizes and the scanning times were the same in both cases.

4.2 Three-time scanning analysis

In the three-time scanning analysis, two cases of different scanning direction were also subjected to the analysis. One case involved scanning from point A to point B for all of the three scannings. The other case involved scanning from point A to point B for the first and third scannings but from point B to point A for the second scanning, as indicated in Table 3.

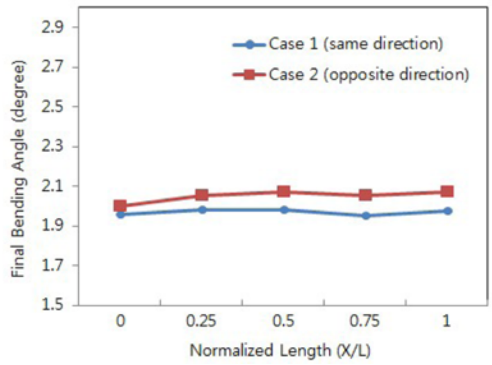


Fig. 12 Final bending angles for different scanning directions in two-time scanning analysis

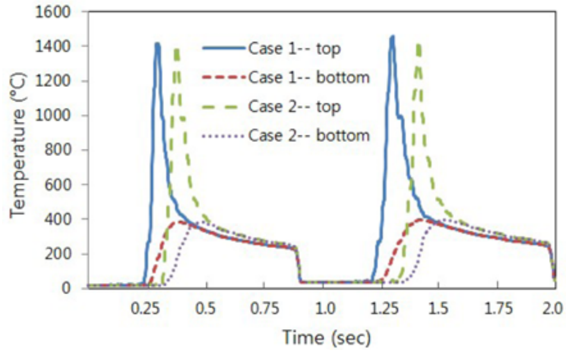


Fig. 13 Time histories of temperature for different scanning directions in two-time scanning analysis (0.06 sec. time delay between each case for viewing clarity)

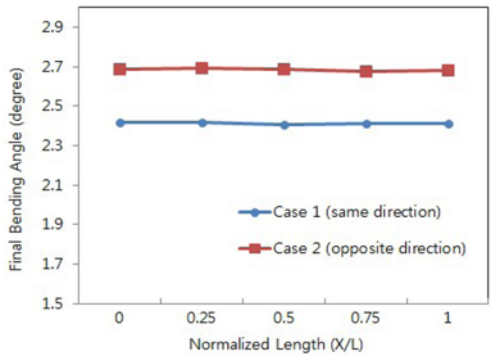


Fig. 14 Final bending angles for different scanning directions in three-time scanning analysis

Fig. 14 shows the final bending angles for the different scanning directions in the three-time scanning analysis. The average bending angle in case 2 is 2.684° , which is about 11% larger than that in case 1 (2.414°). The difference of the bending angle in the two-time scanning described in previous section is 4%, which is much smaller than the difference in the three-time scanning (11%). This means that the final bending angle differences among the different scanning directions become larger with the increase of the scanning times. So, an

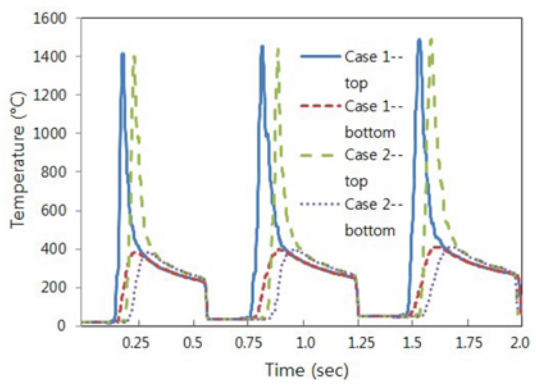


Fig. 15 Time histories of temperature for different scanning directions in three-time scanning analysis (0.06 sec. time delay between each case for viewing clarity)

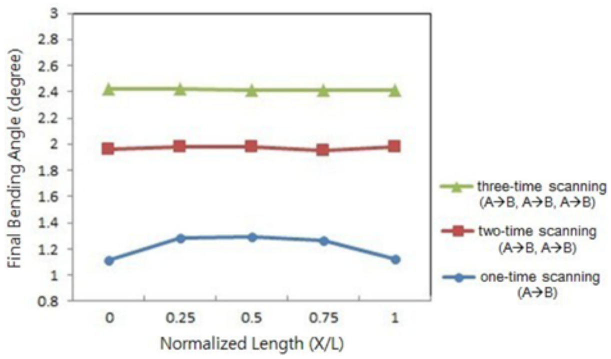


Fig. 16 Final bending angles for different scanning times

investigation into the effect of scanning direction is important. Fig. 15 shows the time histories of temperature for the different scanning directions in the three-time scanning analysis. As described previously, the metal is irradiated by the laser beam for 2 seconds and cooled for 60 seconds during every scanning process. Also, the curve of case 2 was delayed by 0.06 seconds in order to make visible the difference between case 1 and case 2 clearly. It can be seen that the temperature distributions are also almost the same for both case 1 and case 2.

In addition, the effect of the different scanning times on the final bending angle can be seen in Fig. 16. It can be seen that the final bending angle of the three-time scanning was the largest and that that of the one-time scanning was the smallest. This means that the final bending angle also increases as the scanning times increases. However, the bending angle does not increase linearly as the scanning time increases. This is because the existing residual stress after the first scanning results in the smaller stresses in the second and following scanning processes when the parameters of laser beam keep constant.[15] So that the bending angle increment is getting smaller and smaller time by time. Moreover, during the second scanning, the heat affected zone (HAZ) is getting much larger than that in the first scanning, which may affect the bending behavior also.[15,16] I will study more about it in the future work.

