

In-Process Monitoring of Springback in Industrial Bending Using a Laser Sensor-Based Method

X. He^{1,a}, J. Ma^{1,b}, S.A. Tronvoll^{1,c} and T. Welo^{1,d*}

¹Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Trondheim, 7491, Norway

^axu.he@ntnu.no; ^bjun.ma@ntnu.no; ^csigmund.tronvoll@ntnu.no; ^{d*}torgeir.welo@ntnu.no

Keywords: Springback, in-process monitoring, industrial bending, laser sensor

Abstract. Bent tubes and profiles are widely used in many industries such as automotive, aerospace and shipbuilding. In bending of tubes and profiles, springback is normally regarded as a challenge, affecting the dimensional accuracy of products. Springback control significantly determines the production route of products, including logistics. At present, effective in-situ measurement methods are lacking. This makes it difficult to realize in-process, closed-loop control of springback for improving product quality and productivity, while putting improved flexibility on the production route. In this research, an in-process measurement technique for monitoring springback in rotary draw bending was developed. A device with a laser transmitter and receiver was installed on a bending machine to detect displacement changes of the part after being released from the tool. The displacement information was collected by a controller that shows the measured displacement. A series of tube bending experiments together with the developed in-line laser sensor measurement and conventional off-line manual measurements were carried out. The result shows that the in-line laser sensor method provides a good capability for springback measurement. Since the laser measurement method is done with no need to remove the workpiece from the tooling system, it facilitates developing an in-process compensation strategy to control springback.

1. Introduction

Bending of tubes and profiles plays an important role in many manufacturing industries such as automotive, aerospace and shipbuilding. In industrial practice, engineers need to carefully design the processing parameters to reduce or eliminate the defects of the bent shapes, such as springback, over-thinning or even fracture, cross-sectional deformation and wrinkling [1, 2]. Among these, springback is normally an unavoidable problem in tube and profile bending processes. It is mainly caused by the elastic recovery of the material and significantly affects the dimensional accuracy of the product as well as the production efficiency. To control springback, accurate measurement is a prerequisite. In particular, with the transformation to Industry 4.0, inline, real-time measurement/monitoring becomes increasingly important since it enables process digitalization for improving product quality and productivity.

The conventional method of measuring springback is to remove the workpiece from the machine and then use gauges or fixtures to get the springback information. This measuring process is laborious and time-consuming. In addition, the delay of off-line measurement causes extra scrap and waste in mass production. To solve this problem, smart tooling and embedded sensors recently attract more attention to achieve in-line measurement and feedback control in a manufacturing system [3]. The measured information could be direct input to a closed-loop control system as instant and smart feedback in many metal forming processes, which would ultimately improve the final product with higher product quality, energy efficiency and productivity.

In bending of tubes and profiles, some attempts have been made to achieve inline measurements. For example, Ha et al. [4] established a laser-based measurement system to record springback angle in rotary draw bending. In this technique, a laser generator is installed at the tip of the tube and moving with the tube, where the reflection of the laser on graph paper is tracked by a webcam. The springback of the tube is then calculated by image processing the movement of the reflection. Simonetto et al. [5]

proposed a motion-capture method to track the tube orientation in the rotary draw bending process. An inertial measurement unit is installed at the end of a 3-ball segment mandrel, which detects movement as the tube springs back after bending. Integrating with the correction algorithm can compensate the springback, which could be used to developing the real-time control for bending process. The current springback measurement technologies for tube bending need extra-setups or require a mandrel to install the sensor. Moreover, the real-time data can be fed back to improve the process. Staupendahl, Chatti [6] developed integrated force, torque and contour sensors into a 3D profile bending process, gathering processing data to calculate the springback compensation. Ma and Welo [2] built a full-scale 3D bending machine with a flexible tooling concept, which enables the integration of sensor technologies and closed-loop control systems. Welo and Granly [7] provided a closed-loop feedback control system that predicts the springback by an algorithm using instant in-process data. Besides the springback, in-process measurements are also applied to improve other issues. Wrinkles that occur during draw bending can be detected by integrating a laser line scanner and a force sensor in wiper die and mandrel, respectively [8].

