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In-line Springback Measurement for Tube Bending Using a Laser System

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Abstract

Tube bending process is extensively used for many industrial fields such as the automotive, shipbuilding, and aircraft manufacturing industries. However, one limitation of the tube bending process is that it is not easy to control the springback related to elastic recovery after unloading. Since springback is affected by many influential parameters such as bending angle, radius, speed, and material properties, accurate prediction of springback can be complicated. To compensate springback, it is essential to accurately measure the released springback angle. The proposed method herein is to use a laser system to measure the springback angle in-line, without moving the workpiece from the bend die or machine. This in-line laser measurement concept can help save measurement time while potentially improving measurement accuracy. The system can be used to either instantaneously correct springback or to collect data to adjust machine settings between batches. In detail, the laser source can be installed and fixed into the tube, using the laser beam as the reference position to measure the bending angle. After releasing the clamp, the bent tube is recovered and the embedded laser system indicates the position shift on a datum board. The distance from the center of the unloaded tube to the board is set and the recovered distance is easily measured. The released springback angle can be calculated with those two parameters. In addition, the resolution of the measurement can be improved by properly adjusting the distance. In this paper, the capability of the measuring technique is demonstrated in a rotary draw bending machine using AA6xxx aluminum alloy profiles bent at different angles.

Keywords: Tube bending; Springback; In-line measurement; Laser-based measurement

1. Introduction

Metal forming has been an important manufacturing process in aerospace, automotive, architecture, shipbuilding, and other industries. The industry demands that metal forming products be lightweight, high strength, dimensionally accurate and aesthetically pleasing. However, metal forming such as the tube bending process has an inevitable springback issue that often causes global dimensional defects [1]. There is no simple solution to compensate or manage the springback phenomenon. In general, the manufacturing process of metal forming is set up by trial and error that requires significant time to compensate for springback. In other words, the process condition of the optimal springback compensation is found by the operator's expertise [2]. Moreover, feedback control in can be an approach to compensate for springback and control material behavior. Different measurement methods or tools were used for the feedback control of springback [3–7]. Since the measurement quality has an effect on feedback control [8], it is necessary to measure precisely the geometric dimension of the final product for compensating springback or controlling the product quality such as geometric imperfection.

Many studies [9–16] have measured displacement for evaluating springback with contact or non-contact methods. A contacting measurement method is to physically touch the object configuration using a measurement device, e.g. a protractor, sine bar, angle gauge, or a coordinate measuring machine. A linearly variable differential transformer (LVDT) which is a kind of contact measuring device was used in the air bending process, calculating springback with the known tooling

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geometry and the measured displacement from LVDT [9]. A mandrel with an inertial measurement unit (IMU) was used in a roll bending process to monitor the springback and in-line process without separating the workpiece from the bender [10].

A non-contacting measurement is a technique where an optical method like a laser measurement [11–13], or image processing with charge-coupled devices (CCD) [14–16] is applied to sense the object configuration. As shown in Fig. 1, trigonometric principles are used to calculate the target object distance or scan the object surfaces from the reflected optical beams illustrated. A beam receiving or detecting device is an important component to determine the angle or distance in these techniques. Based on the triangulation principles the three-dimensional optical measurement can be used for a pipe bending process to inspect, evaluate, and monitor the pipe springback without moving sensors and workpieces to measure springback [17].

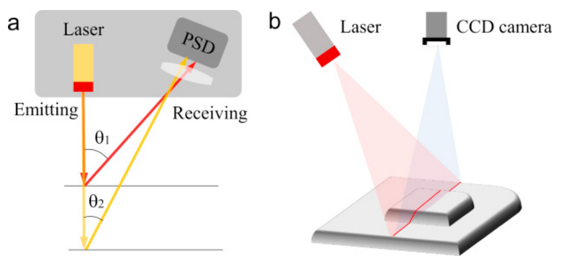

Fig. 1. Triangulation measurements in the non-contacting method: (a) Laser displacement sensor; (b) Laser surface scanner

Laser triangulation for displacement measurement has a fine sensing resolution, about 6,000 Hz and min. 10^{-9} m [18]. In this study, a high resolution, low-cost, and simple in-line springback measurement technique based on a laser system is proposed and validated with the experimental data. A 635 nm wavelength laser having 1 mW powered was used to evaluate the tube bending springback. The effects of parameters such as the distance error of a datum board and the reading error of the laser traveling distance on the performance of the measurement were also investigated.

