International Journal of Precision Engineering and Manufacturing
https://doi.org/10.1007/s12541-020-00352-6

Online ISSN 2005-4602
Print ISSN 2234-7593

REGULAR PAPER

Study on the Formability of Magnesium Alloy Sheets in the Incremental Forming Process with External Heating Sources

Chang-Whan Lee[1] · Dong-Yol Yang[2]

Received: 29 October 2019 / Revised: 13 April 2020 / Accepted: 16 April 2020

Abstract
Magnesium alloy sheets have low formability at room temperature due to their hexagonal closed-packed microstructures. In order to increase the formability of magnesium alloy sheets (AZ31) and fabricate a complex geometry, an incremental forming process with external heat sources such as the near-infrared heater and heated tools can be employed. Cylindrical cup shapes and Pyramidal cup shapes with various angles were fabricated to find out the formability limits. The maximum formable angle of the cylindrical cup shape increased from 20° at the room temperature to 72° by employing the incremental forming process using two external heat sources. It means that the temperature of AZ31 was increased to a proper forming temperature very efficiently.

Keywords Incremental forming · Magnesium alloy sheet · Near-infrared lamp

1 Introduction

A magnesium alloy has excellent mechanical properties, usually attributed to high specific strength [1, 2]. An application of magnesium alloy sheets is increasing in industries such as in transportation equipment for automobiles, airplanes, and general machines [3]. However, a magnesium alloy sheet has low formability at room temperature due to its hexagonal closed-packed (HCP) microstructure. A magnesium alloy sheet is not suitable for the sheet metal forming process in room temperature. Figure 1 shows the engineering stress and engineering strain curves of the specimen used in this work [4]. As the temperature increases, the elongation of the material increases, and at the same time, the flow stress of the material decreases. Compared with the room temperature, the elongation of the material at 250 °C increased 2.7 times. Also, the material shows isotropic behavior.

There have been numerous researches on the warm forming of magnesium alloy sheets [5]. It was found that warm forming with a temperature of approximately 250 °C maximized the formability of a magnesium alloy sheet (AZ31). Zhang et al. [6] analyzed warm deep drawing experiments of rolled magnesium alloy sheets. Zhang et al. [7] evaluated the limit drawing ratio (LDR) and limit dome height (LDH), which is the formability measurement in the drawing process, at temperatures from 50 to 240 °C. Wang et al. [8] studied the evolution of springback and neutral layers of magnesium alloy sheets concerning temperature. Park and Kwon [9] manufactured a lightweight dash panel part using AZ31 by the increasing working temperature around 250 °C.

The incremental forming process of the sheet metal is one of the emerging forming technologies which can offer flexibility [10, 11]. In the incremental forming process shown in Fig. 2, as the tool moves along a certain path, very small plastic deformation occurs. The final target shape can be formed by moving the tool according to the shape to be manufactured. The incremental forming process does not require a specific die set according to the target shape, and thus it is utilized in the manufacturing of various products required in small quantities. The forming limit of the incremental forming process is higher than that of the other sheet metal forming processes.

Ambrogio et al. [12] and Kim et al. [13] investigated the formability of AZ31 in a warm incremental forming process. The formability of AZ31 magnesium alloy increased dramatically in warm forming conditions near 250 °C.

✉ Chang-Whan Lee
cwlee@seoultech.ac.kr

1 Department of Mechanical System Design Engineering, Seoul National University of Science and Technology, Seoul, South Korea

2 Department of Mechanical Engineering, KAIST, Daejeon, South Korea

Published online: 13 May 2020

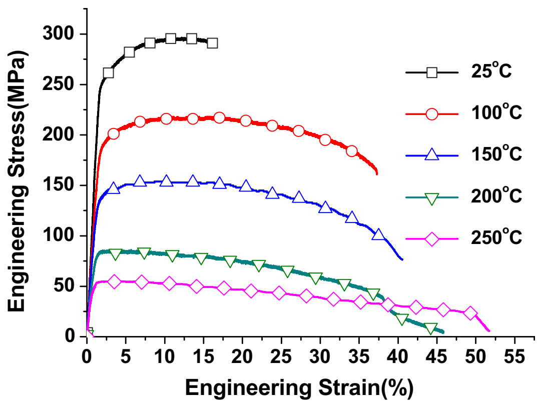

Fig. 1 Engineering stress-engineering strain curve of AZ31 sheets [4]

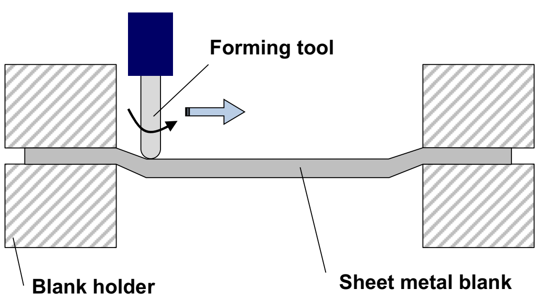

Fig. 2 Incremental forming process of a sheet metal

Previous warm forming processes heated the die-set and the sheet metal. The warm forming process requires more energy than heating the sheet metal only. Therefore, the problem can be solved by using an external heat source, which can be used to heat the material reliably. Duflou et al. [14] developed the laser-assisted incremental forming process. By using a laser at the opposite side of the tool, the formability and dimensional accuracy were increased. Fan et al. [15] and Ambrogio et al. [16] studied a low-cost incremental forming technique, employing an electric current to heat the sheet metal. Lee et al. [4] proposed a new incremental forming process using external heating sources. Two types of external heating sources, such as a near-infrared (NIR) heater and the heated tool were employed in order to increase the temperature locally. They presented the possibility of the incremental forming process with external heating sources. However, detailed researches were not studied.