Although several attempts have been made to enable inline measurement of springback, effective methods for general bending processes in mass production are still lacking. This project is aiming to establish and validate a springback measuring method that can both detect the springback in a simple low-cost way and is suitable for various types of bending processes and tubular dimensions. A laser displacement sensor is fixed on the bending machine with a designed fixture, measuring the springback of the workpiece in process. The capability of the measurement method is validated by comparing the experimental data with ones from off-line measurements.

2. Measurement Method and Experiments

2.1 Rotary draw bending (RDB) process

Rotary draw bending process was used in this study, which is commonly used to manufacture high-precision bent shapes. Fig. 1 shows the bending machine STAR EVO 800 CN6 GEN 2P, employing bending dies with a radius of $R=222$ mm ($R/D=3.7$), used in this study. This machine has a tolerance of $\pm 0.1^\circ$ in the bending angle, which is ignored in this method. Thus, it is assumed that the bend die is rotated to an accurate angle when calculating springback. Both clamp closure and pressure die are driven by a system with hydraulic cylinders. AA6060-T4 aluminium alloy tubes, with a diameter of 60 mm and a thickness of 3 mm, were used in bending experiments.

In the process of rotary draw bending, the tube can be divided into three segments; the one pressed by pressure die, the bent segment contacting with bend die, and the one by the clamp die. The friction between the clamp die and tube provides a force to draw the tube and rotary along the bend die to a prescribed angle. The middle bent segment is regarded as a deformation area, which makes the major contribution to springback after releasing the die clamp.



Figure 1. STAR EVO 800 Bending machine.

The experiments are divided into three groups with different bending angles; i.e, 15° , 45° and 90° . Accordingly, the length of the tube segments is different since the larger bending angle requires a larger length. Each group has five samples for the repeated tests, and the bending velocity remained at 25° per second for all the bending tests.

At the beginning of each experiment, the tube is loaded manually into the end collet. Then auto mode is activated until the bend die reaches the preset angle. During bending, the pressure first presses the tube, followed by lamping of the clamp die. The bending arm, in which the bend die and the clamp die were installed, then rotates along the bend center to form the straight tube segment to a given curvature. After bending, the clamp die will be released and springback will occur simultaneously, as shown in Fig. 2.

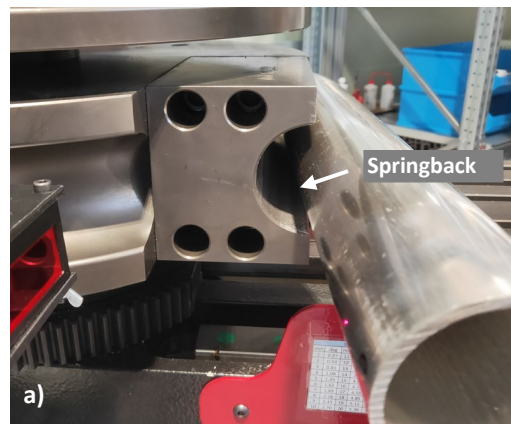


Figure 2. Springback after releasing clamp die.

There are fifteen samples measured by laser displacement sensor, and the angles of these tubes are also manually measured. The result of manual measurement will be compared and discussed in the next section.

2.2 Design of in-process measurement

In the RDB process, the springback behavior leads to a movement of the last segment after the clamp die is released. This in-process measurement method is intended to capture the displacement of the tube, and calculate the springback angle through the known sensor position and the geometric relationship between the machine and the dies. A sensor is installed on the machine, enabling the measurement of the distance to the tube while transmitting the position information to a controller that processes and displays the data.