2. A Laser measurement method (LMM)

In metal forming, the workpiece recovers elastically after unloading. The tube bending process has the springback phenomenon as shown in Fig. 2. The profile is bent along the bend die, while being clamped in the rotary draw bending process. After releasing the loading, the deformed profile's shape is changed due to springback. It is significant to acquire the data by an in-line measurement to control springback in real time. Thus, a laser measurement method is developed to efficiently and accurately measure the springback angle.

2.1. Springback

Springback is an inevitable phenomenon in the tube bending process. Fig. 2 simply shows the fundamental concept of the tube bending with the bent tube configuration in the loading (gray-colored tube) and unloading (blue-colored tube) conditions. r_1 and r_2 are the radii of curvature upon loading and unloading, respectively. θ is the springback angle which is the difference between θ_1 and θ_2, the initial bending angle and final bent angle.

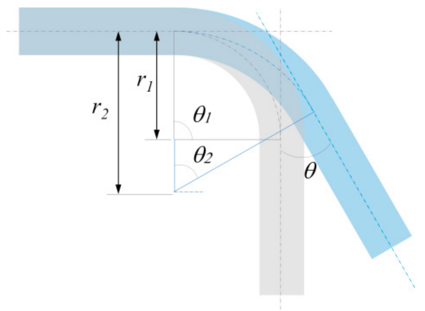

Fig. 2. Workpiece configuration in loading and unloading

The springback curvature is changed due to elastic recovery upon unloading. The change of curvature due to springback is related to the bending moment (M_f) and flexural rigidity (EI). The bending moment and curvature change in pure bending, assuming linear work-hardening and a simple plastic stress-strain model, are expressed as follows [1]:

$$M_f = \sigma_{0.2} w(\alpha_p + \frac{E_t kh}{2\sigma_{0.2}}) \tag{1}$$

$$\Delta k = \frac{M_f}{EI} \tag{2}$$

$$\Delta k = (\frac{1}{r_1} - \frac{1}{r_2}) = \frac{2}{Eh}\sigma_{0.2}(\alpha_p + \frac{E_t kh}{2\sigma_{0.2}}) \tag{3}$$

where $\sigma_{0.2}$ is the initial yielding stress; w is the moment of resistance; α_p is the shape factor which is the ratio between the static moment of cross-sectional area and section modulus of cross-sectional area; E_t is the strain hardening; k is the curvature; and h is the height. The springback ratio, m, is described as the ratio between the springback angle, θ, and bending angle, θ_1 shown in Eq. (4). The springback ratio was used to calculate the distance for calibration.

$$m = \frac{\theta}{\theta_1} = 1 - \frac{\theta_2}{\theta_1} \tag{4}$$

Predicting material behavior after unloading is a limitation of an analytical model approach because this is difficult and complicated when considering material properties and bending conditions [19]. A prompt and accurate measurement of springback is needed to reduce time for the compensation process and to increase measurement efficiency.

2.2. In-line measurement approach

In this work, a laser measurement method is used for an in-line measurement approach aimed at measuring the springback angle, θ. The advantage of this method is that the springback data are collected without taking the workpiece out from the tube bender. The basic scheme of the measurement method is illustrated in Fig. 3. The laser beam is aligned in the profile's longitudinal direction. The laser assembly is installed at the tip of the profile. Thus, the installed laser beam indicates the current tube direction as a reference after loading.

