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On-line Thickness Measurement System for the Metal Spinning Process

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Abstract. Spun-part wall thickness is a key output parameter of spinning products. Thickness affects the spun part strength: Low thickness leads to cracks on spinning products. Hence, it is crucial to measure and control wall thickness. However, thickness measurement and a control system for the spinning process are still offline methods. That is, these parameters must be measured after the spinning process is completed. In this method, the cross section of the spun part is cut, and the wall thickness is measured using a measurement tool. Thus, the measurement system is not applicable as online method. Hence, this study proposed the online thickness measurement method for the spun. Here, the mandrel-less spinning machine and a line laser measurement system were developed. The line laser measurement system, including two sets of line lasers and cameras, was attached on the spinning machine. Both sets of line lasers and cameras were used to measure the thickness profile of the spun part. The first set of a line laser and camera was used to capture the surface profile in the front of the spun part, while the other set was used to capture the surface profile behind the part. Then, the digital image processing (DIP) was estimated the spun thickness by using both images. In the experiments, the spun part was formed by the variation of degrees of angle and spinning distance. In each experiment, the spun-part thickness was measured by the cross-section method and line laser measurement method. Both results were compared and discussed. The result revealed that the thickness estimated by the line laser measurement system is similar to that estimated by the cross-section measurement method. An average error of 3.67% was obtained by the line laser measurement system.

Keywords: Digital image processing; Real-time thickness measurement; Sheet metal spinning

1. Introduction

Metal spinning is a conventional sheet metal formation process that utilizes a compression force between the roller (tool) and mandrel to form a blank sheet. A workpiece is formed under a compression force and bending force. This process exhibits advantages of flexibility, cost-effectiveness, and using simple tools. Owing to these reasons, it is still used widely in the sheet metal industry.

First, the spinning process is employed for the formation of a symmetrical metal sheet. A mandrel and roller are used in the spinning process. The mandrel is used to support a workpiece during the roller pressing over the workpiece. If the shape of the product is changed, the mandrel also must be changed. Hence, traditional spinning is not a flexible formation process. Several researchers have proposed the development of a non-symmetrical spinning process and mandrel-less spinning. Awiszus and Meyer. (2005) has

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employed spring-controlled rollers to control the tool path in non-symmetry spinning. In 2019, Hirohiko (2019) has developed a computer control system for the spinning process by using servo motors and force sensors to control the tool path in non-symmetry spinning.

1.1. Mandrel-less Spinning

In 1996, Kitazawa et al. (1996) have developed mandrel-less spinning to increase flexibility. A blank sheet was clamped to a blank holder without a mandrel. Next, the roller was moved to press the spun part. This method could be employed for the formation of a part without using a mandrel, but the blank sheet must be sufficiently strong for spinning. Shima et al. (1997) have developed two rollers for the spinning process, which were used for clamping and forming the part. In 2011, Music and Allwood (2011) have developed a flexible spinning method by using three sets of rollers: blending roller, support roller, and working roller. These rollers could form the part in the same manner as that performed by traditional spinning. In the above-described study, the spinning process can be employed to form an asymmetrical part without using a mandrel. In this study, an on-process thickness measurement system was developed and installed on a mandrel-less spinning machine as the measurement system needed to capture font and back images of the spun-part surface. Spinning using a mandrel cannot capture the back surface images of the workpiece because its surface is behind the mandrel.

1.2. Thickness Measurement Method for the Spun Part

The measurement method for the spun-part wall thickness involves the formation of a spun part and cutting of its cross section. Next, a measurement tool is used to measure the thickness of the cross section. This method has been employed by Avitzur and Yang (1960). These authors have drilled a blank sheet and plugged holes with the same material before spinning. Kalpakcioglu (1961) has employed the grid line method. Quigley and Monaghan (2000) have employed a surface etching method. They have etched a circular pattern on a blank sheet surface before spinning the blank sheet. Next, the blank sheet is used for spinning, and the spun part is cut and measured after the completion of the spinning process.

The spun-part wall thickness is a key parameter because thickness affects the strength of the part. However, all of the spun-part thickness measurement methods are offline methods, which cannot be applied for real-time monitoring. In this study, an online thickness measurement method for metal spinning is developed.

1.3. Sheet Metal Thickness Measurement Method

A laser displacement sensor is typically used for measuring the sheet metal thickness. In this method, two sets of laser displacement sensors are used (Figure 1a). The first set of sensors is used for the measurement of the distance from the sensor to the top sheet metal surface, while the other sensor is used for the measurement of the distance from the bottom sheet metal surface. Next, the sheet metal thickness is calculated by using both distances (Ancheng et al., 2014). As laser measurement is a non-contact method, it can be applied to on-line measurement. Saurabh et al. (2019) have used a laser sensor for the on-line measurement of the wire steel diameter. Laser sensors have been used to measure the thickness of a workpiece placed between the laser receiver and transmitter. In addition, a line laser can represent the workpiece profile; thus, it can be applied to measure the workpiece geometry. Noll and Krauhausen (2008) have developed an on-line system to measure the flatness of a steel-rolled product by using a laser sensor. On the other hand, laser sensors have been applied for various on-line measurement systems, including the detection of microcracks on a specimen surface (Andreas et al., 2018) and on-line measurement of a liquid droplet size (Emir et al., 2021).