In this work, the incremental forming process using two external heating sources is investigated experimentally. In addition, the effect of the external heating sources and forming limits of AZ31 is studied through the fabrication of cup shapes having various angles. The macroscopic observation was conducted to find out the formability improvement.

2 Experimental Setup

A NIR heater is a low-cost heating device compared to the other heating devices such as a laser or an induction heating [17]. The maximum temperature of the NIR heater is 900 °C, and the efficiency is nearly 90%. It is non-toxic, lead-free, odorless, noiseless and can be installed easily with other forming tools. Unlike other heating sources, more than 90% of the heat is transferred by radiation. An LCB-50 (Inflidge Industrial Ltd.) was employed. The maximum power of the NIR heater was 75 W. The distance between the NIR heater and the sheet was 35 mm, which is the focal distance. The condensed diameter of the light was 2 mm.

The heating of the tool uses high-frequency induction heating, to locally raise the temperature of the tool without affecting the surroundings. The heated tool locally raises the temperature of the material by conduction in the area in contact with materials.

Experimental equipment with two external heat sources was constructed as shown in Fig. 3. The three-dimensional position of the spindle was fixed. The spindle was connected to a DC motor. The maximum rotation speed of the spindle is 5000 rpm. The material is connected to a sheet holder. The sheet holder is movable in the x, y, and z directions. The advantage of fixing the tool in a three-dimensional position is that it is not necessary to move the tool and the external heating sources simultaneously. Because the tool is fixed, the NIR heater can always be locally heated to the point where deformation occurs by placing it directly underneath the material-tool contact.

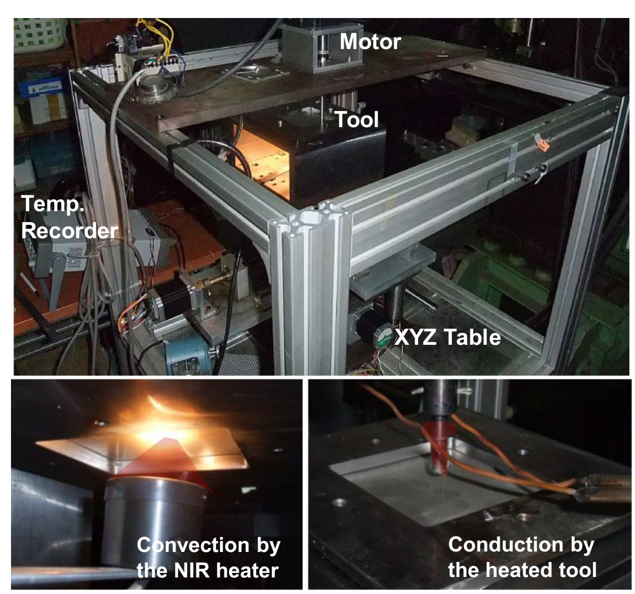

Fig. 3 Experimental setup of the incremental forming process and two external heating sources

The movement speed of the holder was fixed at 400 mm/min. The revolution speed of the tool was 200 rev/min. The pitch in the z-axis in one cycle was 0.5 mm. The process variables, such as the rotation speed, the tool speed, and the step size in the z-direction (Δz) has large effects on the formability and surface quality [11]. The pitch in the z-axis has large impact on the surface roughness. Small pitch in the z-axis, small size of the tool and slow moving speed of the tool reduce surface roughness. In The objective of this work is to study the feasibility of the incremental forming process with external heating sources. Therefore, the process variables such as rotation speed, step size, and the tool speed were fixed with above values.

Three DC motors controlled the movement of the sheet holder. The G-code for the three-axis table was generated using a MATLAB program with the desired tool path. Two examples of tool paths are shown in Fig. 4. The tool path was generated with a spiral tool path instead of a contour tool path because the spiral tool path results in a smooth surface of the final products [11, 18].

3 Experimental Results

3.1 Effects of the NIR Heater

In previous works, it was found that the deformation in the incremental forming process is mainly shear deformation, and follows the sine rule [19]. Instead of LDH and LDR, the maximum forming angle of the cup was used as a measure of formability. As the angle of the cup (θ) increases, the plastic strain in the wall angle increases. In the incremental forming process of the cup shape, the angle of the cup shape represents the formability of the material. If the cup angle is high, large plastic deformation occurs.

The effects of the NIR heat were studied. Figure 5 presents the temperature distribution when the NIR heater was placed in the center. The temperature was measured with the thermal camera (NEC Thermo Tracer). The maximum temperature was 160.9 °C.