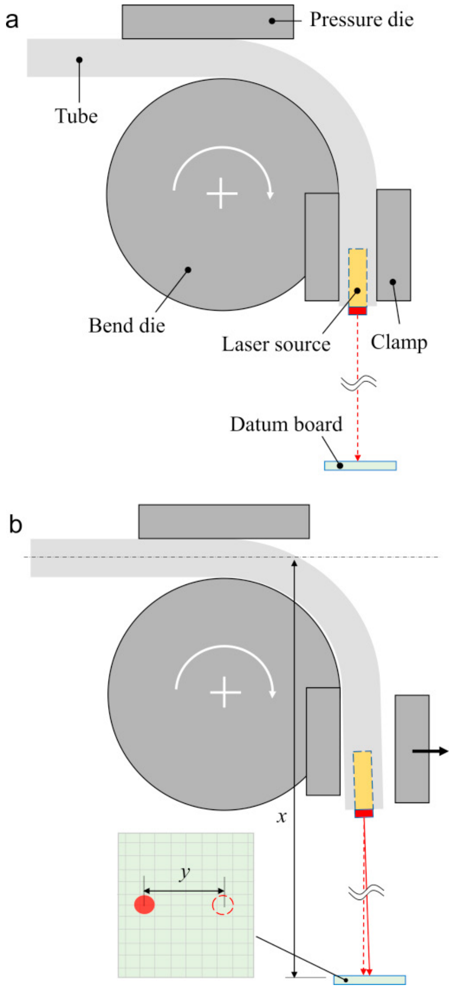

Fig. 3. Schematic of the laser measurement: (a) Loading; (b) Unloading

The embedded laser is pointing at the datum board located at a certain distance from the tube as shown in Fig. 3(b). After releasing the clamp, the workpiece geometry changes due to springback and the laser beam indicates the change of angle. The dotted line is the reference of the desired bending angle and the red line is the direction of the bent tube after unloading. The distance from the tube to the board location, x, is known, and the laser traveling distance, y, is also captured. Then, the springback angle can be calculated by the simple triangulation principles. The beam travel distance, AB, on the datum board (shown in Fig. 4) needs to be calibrated due to the different apex, C'', after springback. The line CA is the initial length before springback, and the line $C'B$ is the final length after springback. However, the line $C'B$ is shifted to the line CB' in order to match the point between C and C'' for springback calculation. The length for the calibration distance, D, is expressed as followings:

$$\overline{OC} = \frac{r_1(\sec\theta_1 - 1)}{\tan\theta_1} \tag{5}$$

$$\overline{OC'} = \frac{r_2(\sec\theta_2 - 1)}{\tan\theta_2} \tag{6}$$

$$\overline{C'C} = \frac{r_1(\sec\theta_1 - 1)}{\tan\theta_1} - \frac{r_2(\sec\theta_2 - 1)}{\tan\theta_2} \tag{7}$$

$$\overline{BB'} = D = \frac{\sin\theta_2}{\cos(\theta_1 - \theta_2)}\left[\frac{r_1(\sec\theta_1 - 1)}{\tan\theta_1} - \frac{r_2(\sec\theta_2 - 1)}{\tan\theta_2}\right] \tag{8}$$

The calibration distance, D, for springback calculation can be represented by

$$D = \frac{\sin(\theta_1(1-m))}{\cos(\theta_1 m)}\left[\frac{r_1(\sec\theta_1 - 1)}{\tan\theta_1} - \frac{r_1\{\sec(\theta_1(1-m)) - 1\}}{(1-m)\tan(\theta_1(1-m))}\right] \tag{9}$$

Then, springback angle, θ, can be expressed by

$$\theta = \arctan\left(\frac{y+D}{x}\right) \tag{10}$$

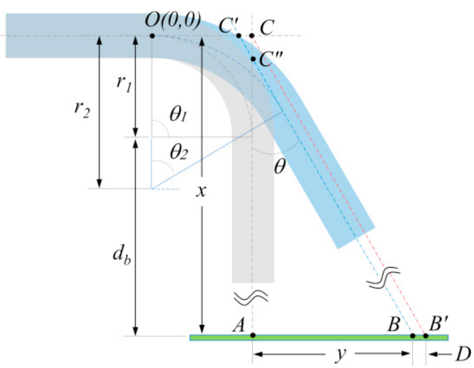

Fig. 4. The geometry for springback calculation

2.3. The expandability of the measurement method

By using additional optical components, the proposed method is also applicable when bending in limited spaces. As shown in Fig. 5, an optical mirror reflects the beam, and the incident beam path is changed to the reflected beam path based on the law of reflection, which indicates that the incident angle is equal to the reflection angle. The laser beam travels straight without any optical mirror; however, the beam can be folded in the desired direction by the application of one or multiple optical mirrors. This allows the beam path from the tube to be controllable. In other words, the small space is not a critical factor to measure the springback with the proposed laser measurement. At the same time, the measurement accuracy can be improved by increasing the length of the beam path by decreasing the relative set-up error of the datum board at a certain distance. Moreover, the original beam path can be divided into two or more paths for other monitoring purposes as shown in Fig. 5(a). The split beam enables the system to be extensible.