On the other hand, it can be seen from Fig. 16 that the curvature of the three-time scanning (green curve) is the smallest, but that of the one-time scanning (blue curve) is the largest. This indicates that the final bending angle difference among the different positions of the sheet surface is the smallest in the three-time scanning. That's to say, if the steel sheet is scanned more times using the laser beam, the difference of the final bending angles at different positions can be reduced. This phenomenon owes to the residual stress of the material which is larger at the center (large deformation zone) than at the edge (small deformation zone) after the first scanning. During the second scanning process, as the parameters of laser beam are the same all over the length, a larger deformation will be generated at the edge than at the center. Thus, it can be concluded that bending deformation is more uniform if the steel sheet is scanned more times by the laser beam.

5. Conclusions

Through the comparison between the finite element analysis results and the experimental results, it can be seen that the analysis results are in good agreement well with experimental results. This indicates that the analysis using ABAQUS is reliable for predicting the bending angle in laser bending process.

From the analysis results, it is shown that the final bending angle increases as the laser power increases and the scanning speed decreases. Furthermore, the final bending angle increases almost linearly with the increase of the line energy. From the results of multiple scanning analyses, it is shown that higher bending angle can be achieved when the scanning direction is changed than when the scanning direction is the same. Also, it is shown that the bending angle become more uniform as the sheet is scanned more times.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Ministry of Knowledge Economy and related researchers and professors of the Korea Institute of Industrial Technology and Seoul National University of Science & Technology.

REFERENCES

1. Kitamura N., "Technical Report of Joint Project on Materials Processing by High Power Laser," JWES-TP-8302, pp. 359-371, 1983.
2. Kim, J. and Na, S. J., "Feedback Control for 2D Free Curve Laser Forming," Optics & Laser Technology, Vol. 37, No. 2, pp. 139-146, 2005.
3. Jung, H. C., "A Study on Laser Forming Processes with Finite Element Analysis," Ph.D. Thesis, Department of Mechanical Engineering, University of Canterbury, 2006.
4. Cheng, J. and Yao, Y. L., "Process Design of Laser Forming for Three-Dimensional Thin Plates," Journal of Manufacturing Science and Engineering, Vol. 126, No. 2, pp. 217-225, 2004.

5. Akinlabi, S. A. and Akinlabi, E. T., "Experimental Investigation of Laser Beam Forming of Titanium and Statistical Analysis of the Effects of Parameters on Curvature," Proc. of the International Multi Conference on Engineers and Computer Scientists, 2013.

6. Majumdar, J. D., Nath, A., and Manna, I., "Studies on Laser Bending of stainless Steel," Materials Science and Engineering: A, Vol. 385, No. 1, pp. 113-122, 2004.

7. Venkadeshwaran, K., Das, S., and Misra, D., "Finite Element Simulation of 3-D Laser Forming by Discrete Section Circle Line Heating," International Journal of Engineering, Science and Technology, Vol. 2, No. 4, pp. 163-175, 2010.

8. Zhang, L. and Michaleris, P., "Investigation of Lagrangian and Eulerian Finite Element Methods for Modeling the Laser Forming Process," Finite Elements in Analysis and Design, Vol. 40, No. 4, pp. 383-405, 2004.

9. Shichun, W. and Zhong, J., "FEM Simulation of the Deformation Field During the Laser Forming of Sheet Metal," Journal of Materials Processing Technology, Vol. 121, No. 2, pp. 269-272, 2002.

10. Chen, Y., Zhou, J., Huang, S., and Sun, Y. "Study on the Numerical Simulation of Laser Forming of Sheet Metal based on ABAQUS Code," Journal of Applied Laser, Vol. 27, No. 3, pp. 175-180, 2007.

11. Kyrsanidi, A. K., Kermanidis, T. B., and Pantelakis, S. G., "An Analytical Model for the Prediction of Distortions Caused by the Laser Forming Process," Journal of Materials Processing Technology, Vol. 104, No. 1, pp. 94-102, 2000.

12. Simulia, "Abaqus 6.10," http://abaqusdoc.ucalgary.ca/ (Accessed 30 DEC 2014)

13. Ko, D. C., Lee, C. J., and Kim, B. M., "Production of CO2 Laser Forming Machine for Bending of Sheet Metal Using the FE-Analysis," Transactions of Materials Processing : Journal of the Korean Society for Technology of Plastics, Vol. 15, No. 4, pp. 318-325, 2006.

14. Bao, J. and Yao, Y. L., "Analysis and Prediction of Edge Effects in Laser Bending," Journal of Manufacturing Science and Engineering, Vol. 123, No. 1, pp. 53-61, 2001.

15. Feng, S. X., "Laser Bending and Forming Technology of Functionally Graded Materials (Chinese Edition)," Metallurgical Industry, pp. 108-113, 136-140, 2013.

16. Wang H. Y., Li C. and Luo G., "Controlling the Heat Affected Zone (HAZ) in HF Pipe and Tube Welding," Welded Pipe and Tube, Vol. 35, No. 4, pp. 66-70, 2012.