In order to investigate the effect of the external heating sources, the incremental forming process without external

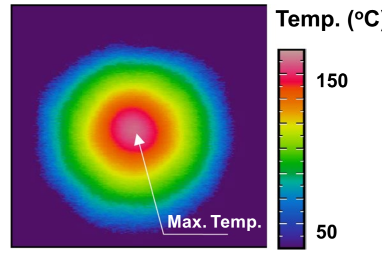

Fig. 5 Temperature distribution of the AZ31 sheet with the NIR heater

heating sources was performed. The cup shape with various angles were tested. The diameter of the cylindrical cup shape was 60 mm. In the forming process without external heating sources, the cylindrical cup shape with the angle (θ) of 20° was fabricated. However, there was a fracture in the forming of the angle of 25°. Figure 6 presents the fractured surface of the cylindrical cup shape with the angle of 25°. Without any heating sources, the formability of AZ31 is too low.

Figure 7 presents the experimental results of the incremental forming process with the NIR heater. The cup shapes with angles (θ) of 30°, 37.5°, and 45° were fabricated. When the NIR heater was employed, the maximum forming angle of the cup was 45°. The radius of the base circle was 42 mm. By employing the external heating source, the maximum formable cup angle was increased from 20° to 45°. It means that the formability increased due to the increase in temperature with the NIR heater.

However, some problems were observed on the surface. As the angle of the cup shape increases, microcracks occurred on the surface in the transverse direction. On surface A, the surface was very clear. However, on surface B, microcracks can be observed. On the surface C, as shown in Fig. 7f, the cracks occurred along the rolling direction (R/D) on the surface of the material. These cracks on the surface mean the low formability of the material, and that the sheet was not heated sufficiently for the forming process. Therefore, it is necessary to raise the temperature of the tool to increase the local temperature of the material further.

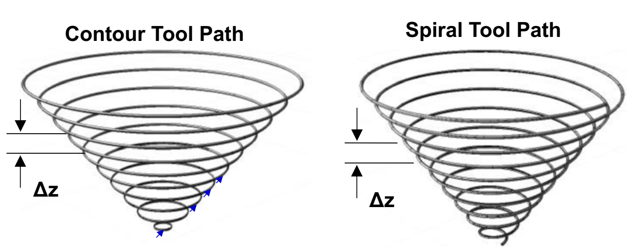

Fig. 4 Tool path for the incremental forming

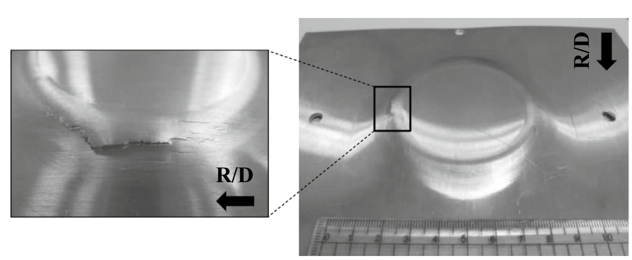

Fig. 6 Fractured surface of the cylindrical cup shape with the angle of 25°

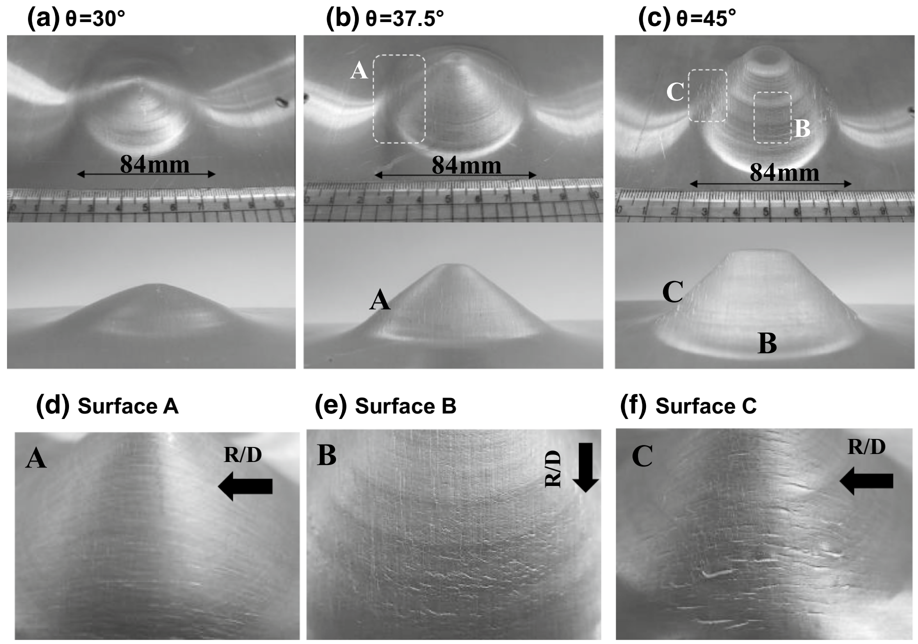

Fig.7 Experimental results of the incremental forming process using NIR heater

3.2 Effects of the Heated Tool

In order to investigate the effect of the heated tool, a pyramidal geometry with an angle of 45° was formed. The size of the pyramid was 60 mm × 60 mm × 25 mm. Three cases were compared: (1) the pyramidal shape was fabricated with the NIR heater only, (2) the pyramidal shape was fabricated with the heated tool, (3) the pyramidal shape was fabricated with both heating methods. The tool temperature was controlled to 300 °C using a thermocouple. The NIR heater was operated at maximum power (75 W).