Measurement accuracy can be affected by factors such as the beam spot size, tilted surface, unevenness surface, and so on [20]. Unlike a plate or sheet metal in a press brake bending, the round tube measurement of springback using a laser device with a receiving sensor like in Figure 1(a) has the possibility of reduced sensing and measuring accuracy. For instance, a misaligned or rounded surface can cause unwanted beam reflection or intensity reduction due to the convex surface of a tube. In that case, the higher power laser is necessary to send the beam to a receiver because the receiver cannot detect a weak laser. However, a noticeable, positive feature of the proposed method is that the laser beam installed into the tube does not measure the rounded surface but indicates the tube direction, which is used for an imaginary neutral line of the tube. The measurement mechanism in this study is appropriate for the single bending process because the reference beam of the multiple bending process before springback is not easily defined. The laser beam for measuring is only related to the loading and unloading status in this study.

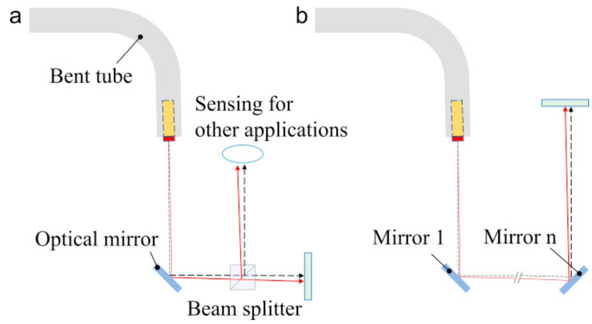

Fig. 5. Expandability for the measurement and limited space: (a) split laser beam paths; (b) a laser beam path with multiple mirrors

3. Experiment and measurement

A 400mm long AA6060-T4 tube was bent by a rotary draw bending (RDB) machine at four different bending angles which were 30, 60, 90, and 120°. In this study, a mandrel and a wiper die were not used. The tube outer diameter was 16 mm, and the thickness was 2 mm. The bending radius was 40 mm. The datum board was located at a distance, d_b in Fig. 4, of 3.2 m from the center of the bend die. The bending process was repeated with the six repeats at each angle. One of the samples with the maximum deviation was removed for the robust measure.

Fig. 6. shows the experimental procedure based on the laser measurement. The laser measurement device is installed into the tube, and then the bending process with a given angle is conducted. The laser beam indicates the longitudinal direction of the tube on the board in Fig. 3. The initial laser beam spot is used for the reference to calculate the beam travel distance, and the acquired distance data, beam travel distance, is input as given in Eq. (10). However, updating the beam travel distance, adding a calibration value, *D*, in Fig. 4 is needed to reduce the measurement error.

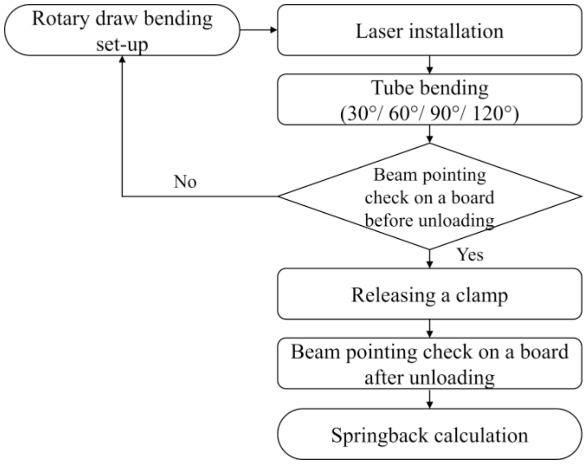

Fig. 6. Experimental procedure for the springback measurement

A tube recovers elastically by springback after the clamp release. Though the laser beam pointed along the tube direction, the pointing direction was changed as the tube configuration changed. Fig. 7(a) shows the laser device in the status of a clamp released and, when facing the datum board, the laser beam traveling from the right to the left side. The right-sided beam spot of Fig. 7(b) indicates the original position before loading, and the left-sided beam is the position after unloading. Hence, the beam travel distance can be determined with the two points from loading and unloading in Fig. 7(b), and then the springback angle was calculated using Eq. (10). Additionally, a piece of graph paper was used for a datum board to easily obtain the beam traveling distance before and after springback.