Laser sensors are an on-line measurement method, which can be applied to closed-loop control systems. Malik and Grandhi (2009) have applied laser sensors for the flatness control of closed-loop rolled steel. Researchers have used flatness results to compare the flatness setpoint and data sent to the controller. If the flatness out of spec, the controller will adjust the process parameters. James and Julian (2014) have used line lasers to measure profiles of the metal-spun product, corresponding to real-time measurement. The results from the system were used as a feedback signal. Hence, these results are utilized to calculate the spinning toolpath for the purpose of reducing the spring back of the spun product.

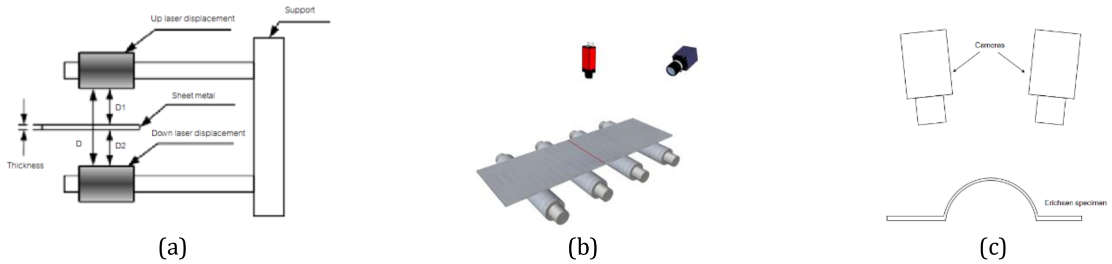


Figure 1 Application of a laser sensor for: (a) thickness measurement (Ancheng et al., 2014); (b) flatness measurement (Noll and Krauhausen 2008); and (c) the 3D DIC technique (Aydin et al., 2018)

Digital image correlation is another important technique for measuring stain and thickness in material testing applications. As a white-light speckle technique, DIC is a non-contact optical measurement technique that is based on the comparison of deformed and undeformed digital images. Aydin et al. (2018) have employed a 3D DIC method with the Erichsen cupping test (Figure 1c). The result show, DIC method can detect specimen cracks and measure thickness reduction during testing. However, this technique is more complicated, which is still only used in material testing applications (Quanjin et al., 2020).

In this study, line laser lighting was utilized for the measurement of the spun-part thickness. The principle of the line laser thickness measurement system was adapted from the laser displacement sensor system. This system used two sets of line lasers and cameras for capturing the spun-part surface profile. The first set was used to capture the inner surface, while the other set was used to capture the outer surface of the part. Then, image processing software was utilized to calculate the spun-part thickness. Line laser thickness measurement systems are advantageous as they are non-contact measurement systems. Therefore, such a system can be applied for on-process thickness measurement. However, this system can be used only for mandrel-less spinning, and the environment light also must be controlled when using this system. Limitations of this system are discussed in conclusions.

2. Methods

In this study, a mandrel-less spinning machine and a line laser thickness measurement system were constructed. The line laser thickness measurement system was installed on the spinning machine. The spun-part thickness was measured during the spinning process by using the line laser measurement system. After spinning was completed, the spun parts were cut into cross section, and the thickness of cross sections were measured by using vernier caliper. Finally, the thickness estimated by the line laser thickness measurement system and that measured from the spun-part cross section was compared.

2.1. *Spinning Experiment Setup*

The mandrel-less spinning machine was developed from a Mini CNC lathe machine. A general mandrel (cylinder mandrel) can be used for each spun part. In the experiments, the cone part was spun. The angle of the cone can be changed by adjusting the tool path of the lathe machine. The tool path was controlled by a computer program. The rollers were designed to follow a "spinning with 2 rollers" method. Two rollers were installed parallel to each other, which were used for forming and holding a blank sheet simultaneously. Figure 2 shows the spinning machine.