Figure 8a presents the experimental results with the NIR heater. The height of the products when the fracture occurs (h_f) is 8.4 mm. Figure 8b presents the experimental result with the heated tool. The height of the products when the fracture occurs (h_f) is 9.4 mm. In both cases, the fracture occurs along the rolling direction. When the individual heater was used in the incremental forming process, although the sheet was heated, it was not enough to increase the formability of the AZ31 sheet.

The maximum forming angle of the cup shape using the NIR heater was only 45°. However, it was not possible to form a pyramidal shape with an angle of 45°, as shown in Fig. 8a. However, for the pyramidal shape, the tool path was a rectangular shape. In order to form a pyramidal shape, the tool moves along the transverse direction after the rolling direction, in turn. In the forming process of the pyramidal shape, the crack occurs along the rolling direction. Because of the geometric constraint of the circular shape, the formability of the material was increased.

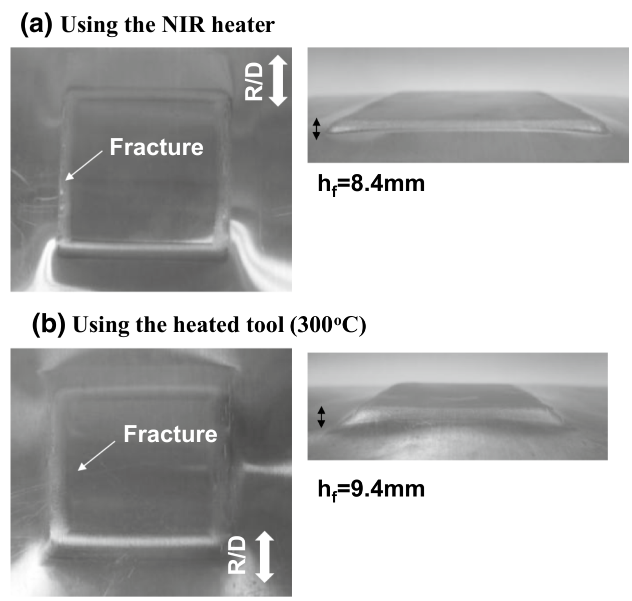

Fig. 8 Experimental results of cup shape, **a** using the NIR heater only, and **b** using the heated tool only

3.3 Incremental Forming Process Using Two External Heat Sources

In order to increase the formability, the two external heated tools (the NIR heater and the heated tool) were employed at the same time. The temperature of the sheet shown in Fig. 9 was measured with the thermal camera in the forming process of the cup shape. Due to some noises, external heating sources were turned off. The maximum temperature occurred at the contact point between the tool and the sheet.

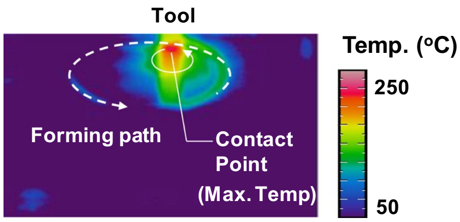

Fig. 9 Temperature distribution with two external heat sources

The value was over 250 °C, which is the recommended forming temperature for AZ31.

Figure 10 shows the experimental results when two external heated sources were used. The size of the pyramidal shape was the same as in the previous experiments. A pyramidal shape with an angle of 45° was fabricated without any defects. On the surface of the products, there were no microcracks.

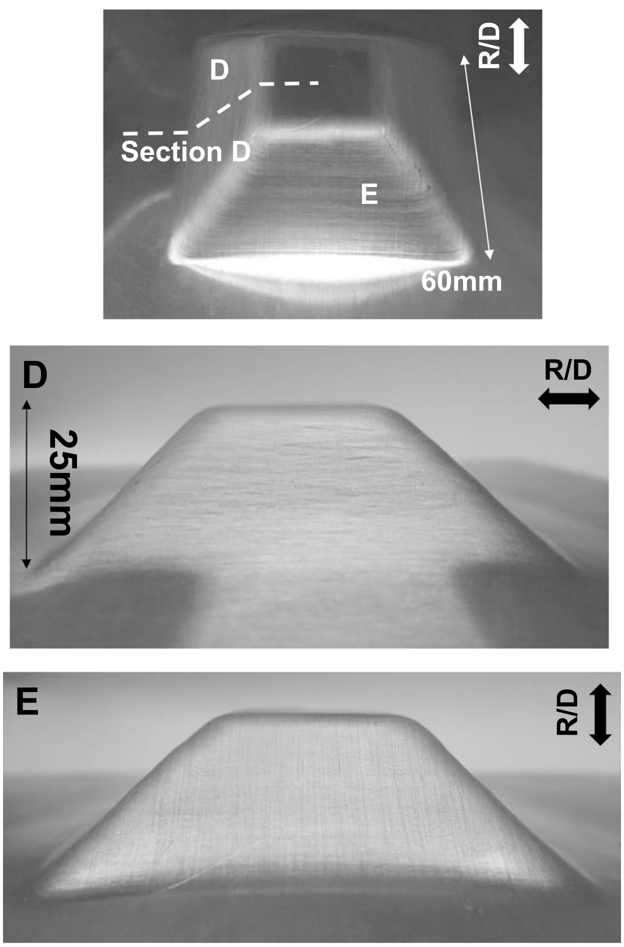

Fig. 10 Experimental result of the pyramidal shape (45°) using two external heating sources