The distance between sensor and tube is recorded as D_1 when the machine stops bending. Fig. 2 shows the springback of the formed tube after releasing the die. This distance is recorded as D_2 ; hence, the displacement d is:

$$d = D_1 - D_2 \quad (1)$$

Since this method measures the moving displacement of the tube instead of directly measuring the springback angle, a geometrical model needs to be established for calculation of the final springback. As shown in Fig. 3, the curve \widehat{ABD} is the central axis of the tube before releasing the clamp die, and the curve $\widehat{AB'D'}$ is the axis after releasing. \overline{DB} and $\overline{D'B'}$ are tangent to a curve at points B and B' , which intersect at an external point C and intersect with the extension line of the unbent part of the tube at E and E' respectively. Consequently, $\angle DCD'$ is the springback angle of the bent tube after unloading.

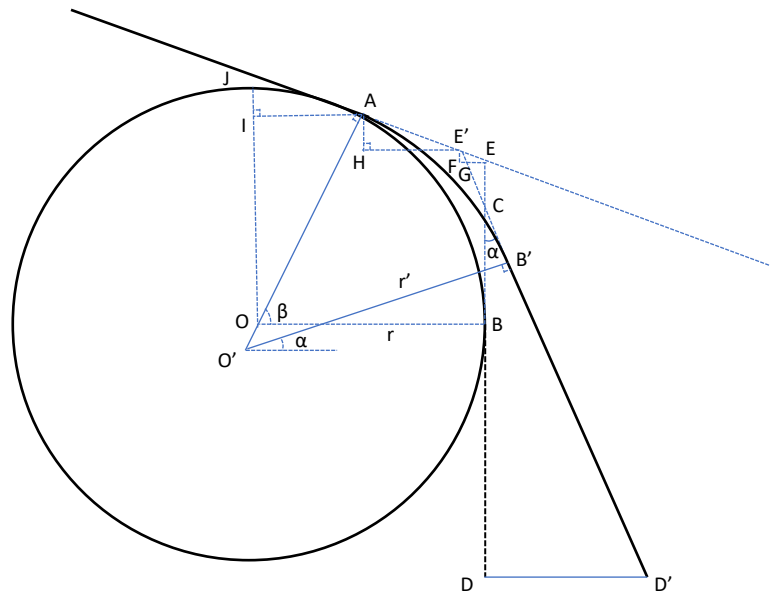


Figure 3. Geometrical calculation of springback angle.

Moreover, to calculate the springback angle, it is assumed that the bent tube after springback still has a uniform curvature along the curved area, with the same arc length of geometrical centreline as before springback. O and O' , r and r' , D and D' are the bend centers, radius and the points measured by laser displacement sensor before and after springback, respectively. Therefore, the springback angle can be calculated based on the relations:

$$\tan \alpha = \frac{DD'}{CD}; \quad (2)$$

$$\widehat{AB} = \beta \cdot \frac{\pi}{180} \cdot r = (\beta - \alpha) \cdot \frac{\pi}{180} \cdot r' = \widehat{AB}'. \quad (3)$$

Making horizontal lines IA , EF , HE' and vertical lines IJ , $E'F$, HA for calculation,

$$IA = r \cdot \cos \beta; \quad IJ = r \cdot (1 - \sin \beta); \quad (4)$$

$$HE' = r' \cdot \tan \frac{\beta - \alpha}{2} \cdot \sin \beta; \quad HA = r' \cdot \tan \frac{\beta - \alpha}{2} \cdot \cos \beta; \quad (5)$$

$$CE = r \cdot \left(1 - \cos \beta - \frac{\beta}{\beta - \alpha} \cdot \tan \frac{\beta - \alpha}{2} \cdot \sin \beta \right) (1 - \cot \beta \cdot \tan \alpha) \cdot \cot \alpha. \quad (6)$$