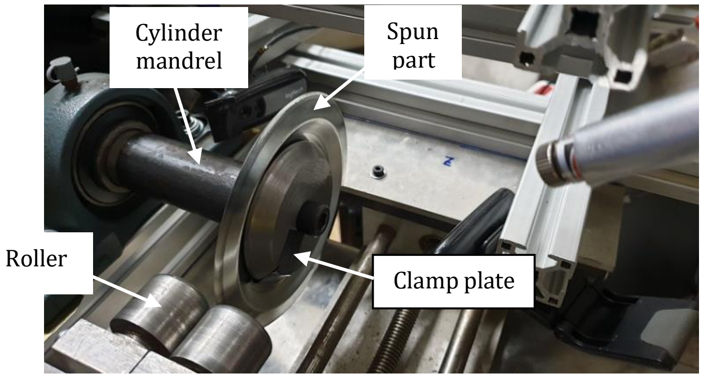


Figure 2 The mandrel-less spinning machine

The deep drawing quality cold rolled steels (SPCE) was used as the blank sheet material with a thickness of 0.65 mm and a diameter of 80 mm. Blank sheets were spun to a cone shape at 25, 35, and 45 degrees. The feed rate and spindle speed were 0.4 mm/round and 250 rpm, respectively. A blank sheet was formed on the spun part by moving the roller. The degree of angle (θ) was controlled by controlling the ratio of X and Z axis moving speed and moving distance (Figure 3). After spinning was completed, the cross section of the spun parts was cut, and the wall thickness was measured by using a digital vernier caliper (resolution = 0.001 mm.). These thickness results were compared with those obtained from the line laser thickness measurement in the "results and discussion" section.

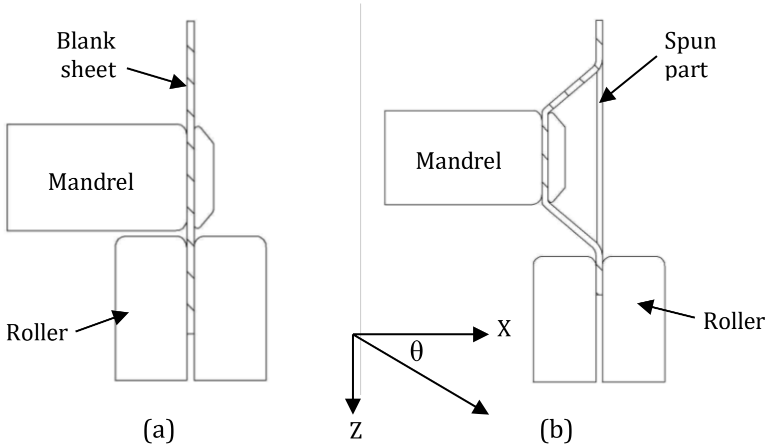


Figure 3 The roller moving from (a) initial state to (b) completion of the spinning process

2.2. *Setup of the Line Laser Thickness Measurement System*

The line laser thickness measurement system included hardware and digital image process program (DIP). The hardware included two sets of line lasers and cameras. The first set was used to capture the inner side of the spun part, while the other set was used to capture the outer side. Then, the images were transferred to DIP for the calculation of the spun-part thickness. Figure 4 shows the flow diagram.

2.2.1. Hardware

Figure 5a shows the schematic of the line laser thickness measurement method. The spun part was clamped to a general mandrel by using a clamp plate.

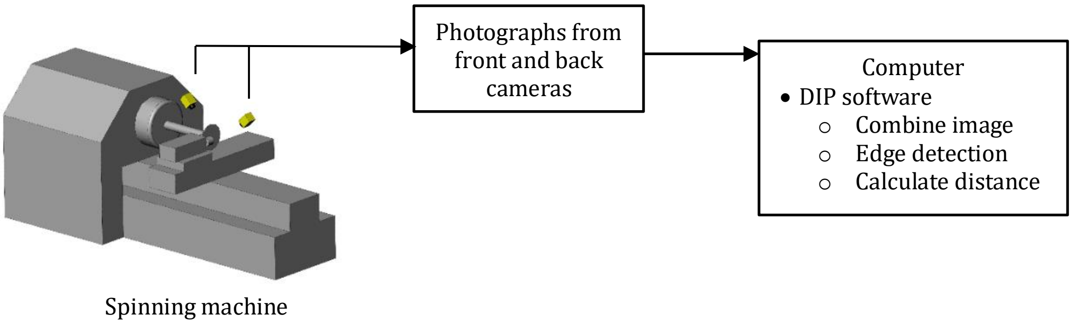


Figure 4 Schematic of the line laser thickness measurement method

The first set of laser and camera (line laser No.1 and camera No.1) was installed behind the part, while the second set of laser and camera (line laser No.2 and camera No.2) was installed in the front. During spinning, camera 1 and camera 2 were used to capture the front and back images, respectively. The images captured by cameras 1 and 2 were transferred to the DIP program.

Resolution of both cameras was 1280 × 1024 pixels. The front and back cameras were installed at the same distance from the workpiece. The line lasers were installed over the position of the cameras. In the first step, the cameras and lasers were set up by clamping the blank sheet to the mandrel, and the line lasers were switched on. The cameras were used to capture both of the line laser reflection images. The position and angle of the cameras and line lasers were adjusted until both of the line laser reflection images were parallel and also in the vertical direction.