Figure 11 displays the sectional view of the formed products. The initial thickness of the sheet is 1 mm, the minimum thickness of the products is 0.65 mm, and the angle of the wall is 45°. At the slope of the pyramidal shape, the thickness distribution was significantly small. The strain can be calculated from the thickness ratio. When t_f is the thickness after the forming process and the t_0 is the initial thickness, the strain is $\ln(t_0/t_f)$. In this case, the strain is 0.43. In addition, the thickness of the sheet after the incremental forming process can be predicted using the sine law, as shown in Eq. (1). The predicted wall thickness was 0.707 mm. The difference between the predicted value and the measured value was very small.

$$t_f = t_0 \sin(90 - \theta) \tag{1}$$

However, the shape had some defects. In this experiment, the die was not used. The working area of the sheet was 100 mm × 100 mm, and the size of the pyramidal shape was 60 mm × 60 mm × 25 mm. The size of the pyramidal shape was smaller than the size of the working area. Due to the bending of the sheets, unwanted deformation occurred. In order to reduce the unwanted bending deformation in the sheet, a die shape corresponding to the desired shape was required.

Furthermore, it was found that when the conduction and radiation are simultaneously employed to heat the sheet, the cup shape could be formed with an angle of 60° or more. As shown in Fig. 11, the cup shape can be formed without cracks. The surface roughness was also significantly reduced compared with the case where the heated tool was not used. Section F in Fig. 11 shows the surface of the transverse direction. The surface roughness in section F in Fig. 11 is slightly higher than the surface roughness in the section G in Fig. 12.

The sectional view of section F and section G is presented in Fig. 13. Section F, which has a higher surface roughness, shows the smaller thickness. The original thickness of the material was 1 mm. The minimum thicknesses for sections

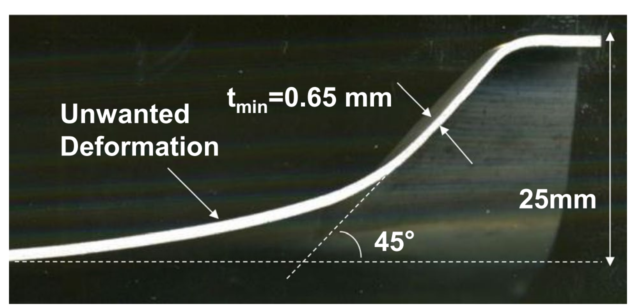

Fig. 11 Sectional view of the pyramidal shape (45°) along section D

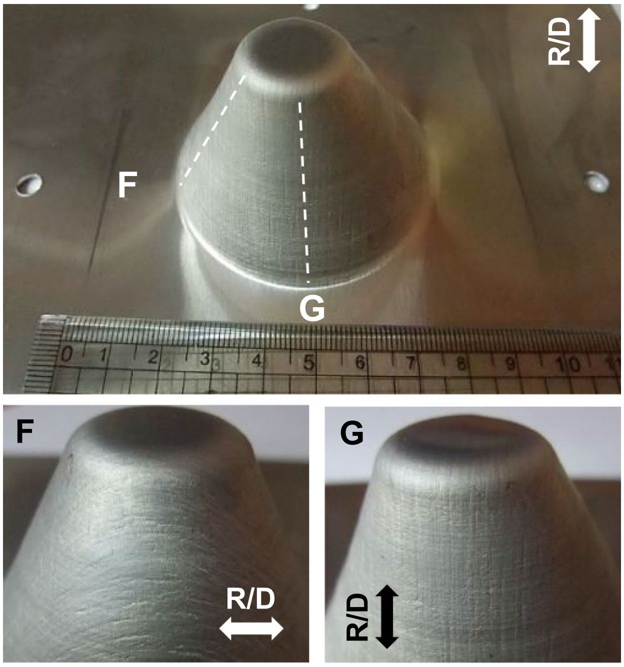

Fig. 12 Experimental result of the cup shape (60°) using two external heating sources

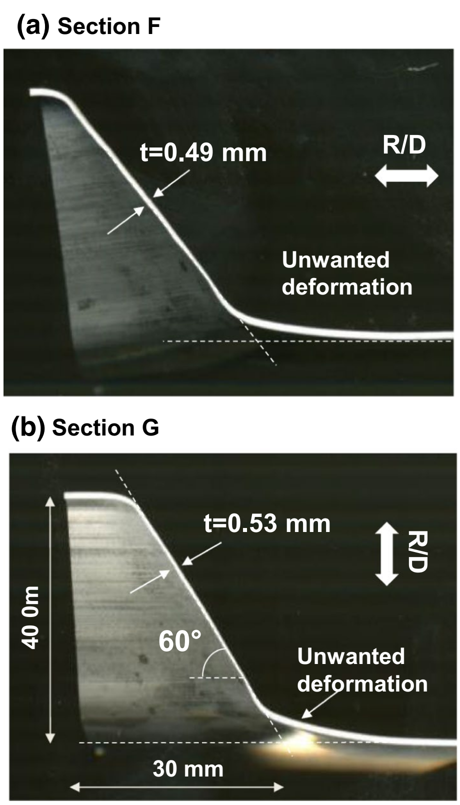

Fig. 13 Sectional view of the cup shape (60°), **a** Section F and **b** Section G

F and G were 0.49 mm and 0.52 mm, respectively. There were some differences in the minimum thickness between the section F and the section G. Due to the process asymmetry and anisotropic properties of the material, thickness changes resulted. The predicted wall thickness from the sine was 0.5 mm; the average value of the thickness from experimental results was almost the same. The difference in the predicted value and the average value was 0.01 mm, which is 1% of the initial thickness.