The springback angle α can be calculated by combining Eq. 3 - Eq. 6, yielding:

$$\tan \alpha = \frac{DD'}{BD+r \cdot \left(\left(1 - (1 - \sin \beta) \frac{\beta}{\beta - \alpha} \tan \frac{\beta - \alpha}{2} \cos \beta \right) - \left(1 - \cos \beta \frac{\beta}{\beta - \alpha} \tan \frac{\beta - \alpha}{2} \sin \beta \right) (\cot \beta + (1 - \cot \beta \tan \alpha) \cdot \cot \alpha) \right)} \quad (7)$$

2.3 Measurement method

2.3.1 Laser displacement sensor

The sensor used in this project is an OMRON ZS-LD80 sensor with a 2D CMOS (Complementary Metal Oxide Semiconductor) laser type displacement sensor head as shown in Fig. 4. The measurement distance is 80 ± 15 mm and the maximum resolution is $2 \mu\text{m}$. The light source is a visible semiconductor laser with a wavelength of 650 nm. The beam is line-shaped with the size of $900 \times 60 \mu\text{m}$. In the sensor head, the laser beam is generated by a generator, and then diffusely reflected by the object. One of the rays will be received by a CMOS through layers of lenses. The data detected by the sensor head is transferred to a ZS-HLDC controller that shows the distance of the object and sensor head.

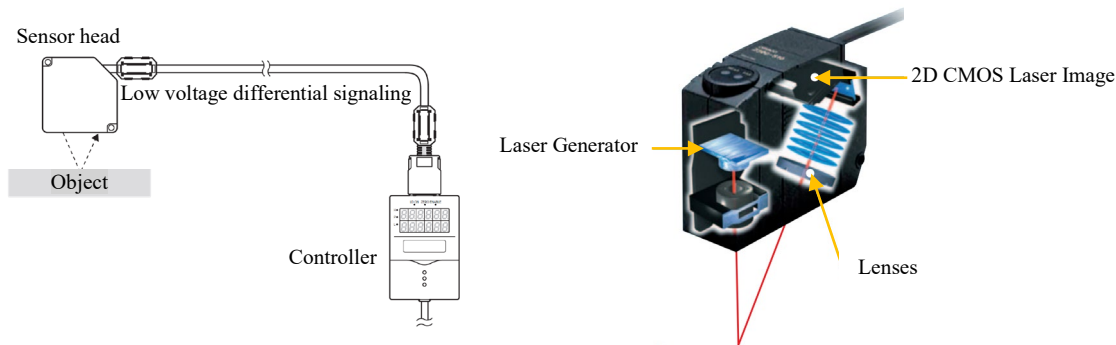


Figure 4. Laser displacement sensor

The measurement error caused by the ambient temperature change is negligible since the operating temperature of the sensor is 0 to $50 \text{ }^\circ\text{C}$ and the temperature characteristic is 0.01% FS (full scale) / $^\circ\text{C}$. According to the linearity characteristic of the laser sensor by materials for diffuse reflection. For aluminium alloy that is used in this project, the error of inclination angle of 0° , inclination angle horizontal and vertical of $\pm 15^\circ$ is below $\pm 0.1\%$ FS. As a result, full scale of the sensor is used in this project and the inclination angle between sensor head and workpiece is below $\pm 15^\circ$. The maximum inclination error is:

$$r_{\text{inclination}} = 30 \times 0.2\% = 0.06 \text{ mm} \quad (8)$$

2.3.2 Fixturing and installing

The laser displacement sensor has a reasonable resolution applicable for the measurement in the general tube bending process. However, the main error comes from the setting up of the sensor:

- (1) Precision of position: as compared with the method by Taekwang Ha [9], in which a longer laser traveling distance was used, the calculated springback angle in this method is more sensitive to the position accuracy of the sensor as it is placed closer to the bending center.
- (2) Measuring angle: the deviation of the measuring angle will cause the dislocation of the measuring position on the tube, which enlarger the measured displacement, since round tubes were used in the experiment. Moreover, the angle of the surface will also lead to an inclination error according to Eq. 8.
- (3) Fixture rigidity: since the sensor is installed on a moving die, the vibration of the die may affect the accuracy mentioned above, resulting in measurement errors.