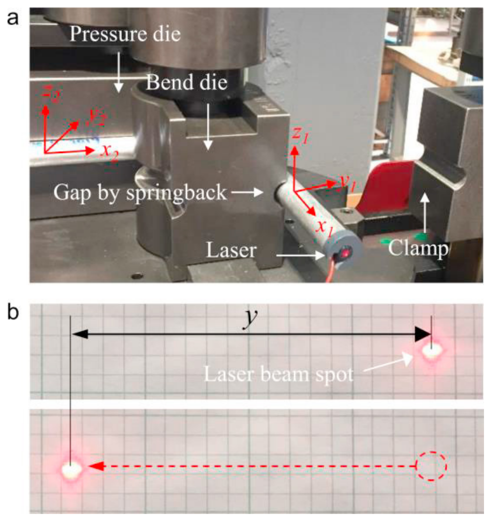

Fig. 7. (a) a laser device after springback; (b) beam travel on a datum board

As illustrated in Fig. 8, the measuring sample was clamped, and the springback angle was measured at the intrados of the tube by a coordinate measuring machine (CMM) Leitz PMM-

C600. It is common to use a tip ball to detect the object in the CMM measurement. However, a tip ball extension bar was used to touch an edge point of intrados whose tangent line is parallel to the tip ball extension. Because the probe system [21] interfaces with the measurement system of a CMM, the accuracy of a CMM is influenced by the probe system. While the uncertainty of a CMM affects the performance of the machine, the measurement errors are mostly from the probe system [22].

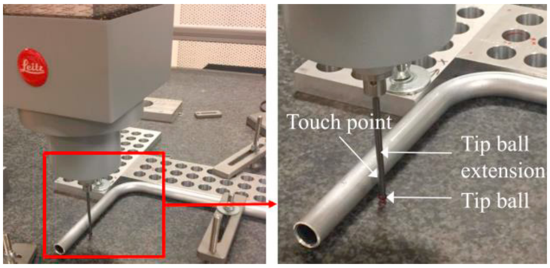

Fig. 8. The springback measurement by CMM

4. Springback measurement analysis

The measured data from the laser measurement method was compared and validated with the CMM results. In addition, the sensitivity of the laser measurement method was analyzed based on the geometric and reading errors of the distances of x and y of Fig. 4.

4.1. Springback calculation and validation

It is necessary for the travel distance of the laser beam to be updated for accurate calculation of springback in the LMM. However, there still exists an unknown parameter, the springback ratio in Eq. (9). The springback ratio is needed to calculate the calibration distance. The initial springback ratio, m_1, was calculated with x and y of Fig. 4 and without considering the calibration distance. Accordingly, the springback angle calculated by the initial springback ratio led to the measurement error, the difference between $\angle ACB$ and $\angle ACB'$. The updated springback ratio, m_2, was obtained with the consideration of calibration distance. The calculation procedure for the springback ratio is shown in Fig. 9.

Using the approximate value, the average springback ratio of the LMM and CMM is shown in Table 1. The springback ratio of the CMM in Table 1 was calculated from the measured springback angle, and the obtained values were averaged. The increased value of springback ratio, Δ, was not significant at the lower bending angle. However, the springback angle for 120° bending was increased from 2.477° to 2.507°, approximately 1.21 %, by updating the springback ratio. The updated springback ratio, m_2, was used for calculating the springback angle to reduce the measurement error. It was observed that the CMM springback measurement was more than the in-line measurement, and the error of the springback ratio was increased for a higher bending angle, see Table 1. The release of a clamp without a wiper die and a mandrel could affect the springback angle, rotation with respect to the z_2 axis, on the other side of the tube in Fig. 7(a). This bending condition without the wiper die and a mandrel caused the measurement limitation of the LMM.