In both sections, the unwanted deformation occurs. The working area of the sheet was 100 mm × 100 mm. The size of the cup shape was 60 mm in diameter and 40 mm in height. Due to the small size of the products, unwanted bending deformation occurred. In sections F and G, unwanted deformation was observed. The amount of the unwanted deformation of the cup shape was smaller than that of the pyramidal shape because the cup shape gives a geometric constraint to the products.

3.4 Incremental Forming Process for Maximum Forming Angle

An experiment with varying cup angle was conducted with two external heat sources. The geometry of the section is shown in Fig. 14. The tool path was generated using Eq. (2). In this experiment, θ_i was 30°, r_i was 43 mm, α was 1.2, and Δz was 0.05 m. Figure 15 shows the experimental results. The diameter of the base circle was 86 mm. The final height of the product was 34.4 mm, and the final slope of the product was 72°. At this point, the fracture occurred on I along the rolling direction as shown in Fig. 15.

$$z_n = z_{n-1} + \Delta z,\ \ \theta_n = \theta_{n-1} + \alpha \Delta z,\ \ r_n = r_{n-1} - \frac{\Delta z}{tan(\theta_n)} \tag{2}$$

Figure 16 shows the sectional view along section H. Figure 17 shows the distribution of the thickness of the predicted results and measured results with respect to the radius. As the angle of the cup shape increases, the thickness

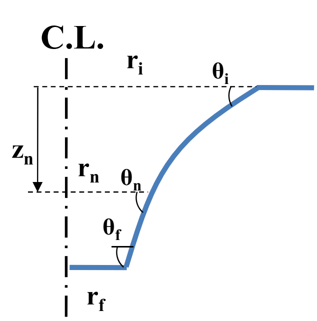

Fig. 14 Sectional geometry of the cup shape with varying angles

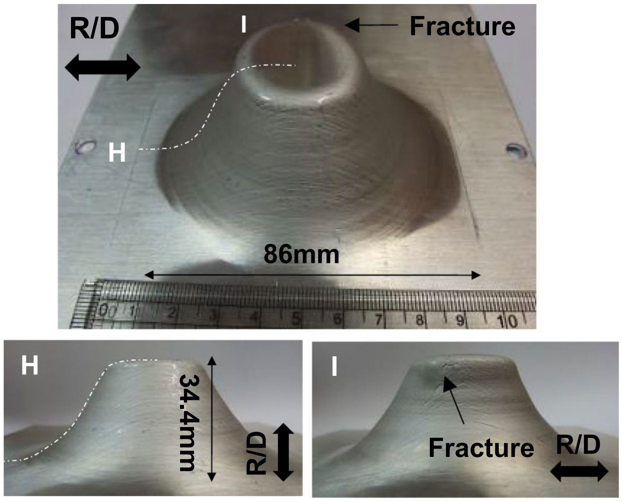

Fig. 15 Experimental result of cup shape with varying angles using two external heating sources

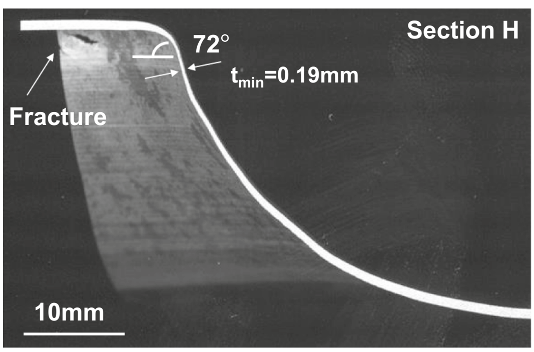

Fig. 16 Sectional view of the cup shape with varying angles at section H

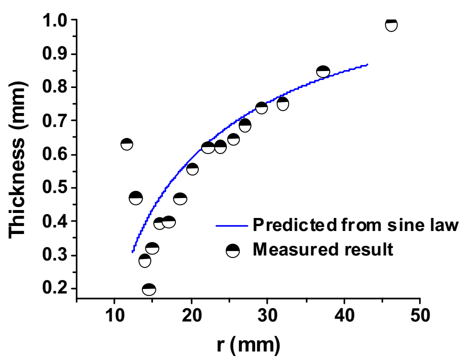

Fig. 17 Thickness distribution with respect to the radius (r)

of the wall decreases. In the normal direction of the fracture surface, the minimum thickness is 0.19 mm. At this point, the fracture strain is $\ln(t/t_{min}) = 1.66$. By using two external