- (4) Machine rigidity: the rigidity of bend die and end collet could affect the results as the setup measures springback relative to the tooling [10].

Therefore, a robust fixture is designed to install the sensor to the bending machine, as shown in Fig 5. The fixture consists of three main parts: a clamp, a connector and two press bends. The position of clamp in the connector can be moved to a certain extent, so as to adjust the distance between the sensor head and workpiece. Therefore, the position and angle of the sensor can be accurately adjusted for calibration.

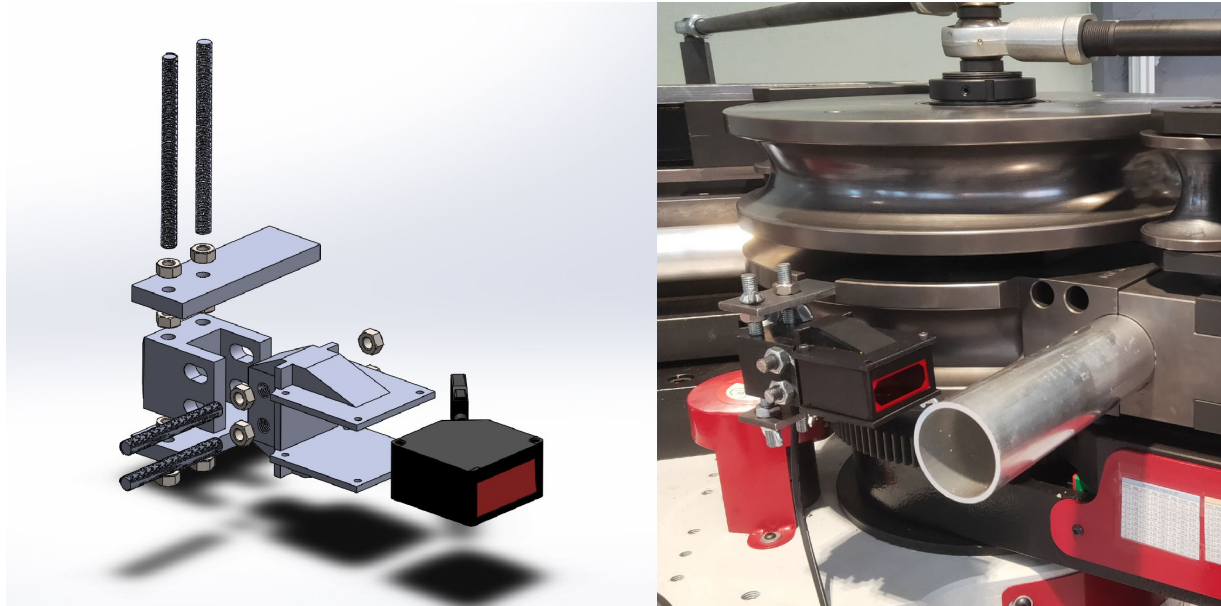


Figure 5. The fixture of sensor head and setting up on the machine.

3. Results and Discussion

3.1. Analysis of measurement accuracy

As described in Section 2, three groups of experiments with different bending angles: 15°, 45° and 90°, were carried out and five repeated tests were performed for each group. The measured distance after bending D_1 (before unloading), after releasing the claim clamp D_2 (after unloading), displacement and springback angle are shown in Table 1.

Table 1. Result of springback angle measurement and comparison with manual measurement.