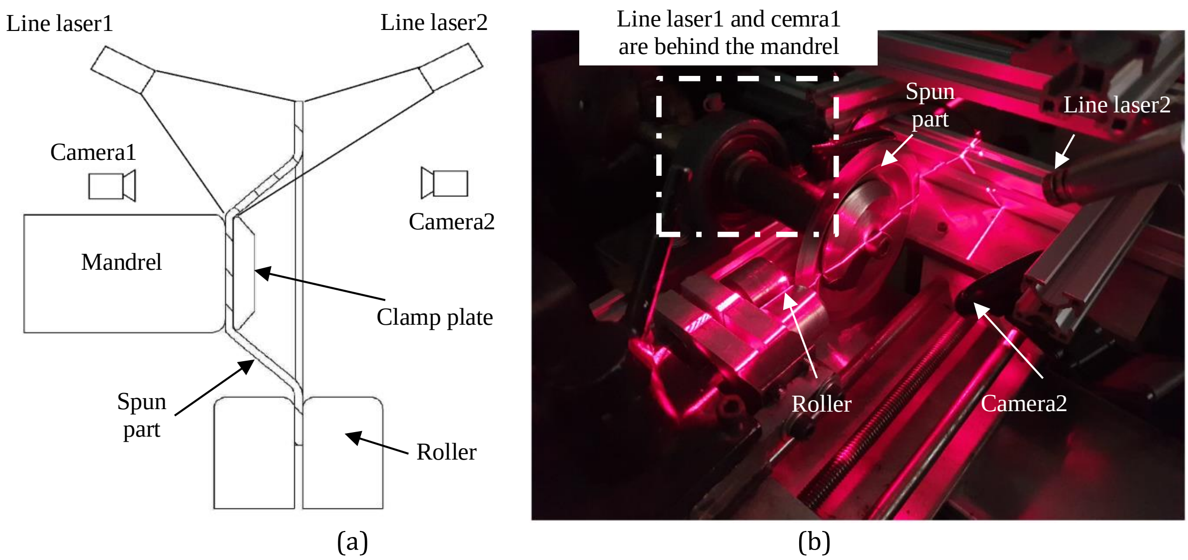


Figure 5 (a) Schematic of line laser thickness measurement method; and (b) the measurement system while the spinning machine was in operation

2.2.2. DIP program

The DIP program was employed to capture images from both cameras (front and back cameras) at a speed of 1 frame per second. As the processing time for the DIP program was 0.8–1 s, the capture speed was configured to cover the processing time. In the first step, the DIP program sent the capture command to both cameras simultaneously. Next, the DIP program combined both images, which was performed by the image addition function. The combined image had two light lines from the front- and back-line lasers. The light lines were reflected from spun-part surface so shape of light lines were as same as the spun-part surface profile. Next, the edge detection technique was utilized to find the front and back edges. The distances between both edges were calculated by using a mathematical method. The distance corresponded to the thickness of the spun part. The smaller distance between light lines corresponded to low thickness, while a larger distance between light lines corresponded to a higher thickness. Figure 6 shows the flow chart of the DIP program.

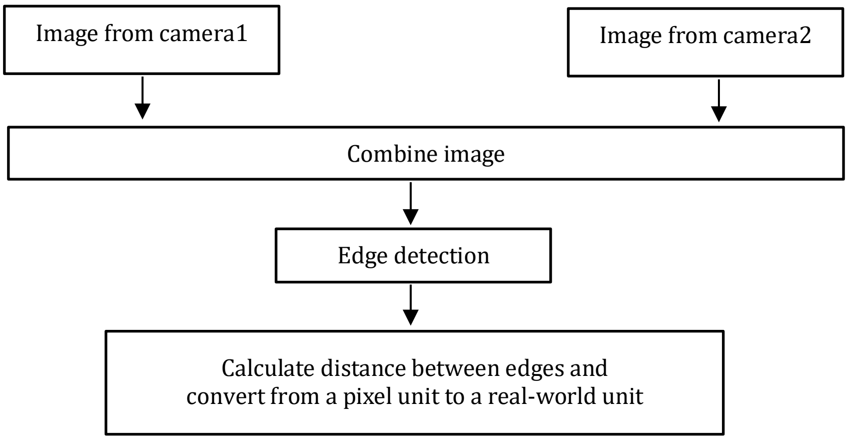


Figure 6 Flow chart of the DIP program

2.2.3. Combine image

The digital images from the front and back cameras were saved in the matrix format. The image addition function was utilized to combine both images. The pixels in both matrixes were directly added. Figure 7 shows the combined image. The combined images exhibit two light lines, one from the front camera and the other from the back camera.