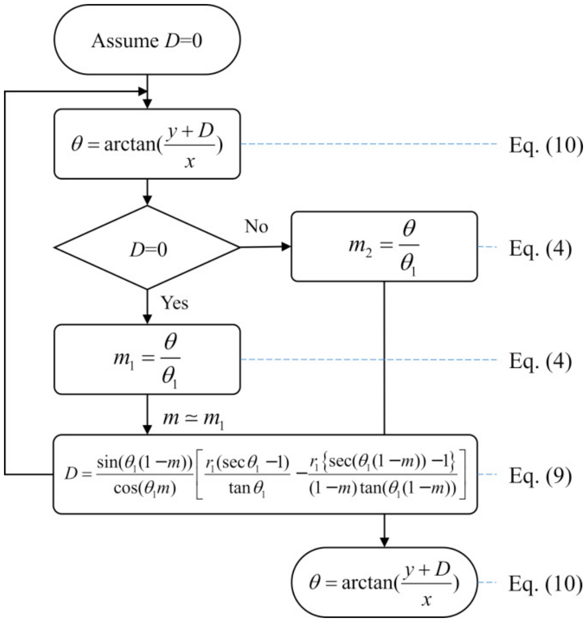

Fig. 9. Procedure for springback calculation

Table 1. The springback ratio of the LMM and CMM

θ_1 (°)	LMM			CMM	Error (%)
	m_1	m_2	Δ	m	
30	0.03384	0.03385	0.00001	0.03419	1.00
60	0.02367	0.02370	0.00003	0.02485	4.63
90	0.02196	0.02205	0.00009	0.02411	8.54
120	0.02064	0.02089	0.00025	0.02328	10.27

The measurement data of the five workpieces at each bending angle was listed and shown in Table 2, Fig. 10, and Fig. 11. The box plots were illustrated to visually summarize the measured data distribution of the LMM and CMM. The LMM data was distributed narrower than the CMM data, and there were no outlier points, outside data from 1.5×Interquartile range (IQR) of a box, in both boxplots. As illustrated in Fig. 10, both graphs showed the same increasing trend as bending angle increases. The measurement error was also increased from 1.07 % to 10.24 %. This error trend corresponded with the error trend of the springback ratio. The averaged springback angles of the LMM were in good agreement with CMM at a lower bending angle in Fig. 11. However, the overall springback measurement of the LMM proved to be a good measurement approach to measure in-line springback if not considering the additional springback by unloading without a wiper die and a mandrel. An additional calculation process in the LMM will be necessary to compensate for the springback angle due to the wiper die and a mandrel for an accurate in-line measurement.

Table 2. Measured springback angles

	θ_l (°)	θ (°) #1	#2	#3	#4	#5
LMM	30	0.999	1.053	0.964	1.008	1.053
	60	1.441	1.530	1.388	1.352	1.397
	90	1.935	1.944	1.997	2.024	2.024
	120	2.526	2.517	2.508	2.439	2.543
CMM	30	1.037	1.063	1.013	1.056	0.960
	60	1.489	1.605	1.509	1.360	1.493
	90	2.082	2.256	2.244	2.013	2.256
	120	2.883	2.788	2.753	2.707	2.834

	θ_l (°)	Avg. (°)	Std. dev. (°)	Abs. error (°)	% error
LMM	30	1.015	0.034	0.011	1.07
	60	1.422	0.061	0.069	4.63
	90	1.985	0.038	0.185	8.53
	120	2.507	0.036	0.286	10.24
CMM	30	1.026	0.037		
	60	1.491	0.078		
	90	2.170	0.123		
	120	2.793	0.061		