Bending Angle (°)	15°					45°					90°					Average
No.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
D_1 (mm)	70.210	70.443	70.282	70.446	70.352	69.790	69.807	69.721	69.875	69.987	69.068	68.961	69.065	68.903	69.216	
D_2 (mm)	75.634	75.966	76.759	75.356	75.390	80.513	81.283	81.245	79.342	80.110	94.223	94.335	94.278	93.584	93.796	
d (mm)	5.424	5.523	6.477	4.910	5.038	10.723	11.476	11.524	9.467	10.123	25.155	25.374	25.213	24.681	24.580	
α_1 (°)	0.975	0.993	1.164	0.883	0.906	1.647	1.762	1.769	1.454	1.554	3.313	3.342	3.321	3.251	3.238	
α_m (°)	1.010	0.930	1.030	0.870	0.830	1.770	1.830	1.770	1.570	1.740	3.600	3.680	3.670	3.310	3.410	
δ (°)	-0.035	0.063	0.134	0.013	0.076	-0.123	-0.068	-0.001	-0.116	-0.186	-0.287	-0.338	-0.349	-0.059	-0.172	
$ \delta $ (°)	0.035	0.063	0.134	0.013	0.076	0.123	0.068	0.001	0.116	0.186	0.287	0.338	0.349	0.059	0.172	0.135
P (%)	3.456%	6.762%	13.043%	1.460%	9.122%	6.969%	3.713%	0.032%	7.405%	10.665%	7.961%	9.186%	9.511%	1.782%	5.052%	6.408%
σ_1 (°)	0.099					0.121					0.041					
σ_m (°)	0.077					0.088					0.148					

* D_1 : Laser-Measured Distance (During bending)

D_2 : Laser-Measured Distance (After releasing die)

σ_1 (°): Standard deviation of laser sensor measured springback angle (°)

σ_m (°): Standard deviation of manual measured springback angle (°)

$$\delta = \alpha_1 - \alpha_m$$

$$P = \frac{|\delta|}{\alpha_m} \times 100\% \text{ (%)}$$

Here, d is laser-measured displacement by the Eq. 1. α_l and α_m are the measured springback angle by laser and manual measurement, respectively, δ is the difference between them, $|\delta|$ is its absolute difference, P is the percentage of the absolute difference relative to manual measurement. D_1 is the lowest value of laser-measured distance during the bending process, which has a lower value for larger bending angles. The reason might be the higher pressure applied by the clamp when bending for a larger angle.

Fig. 6 shows a comparison of laser-measured springback and manual measurement springback. In general, as expected, the springback angle increases with the bending angle. At bending angles of 15° , 45° and 90° , the average springback angles measured by laser sensor are 0.98° , 1.64° , 3.29° , respectively, and the average springback angles of manual measurement are 0.93° , 1.74° , 3.53° respectively. The two methods only have an average deviation of 0.05° and 0.099° at the bending angle of 15° and 45° , while the average deviation at 90° is higher up to 0.241° .