The edge detection technique was employed to find the edge of light lines, which is frequently used for image processing. By assumption, an edge is an area with different intensities in the image. Thus, the edge detection method is the method to find the difference of intensity. The 1st-order derivative filter is used for the edge detection technique. In the digital image, the intensity gradient in the image is represented by the matrix format, and DIP uses the operation between the matrix method to solve the problem. The 1st-order derivative can be calculated by using the convolution matrix. The matrix is called a "kernel." The kernel for the 1st-order derivative technique is shown in Equation 1.

$$\frac{\partial f(x,y)}{\partial x} = \begin{bmatrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{bmatrix} \quad (1)$$

The edge detection method is a basic image processing technique, and an image processing library is included in this technique. In this study, an IMAQ library was used for the development of DIP software. IMAQ is an image processing library from the National Instrument Company, which provides the edge detection function. The function collects the intensity value along the search line. Next, a steep intensity gradient can be found by the function. Figure 8 shows the edge detection by using the IMAQ library.

The edge detection function returned the edge points along the search line. These edges were used for calculating the distance between lines. Figure 8b shows the result from the edge detection function. The result found four points per one search line. The distances between two light lines were represented by the distance between point no. 2 and no. 3.

The simple distance formula ($d = \sqrt{\Delta x^2 + \Delta y^2}$) was utilized to calculate the distance between points.

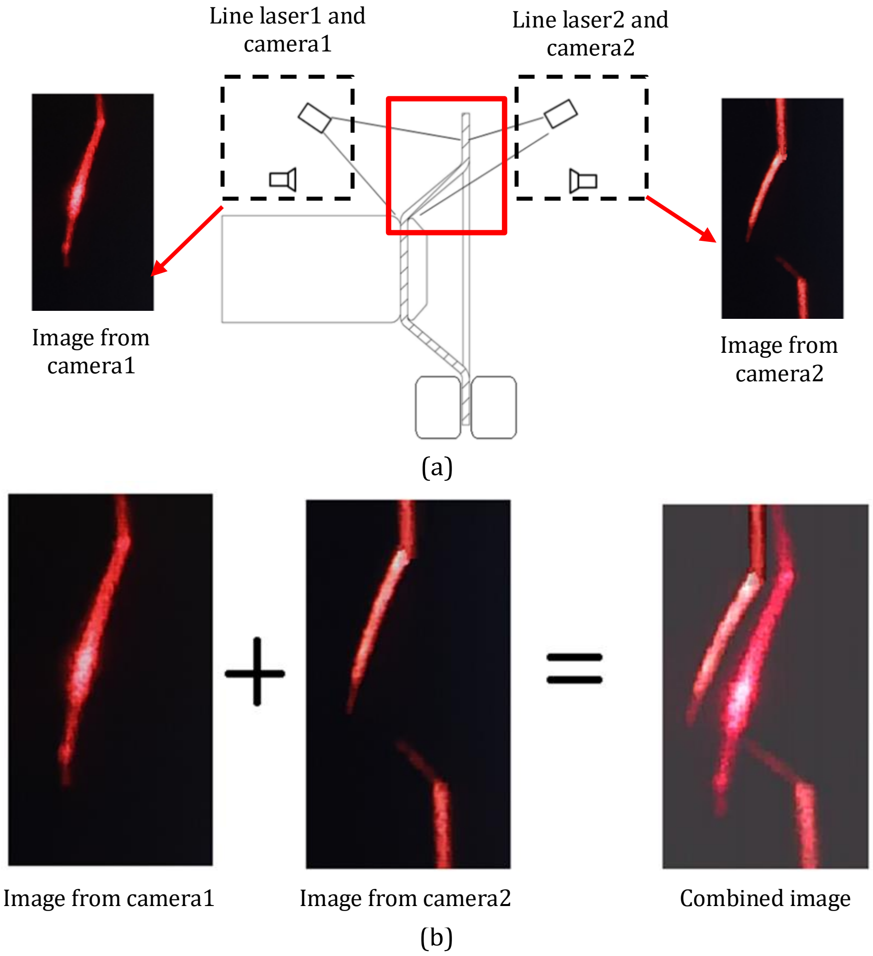


Figure 7 (a) Schematic of the camera installation; and (b) the combined image edge detection

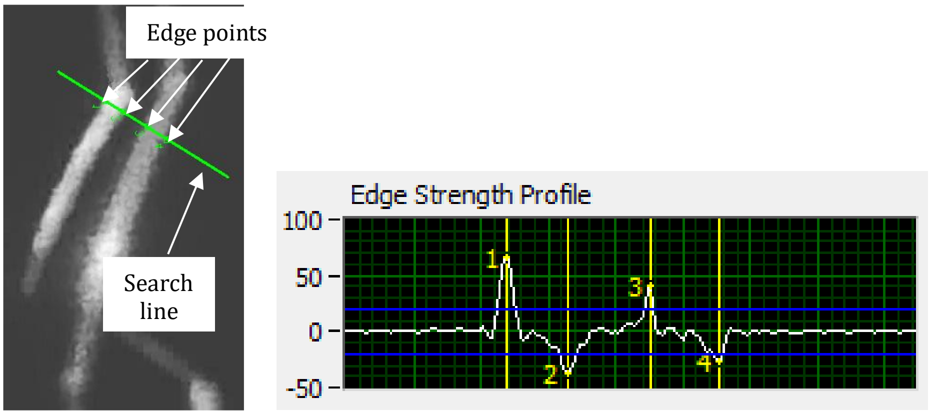


Figure 8 (a) Edge detection function; and (b) pixel intensity profile along the search line Calculate the distance between edges and convert it to a real-world unit

This distance was calculated in pixels. Then, the program was used to convert the distance from pixel to millimeters by using the camera calibration function.