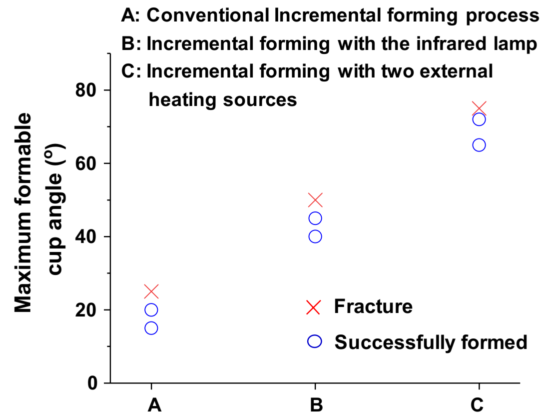

Fig. 18 Maximum formable cup angle with respect to the forming process

heat sources, the maximum forming angle of the slope was 72°.

4 Discussion

4.1 The Current Process: Problems and Improvements

As the temperature of the material increases, the formability and the maximum formable cup angle increase. Figure 18 shows the maximum formable cup angle with respect to the forming process. The proposed method using the two external heating sources shows the highest cup angle.

Since the formability of the magnesium alloy sheet depends on the temperature of the material, it is necessary to accurately measure the temperature of the magnesium alloy sheet in the external heat assisted incremental forming process. However, it is difficult to measure the temperature precisely with a thermocouple or other indirect methods. Attaching a thermocouple to the sheet is not possible because the NIR heater may affect the thermocouple. At the same time, the thermo-graphic camera for measuring temperature is also not accurate due to the usage of the NIR heater. In order to establish stable process conditions later, the problem of material temperature measurement during the process should be resolved.

The power specification of the NIR heater in this work is 75 W. The power of the heater was not enough to heat up the material to 250 °C. If a NIR heater with more power is employed, the material could be heated to 250 °C. In such a case, the heated tool is not necessary. Currently, our research group is developing a new incremental forming process that uses a more powerful NIR heater and can also measure the temperature of the material.

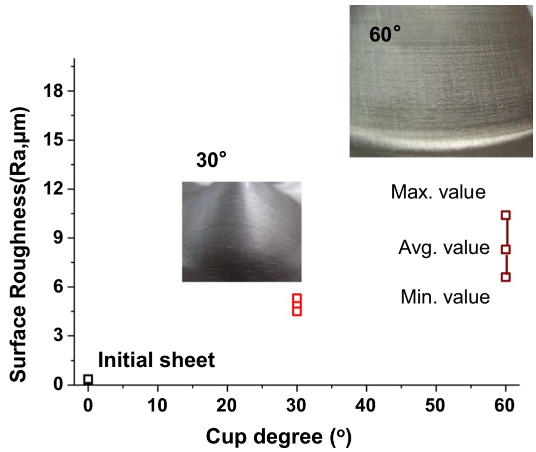

Fig. 19 Distribution of the surface roughness with respect to the cup angle

In the conventional single point incremental forming process, the unwanted bending deformation of the sheet shown in Figs. 11 and 13 is an inevitable problem. When the tool touches the material first, the bending deformation occurs, because there were no supports on the opposite sides of the tool. In the previous works, in remove bending deformation of materials, a die-set or two-point incremental forming process was employed [11].

4.2 Surface Roughness of the Products

The surface roughness is one of the measurement factors of the formability. Figure 19 presents the distribution of surface roughness of the cup-shaped product. The cup-shaped product was fabricated through the incremental forming process using two external heating sources. The surface roughness of the initial sheet was nearly zero. However, a cup shape was shaped with 30°; the average value of the surface roughness (R^a) was observed to be 4.5 um. As the forming angle increases, the average value of the surface roughness also increases. When the angle of the cup shape was 60°, the average value of Ra was 7.8 um. The difference between the maximum value and the minimum value was 4 um.

In conclusion, as the angle of the cup shape increases, the surface roughness increases. With this characteristic, the formability of the material can be predicted. If the surface roughness of the material is measured, the surface roughness can be employed as a measurement of formability.

5 Conclusions

In this work, in order to improve the formability of the magnesium alloy sheet in the incremental forming, two external heat sources were employed. On one side, a NIR heater was employed. On the other side, the tool was heated with the induction coil. The temperature of the material was increased efficiently up to 250 °C, which is the proper forming temperature of AZ31.

During the incremental forming of the cylindrical cup shape at room temperature, low formability of Magnesium alloy sheet limited the maximum cup angle to 20°. But with the employment of a single external heating source such as the NIR heater, the maximum forming cup angle of 45° was fabricated. Furthermore, incremental forming with varying cup angle with two external heating sources yielded the maximum forming angle of 72°. The thickness distribution showed good agreements with the predicted results from sine law. In conclusion, the formability of the magnesium Alloy sheet was improved by the local heating method through the use of external heating sources.

Acknowledgements This work was supported by the National Research Foundation of Korea (NRF) funded by the Korea government (MSIT) (No. NRF- 2020R1C1C1014412).