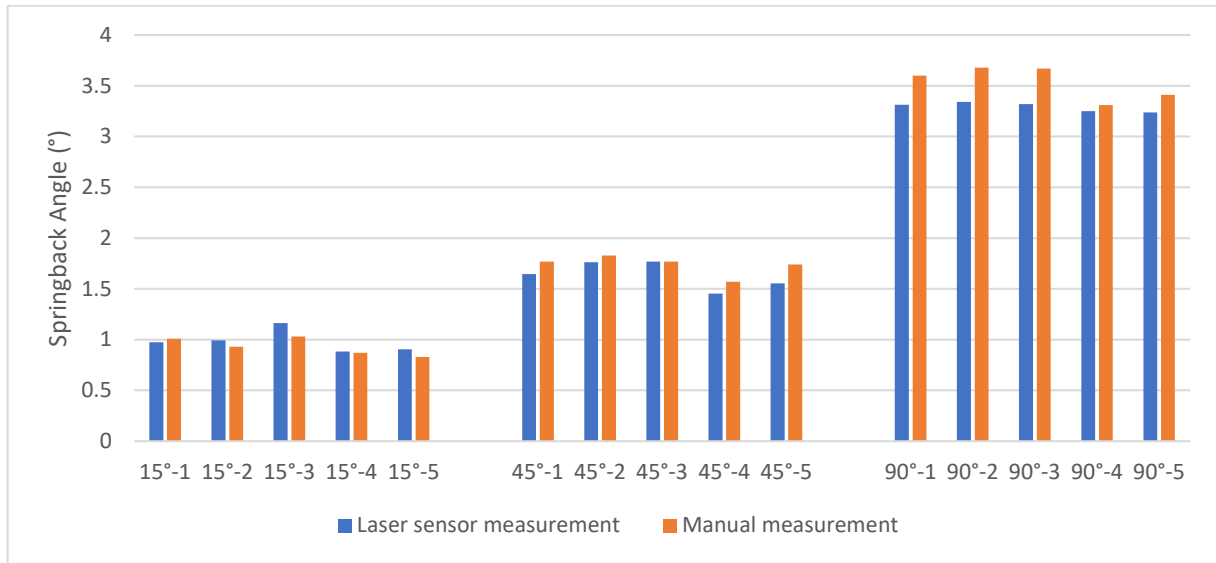


Figure 6. Springback of tube measured by laser sensor and manual measurement.

Compared with the manual measurement, the laser-measured angle is lower at the bending angle of 45° and 90° , and there are larger differences at the bending angle of 90° . The reason may be the systematical reading error in manual measurement and the manual measurement also shows worse consistency. However, the relative error at 90° is not significant, the largest relative error comes from the third sample of bending angle of 15° , reaching 13.04%, although a difference of 0.134° . In general, the average deviation rate is 6.41%, and the minimum is 0.03%.

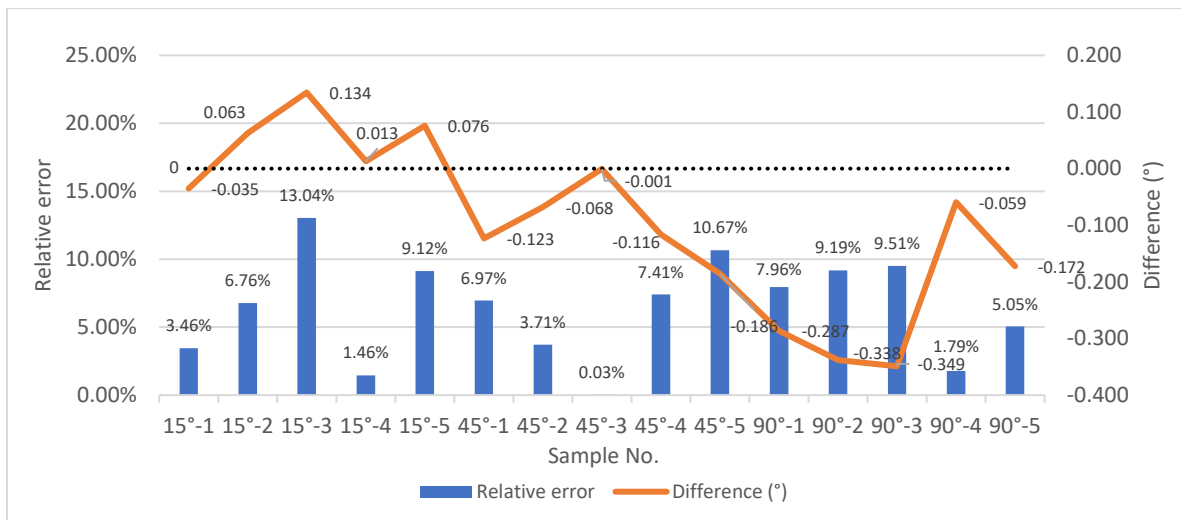


Figure 7. The difference and relative error of measured data.