3. Results and Discussion

Figure 9 shows the combined images, which can be separated into three regions: center of the part, forming area, and flange. At the center, the part was clamped by the clamp plate.

In this region, line light reflects the surface of the clamping plate. Thus, the line laser thickness measurement system cannot measure the thickness of the part in this area. At the forming area, the spun-part thickness was reduced by shear spinning. This forming area must be controlled, and the part thickness must be monitored. Hence, the system is designed to measure the part thickness of this area. In the flange region, the system can measure the part thickness. However, the thickness in this region did not change, corresponding to the blank sheet thickness.

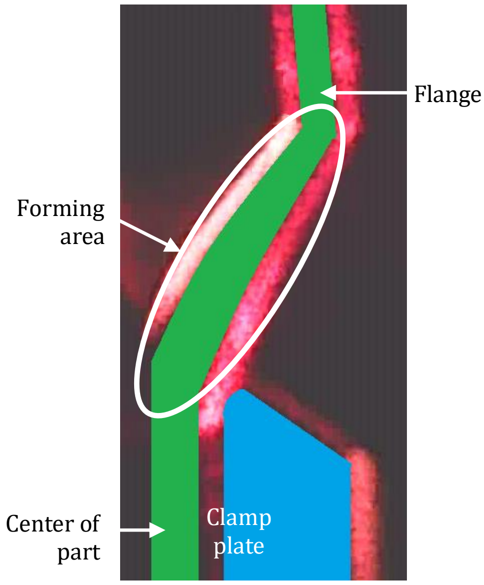


Figure 9 Detail of the combined image

The images were converted to grayscale images before processing by the edge detection function. The search line was created to find the edge point (Figure 8a). The angle of the search line corresponds to the degree of angle in the spinning process (θ). The experiment results are discussed in the next section.

3.1. Experiment Results

Figure 10 shows the spun-part cross section and image from the line laser thickness measurement system at different distances.

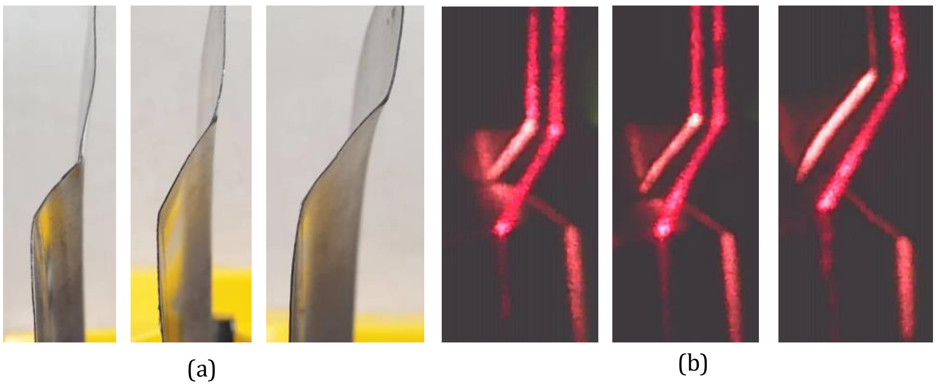
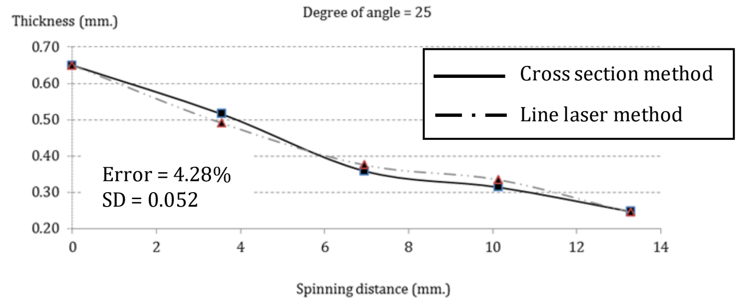
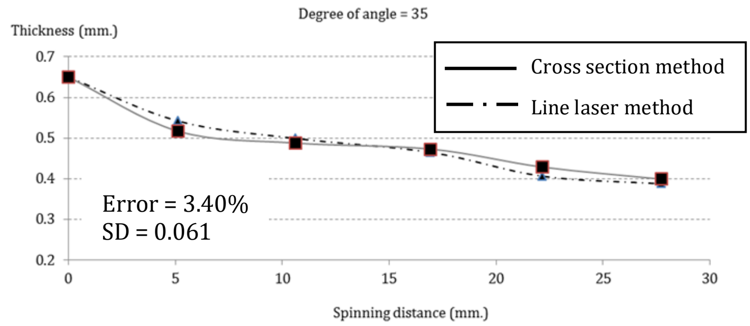