References

1. Kleiner, M., Geiger, M., & Klaus, A. (2003). Manufacturing of lightweight components by metal forming. *CIRP Annals, 52*(2), 521–542. https://doi.org/10.1016/S0007-8506(07)60202-9.
2. Doege, E., & Dröder, K. (2001). Sheet metal forming of magnesium wrought alloys—Formability and process technology. *Journal of Materials Processing Technology, 115*(1), 14–19. https://doi.org/10.1016/S0924-0136(01)00760-9.
3. Yang, D. Y., Bambach, M., Cao, J., Duflou, J. R., Groche, P., Kuboki, T., et al. (2018). Flexibility in metal forming. *CIRP Annals, 67*(2), 743–765. https://doi.org/10.1016/j.cirp.2018.05.004.
4. Lee, C. W., Seong, D. Y., & Yang, D. Y. (2010). Incremental forming process of AZ31 sheet using external heat sources. In: 2010 *Spring Proceedings of the Korean society for technology plasticity conference*.
5. Toros, S., Ozturk, F., & Kacar, I. (2008). Review of warm forming of aluminum–magnesium alloys. *Journal of Materials Processing Technology, 207*(1), 1–12. https://doi.org/10.1016/j.jmatprotec.2008.03.057.
6. Zhang, S. H., Zhang, K., Xu, Y. C., Wang, Z. T., Xu, Y., & Wang, Z. G. (2007). Deep-drawing of magnesium alloy sheets at warm temperatures. *Journal of Materials Processing Technology, 185*(1), 147–151. https://doi.org/10.1016/j.jmatprotec.2006.03.150.
7. Zhang, K. F., Yin, D. L., & Wu, D. Z. (2006). Formability of AZ31 magnesium alloy sheets at warm working conditions. *International Journal of Machine Tools and Manufacture, 46*(11), 1276–1280. https://doi.org/10.1016/j.ijmachtools.2006.01.014.
8. Wang, L., Huang, G., Zhang, H., Wang, Y., & Yin, L. (2013). Evolution of springback and neutral layer of AZ31B magnesium alloy V-bending under warm forming conditions. *Journal of Materials Processing Technology, 213*(6), 844–850. https://doi.org/10.1016/j.jmatprotec.2013.01.005.
9. Park, D.-H., & Kwon, H.-H. (2015). Development of warm forming parts for automotive body dash panel using AZ31B magnesium alloy sheets. *International Journal of Precision Engineering*

and Manufacturing, 16(10), 2159–2165. https://doi.org/10.1007/s12541-015-0278-8.
10. Emmens, W. C., Sebastiani, G., & van den Boogaard, A. H. (2010). The technology of incremental sheet forming—a brief review of the history. *Journal of Materials Processing Technology, 210*(8), 981–997. https://doi.org/10.1016/j.jmatprotec.2010.02.014.
11. Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., & Allwood, J. (2005). Asymmetric single point incremental forming of sheet metal. *CIRP Annals, 54*(2), 88–114. https://doi.org/10.1016/S0007-8506(07)60021-3.
12. Ambrogio, G., Filice, L., & Manco, G. L. (2008). Warm incremental forming of magnesium alloy AZ31. *CIRP Annals, 57*(1), 257–260. https://doi.org/10.1016/j.cirp.2008.03.066.
13. Ji, Y. H., & Park, J. J. (2008). Formability of magnesium AZ31 sheet in the incremental forming at warm temperature. *Journal of Materials Processing Technology, 201*(1), 354–358. https://doi.org/10.1016/j.jmatprotec.2007.11.206.
14. Duflou, J. R., Callebaut, B., Verbert, J., & De Baerdemaeker, H. (2007). Laser assisted incremental forming: formability and accuracy improvement. *CIRP Annals, 56*(1), 273–276. https://doi.org/10.1016/j.cirp.2007.05.063.
15. Fan, G., Gao, L., Hussain, G., & Wu, Z. (2008). Electric hot incremental forming: A novel technique. *International Journal of Machine Tools and Manufacture, 48*(15), 1688–1692. https://doi.org/10.1016/j.ijmachtools.2008.07.010.
16. Ambrogio, G., Filice, L., & Gagliardi, F. (2012). Formability of lightweight alloys by hot incremental sheet forming. *Materials & Design, 34*, 501–508. https://doi.org/10.1016/j.matdes.2011.08.024.
17. Lee, E.-H., & Kim, W.-S. (2020). Electrical–thermal–mechanical analysis of focused infrared heating Process. *International Journal of Precision Engineering and Manufacturing-Green Technology*. https://doi.org/10.1007/s40684-019-00161-x.
18. Lu, B., Chen, J., Ou, H., & Cao, J. (2013). Feature-based tool path generation approach for incremental sheet forming process. *Journal of Materials Processing Technology, 213*(7), 1221–1233. https://doi.org/10.1016/j.jmatprotec.2013.01.023.
19. Kim, T. J., & Yang, D. Y. (2000). Improvement of formability for the incremental sheet metal forming process. *International Journal of Mechanical Sciences, 42*(7), 1271–1286. https://doi.org/10.1016/S0020-7403(99)00047-8.

Chang-Whan Lee received Ph. D. in mechanical engineering in KAIST. He has been an assistant professor at Seoul National University of Science and Technology since 2016. His research interests include simulation and development of the metal forming process, lightweight materials such as magnesium alloy sheets.