At a bending angle of 45° , the two measurement methods showed better agreement in terms of relative error, while at 15° and 90° , the agreement is somewhat less and similar in average, as shown in Fig. 7. However, the consistency of the measurement results at 90° is high for the method of laser-measured method. The standard deviation for the samples the bending angle of 90° is 0.041° for the laser sensor. The lower data consistency is from the manual measurement at this bending angle, where the standard deviation is 0.148° . On the other hand, the standard deviation at 15° is smaller on average of the two methods, both of them are below 0.1° , which may be because the process at this smaller bending angle has better stability.

4. Conclusion

In this research, a laser-based method for springback measurement was developed and tested, allowing in-process monitoring of springback angle in industrial bending processes of tubes and profiles. Using rotary draw bending of aluminium tubes as a case study, this new measurement method was installed and validated. The validation under a wide range of bending angles (15° - 90°), shows that the laser-based measurements have good agreement with the results by the manual measurement method made in a fixture. The average absolute deviation and relative deviation between the two methods are 0.155° and 6.74%, respectively, showing that the laser-based method provides high capability and accuracy in springback measurement for the tube bending process considered herein.

The accuracy of measurement is expected to increase by more precise assumptions and calculations, error analyzing or/and new method development. Also, this in-situ measurement method is part of larger a project that facilitates the industry 4.0 of tube draw bending process for tubes and profiles. Since the developed laser sensor method measures the springback angle with no need to remove the part from the bending machine, future work will focus on improving the bending process by performing an instant compensation step according to the springback angle.

Acknowledgements

This project was funded by Department of Mechanical and Industrial Engineering at Norwegian University of Science and Technology (NTNU) and NTNU Aluminium Product Innovation Center (NAPIC).

References

- [1] Yang, H., Li, H., Zhang, Z.Y., Zhan, M., Liu, J. and Li, G. *Advances and Trends on Tube Bending Forming Technologies*. Chinese Journal of Aeronautics, 2012. **25**(1): p. 1-12.
- [2] Ma, J. and Welo, T., *Analytical springback assessment in flexible stretch bending of complex shapes*. International Journal of Machine Tools & Manufacture, 2021. **160**.
- [3] Cao, J., Brinksmeier, E., Fu, M., Gao, R.X., Liang, B., Merklein, M., Schmidt, M. and Yanagimoto, J. *Manufacturing of advanced smart tooling for metal forming*. Cirp Annals-Manufacturing Technology, 2019. **68**(2): p. 605-628.
- [4] Ha, T., Welo, T., Ringen, G. and Wang, J. *A strategy for on-machine springback measurement in rotary draw bending using digital image-based laser tracking*. International Journal of Advanced Manufacturing Technology, 2021.
- [5] Simonetto, E., Ghiotti, A. and Bruschi, S. *In-process measurement of springback in tube rotary draw bending*. The International Journal of Advanced Manufacturing Technology, 2021. **112**(9-10): p. 2485-2496.
- [6] Staupendahl, D., Chatti, S. and Tekkaya, A.E. *Closed-Loop Control Concept for Kinematic 3D-Profile Bending*. Proceedings of the 19th International Esaform Conference on Material Forming (Esaform 2016), 2016. **1769**.

- [7] Welo, T. and Granly, B. *A new adaptive bending method using closed loop feedback control*. Transactions of Nonferrous Metals Society of China, 2010. **20**(11): p. 2111-2117.
- [8] Borchmann, L., Frohn-Sørensen, P. and Engel, B. *In situ detection and control of wrinkle formation during rotary draw bending*. Procedia Manufacturing, 2020. **50**: p. 589-596.
- [9] Ha, T., Ma, J., Blindheim, J., Welo, T., Ringen, G. and Wang, J. *In-line springback measurement for tube bending using a laser system*, in *23rd International Conference on Material Forming (ESAFORM 2020)*. 2020. p. 766-773.
- [10] Borchmann, L., Heftrich, C. and Engel, B. *Influence of the stiffness of machine axes on the formation of wrinkles during rotary draw bending*. SN Applied Sciences, 2020. **2**(10).