Figure 10 (a) Part cross section and (b) image from the line laser thickness measurement system

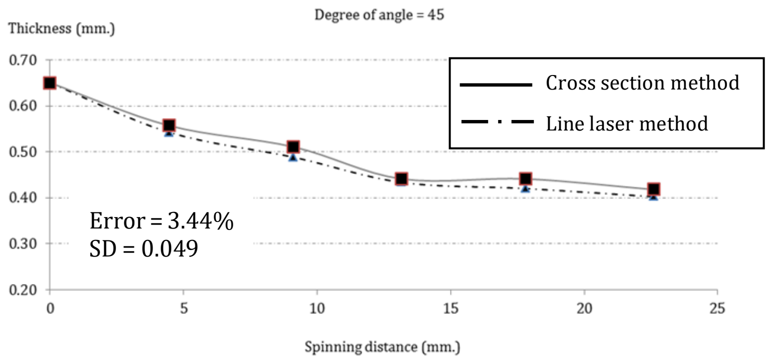
The experiments were spun at three degrees of angles: 25°, 35°, and 45°. All experiments were conducted in triplicate. Figure 11 shows the results.



(a)



(b)



(c)

Figure 11 Thickness result from θ: (a) 25 degree; (b) 35 degree; and (c) 45 degree

During the spinning process, the thickness was calculated by using the line laser thickness measurement system. The thickness was measured at 4–5 positions on each spun part. After the completion of each spinning process, the spun parts were cut, and the cross section at the same position was measured. Then, the thickness values were compared, and the part thickness values were plotted as a function of the spinning distance. The spun-parts thickness were decreased from 0.65 mm (the blank sheet thickness = 0.65 mm). The final thickness values for the parts at 25, 35, and 45 degrees are 0.247, 0.399, and 0.418 mm, respectively. A high degree of angle corresponds to a high thickness. Hence, these results are in agreement with the sine law ($t_1 = t_0 sin\theta$). The sine law method has been employed to calculate the wall thickness by shear spinning (O. Music et al., 2010). If the degree of angle (θ) is high, the final thickness (t_1) is also high. Thus, the result from the line laser thickness measurement is confirmed to be similar to that obtained from the sine law.

Figures 11a–11c shows the errors of the thickness values. The average errors corresponding to 25, 35, and 45 degrees are 4.28%, 3.40%, and 3.44%, respectively. These errors correspond to different values between the thickness values from the cross section method and those estimated from the line laser method. The standard deviation (SD) values for 25, 35, and 45 degree are 0.052, 0.061, and 0.049, respectively. The line laser thickness measurement system can apparently measure the wall thickness of the spun part with a total average error of 3.70%.

4. Conclusions

In this study, the line laser thickness measurement system is developed for the on-process measurement of the spun-part wall thickness. The advantages of this system are as follows: (1) This system is a non-contact measurement system. This method exhibits advantages of no measurement tool wear, high-speed measurement, and real-time measurement. Therefore, the thickness can be measured even during the spinning process; (2) This system is a real-time measurement system. Thus, it can be applied to a closed-loop control system. As part of future studies, the thickness results from this method will be used as feedback signal for the development of a real-time thickness control system. The real time thickness will be compared to the thickness setpoint. If the thickness is different from the setpoint, the thickness control system will adjust the spinning process parameters, such as tool path, spinning depth, and spinning speed; (3) In the other thickness measurement methods, the cross section of the workpiece must be cut, and the cross-section thickness must be measured. Hence, the workpiece is destroyed. However, there is no need to cut the workpiece using the line laser measurement system, and the workpiece can be used after measurement.

However, the disadvantages of the system are as follows: (1) Camera resolution affects accuracy and processing time. If a high-resolution camera is used, the accuracy will increase. However, the processing time also will increase. If this system is applied to the closed-loop control system, camera resolution needs to be optimized because the closed-loop control needs a suitable accuracy and a short processing time; (2) The precaution for this method is environment light. The vision system can be disturbed easily by the environment light. Light from other sources can affect the vision system; (3) During the experiment, the position of camera and lighting must be fixed. The camera movement and lighting lead to result errors; (4) This system can be used only with the mandrel-less spinning process because the line laser and camera cannot be installed to capture the inner side of the part for spinning by the mandrel process.