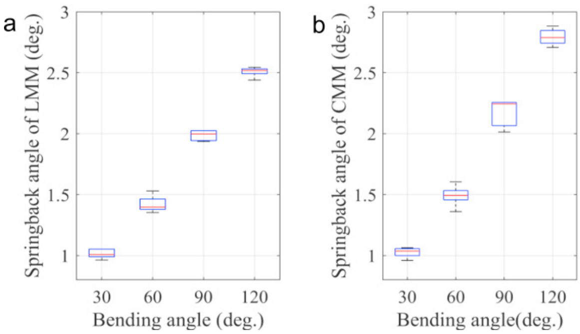

Fig. 10. Box plot diagrams of springback angles: (a) LMM; (b) CMM

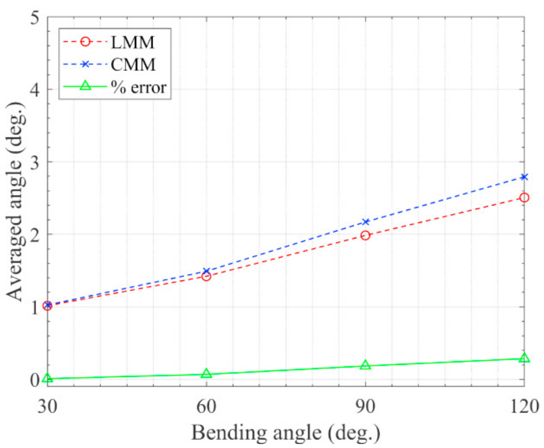

Fig. 11. Averaged springback angle and error of the LMM and CMM

4.2. Measurement error and performance of the LMM

The location error of a datum board and the reading error of the beam travel distance can affect the measurement accuracy. The geometric location error is described as an error between the nominal and actual locations in the measurement system [23]. The sensitivity with respect to both factors was analyzed to investigate the effect of geometric and reading errors. The sensitivity of springback angle regarding geometric and reading errors can be written as

$$\frac{\partial \theta}{\partial x} = -\frac{y+D}{x^2+(y+D)^2} \tag{11}$$

$$\frac{\partial \theta}{\partial y} = \frac{x}{x^2+(y+D)^2} \tag{12}$$

The springback angle sensitivity with respect to the location and reading errors are plotted in Fig. 12 and Fig. 13. To cover all practical values the range of x and y are set from 3200 to 3280 mm and from 115 to 130 mm, respectively. The springback angle sensitivity to the board location was negative, and the sensitivity to the beam travel distance was positive as shown in Fig. 12 and Fig. 13. For datum board distance x, the variation of springback angle decreased as x increased. For distance y, the variation of springback angle decreased as the value of y increased. While the springback angle was increased by the increase of y, Fig. 12 and Fig. 13 show that the springback angle by location error is less sensitive than by reading error of beam traveling. In addition, the positive error of x and the negative error of y based on the same magnitude of each error are good for even little improvement of the measurement accuracy when physically setting the datum board and reading the beam travel distance.

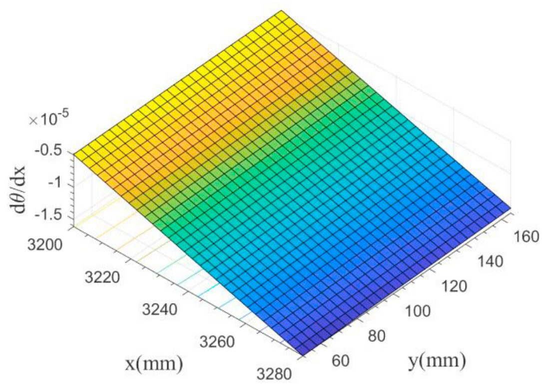

Fig. 12. Springback angle sensitivity to the datum board location

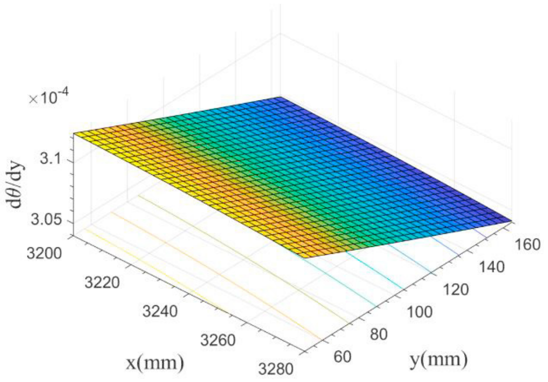

Fig. 13. Springback angle sensitivity to the laser beam travel distance

The theoretically feasible error was analyzed to predict the performance of the laser measurement method and calculated by the combination of x and y values in Table 3 and Fig. 14. The error analysis for the measurement performance was not the analysis of measured data, but the analysis of the theoretical performance based on the possible error range. The reference value of $y+D$ was calculated from the CMM measurement data and the value x. The possible error ranges, ±5 mm for x and ±1 mm for y, were estimated by the experimental data. Since the calibration distance, D, was necessary only for the LMM calculation, the calibration distance was set as zero.