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References

Ancheng, X., Qingquan, X., Gong, C., Xifang, Z., Hua, Z., Xiaojun, L., 2014. Laser On-line Thickness Measurement Technology based on Judgment and Wavelet De-noising. *Sensors & Transducers*, Volume 168, pp. 137–141

Andreas, S., Gede B. S., Mitrayana, Waskito N., 2018. Surface Crack Detection with Low-Cost Photoacoustic Imaging System, *International Journal of Technology*, Volume 9(1), pp. 159–169

Avitzur, B., Yang, C.T., 1960. Analysis of Power Spinning of Cones. *Journal of Engineering for Industry–Transactions of the ASME (Series B)*, Volume 82, pp. 231–245

Awiszus, B., Meyer, F., 2005. Metal Spinning of Non-circular Hollow Parts. *In:* Proceedings of the 8th International Conference on Technology of Plasticity, Verona, Italy, pp. 353–355

Aydin, M., Wu, X., Cetinkaya, K., Yasar, M., Kadi, I., 2018. Application of Digital Image Correlation technique to Erichsen Cupping Test. *Engineering Science and Technology, an International Journal*, Volume 21(4), pp. 760–768

Emir, Y., Suzuki, T., Ito, K., Gabriel, J., Anggono, W.G., Ichiyanagi, M., 2021. Analysis of the Spray Characteristics of Water and Water/Glycerin Mixtures using an Interferometric Laser Imaging for Droplet Sizing Technique. *International Journal of Technology*, Volume 12(1), pp. 101–112

Hayama, M., Murota, T., Kudo, H., 1965. Experimental Study of Shear Spinning. *Bulletin of JSME*, Volume 8(31), pp. 453–460

Hirohiko, A., 2006. Force-controlled Metal Spinning Machine using Linear Motors. *In:* Proceedings of the 2006 IEEE International Conference on Robotics and Automation Orlando, pp. 4031–4036

Hirohiko, A., 2019. Noncircular Tube Spinning based on Three-Dimensional CAD Model. *International Journal of Machine Tools and Manufacture*, Volume 144, pp. 1–9

James A.P., Julian M.A., 2014. Support Roller Control and Springback Compensation in Flexible Spinning, *Procedia Engineering,* Volume 81, pp. 2499–2504

Kalpakcioglu, S., 1961. On the Mechanics of Shear Pinning. *Journal of Engineering for Industry–Transactions of the ASME*, Volume 83(2), pp. 125–130

Kitazawa, K., Wakabyashi, A., Murata, K., Yaejima, K., 1996. Metal Flow Phenomena in Computerized Numerically Controlled Incremental Stretch-Expanding of Aluminum Sheets. *Japan Institute of Light Metals*, Volume 46(2), pp. 65–70

Malik, A.S., Grandhi, R.V., 2009. Recent Developments in Strip-Profile Calculation. *In:* Flat-Rolled Steel Processes. *Advanced Technologies*, pp. 329–339

Molleda, J., Usamentiaga, R., Garcia, D.F., 2013. On-Line Flatness Measurement in the Steelmaking Industry. *Sensors*, Volume 13(8), pp. 10245–10272

Music, O., Allwood, J.M., Kawai., K., 2010. A Review of the Mechanics of Metal Spinning. *Journal of Materials Processing Technology*, Volume 210, pp. 3–23

Music, O., Allwood., J.M., 2011. Flexible Asymmetric Spinning. *CIRP Annals - Manufacturing Technology*, Volume 60(1), pp. 319–322

Noll, R., Krauhausen, M., 2008. Online Laser Measurement Technology for Rolled Products. Ironmaking and Steelmaking, Volume 35(3), pp. 221–227

Polyblank, J.A., Allwood, J.M., 2014. Support Roller Control and Springback Compensation in Flexible Spinning. *Procedia Engineering*, Volume 81, pp. 2499–2504

Quanjin, M., Rejab, M.R.M., Halim, Q., Merzuki, M.N.M., Darus, M.A.H., 2020. Experimental Investigation of the Tensile Test using Digital Image Correlation (DIC) Method. *Materials Today Proceedings*, Volume 27(2), pp. 757–763

Quigley, E. , Monaghan, J., 2000. Metal Forming: An Analysis of Spinning Processes. *Journal of Materials Processing Technology*, Volume 103, pp. 114–119

Saurabh., Kundu, C., Ranjan, R., Kumar, J., Patra, P., 2019. Real Time Online Profile Measurement System for Steel Wire Products. *Diagnostyka*, Volume 20(4), pp. 27–35

Setiawan, A., Bayu, G., Mitrayana, S., Nugroho, W., 2018. Surface Crack Detection with a Low-cost Photoacoustic Imaging System. *International Journal of Technology*, Volume 9(1), pp. 159–169

Shima, S., Kotera, H., Murakami, H., 1997. Development of Flexible Spin-Forming Method. *Journal of the Japan Society for Technology of Plasticity*, Volume 38, pp. 814–818

Wong, C.C., Lin, T.A.J., 2003. A Review of Spinning, Shear Forming and Flow Forming Processes. *International Journal of Machine Tools & Manufacture*, Volume 43(14), pp. 1419–1435