The springback angle error was theoretically decreased as the bending angle increased in Table 3. Since the bent angle was computed by the tangent function with the two known values of x and y, the relative tolerance compared to the reference dimension influenced the springback angle error. The theoretical error trend illustrated in Fig. 14 asymptotically approached a certain value. For instance, the measurement error of LMM at a 30° bending angle was 1.07 % in Table 2, and the theoretically estimated error was +1.89/-1.90 % in Table 3. The LMM error was indeed within the theoretical error range. Also as expected, the other springback angle errors of the LMM in Table 2 are within the error tolerance of Table 3. In addition, it is possible to reduce the measurement error by adjusting the distance of the datum board which is an easily controllable parameter.

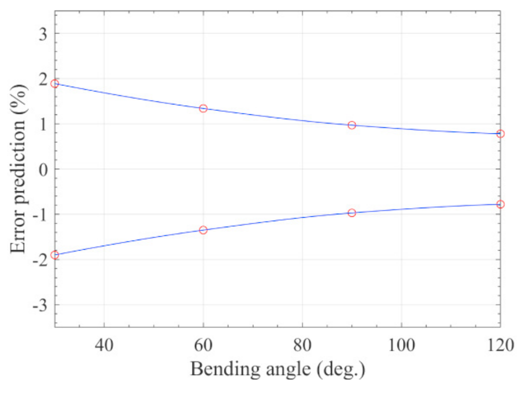

Fig. 14. Measurement error prediction of the LMM

Table 3. Theoretical error analysis of the LMM

θ_1 (°)	x (mm)	y (mm)	% error of θ	θ (°) of CMM	
30	3210.7±5	57.5±1	+1.89/-1.90	1.026	Ref.
60	3223.1±5	83.9±1	+1.34/-1.35	1.491	
90	3240.0±5	121.8±1	±0.97	2.170	
120	3269.3±5	159.5±1	±0.78	2.793	

5. Discussion and conclusions

The laser measurement approach was developed for low-cost and simple in-line measurement of the bending process. The basic approach is that the laser is embedded in a tube simultaneously and moves with the tube during loading and unloading. Accordingly, it is not required to measure the springback angle by taking from the bending machine. The springback angle can be calculated by the principle of the trigonometric function when two known values exist. One of the known values is the datum board location for laser detection. The other value is the laser travel distance on the datum board.

In this study, six workpieces each at 30, 60, 90, and 120° bend angle were applied for springback measurement. The measured data from the laser measurement method (LMM) and coordinate measurement machine (CMM) were compared to validate the LMM data. One of the samples at each angle having the worst deviation based on the CMM was removed to enhance the measurement accuracy.

The sensitivity characteristics of the LMM is that the location error of the datum board is less sensitive to the variation of the springback angle than the reading error of the laser travel distance because the relative length of the datum location is exceedingly long compared to the laser travel distance. Theoretically, the measurement error is within ±2% at a given distance of the datum location in Table 3. Nevertheless, a designed distance can be used for controlling the measurement performance of the LMM. Longer distance of the datum location reduces the measurement error as shown in Fig. 5(b) and Eq. (11). The LMM is flexible to control the measurement accuracy. In addition, the LMM is advantageous to the in-line springback measurement for the primary or 2D bending process. However, springback beyond those processes is a coupled problem, where it is difficult to capture the laser travel distance due to the limitation of the datum board setting. Hence, the improvement of the LMM will be needed for real-time springback monitoring and controlling.

The springback angle error of the LMM gradually increased as the bending angle increased from 30° to 120°. The error ranged from 1.07 % to 10.24 %. However, the bent angle trend of the LMM was similar to the CMM trend as illustrated in Fig. 11, and the precision of LMM was equal or above to the CMM data distribution as shown in Fig. 10. Since a higher bending angle led to higher springback, the springback measurement error at the 30° bending angle was not significant. The measured springback data of the LMM and CMM at the 30° bending was 1.015° and 1.026°, respectively. The 0.011° difference showed the excellent measurement performance of the LMM. If not considering the springback bias introduced by a wiper die and a mandrel, the springback measurement of the LMM can be in a good agreement with the CMM. These geometric constraints from a wiper die and a mandrel caused limitations of the LMM. For the future work, improved calculation process to predict the springback ratio will be needed to consider additional springback error after unloading.

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