Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-13-0072

Influences of bend severity, tool shape, forming wall angle, and stepdown size on pillow defect of stainless-steel sheets in single point incremental forming

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KEYWORDS: Pillow effect of stainless-steel sheets, single point incremental forming, stepdown size, bend severity, forming wall angle

Aluminum alloys are lightweight and ductile, and thus widely formed in single point incremental forming (SPIF) technology. Comparing to aluminum alloys, stainless steel sheets are more difficult to deform because pillow defect or bulging defect can easily occur during SPIF process. Pillow defect generated at the sheet center during SPIF process is a major forming limitation that affects the part's formability and increases the forming load. This study aims to systematically investigate the influences of bend severity, tool shape, forming wall angle, and stepdown size on the formation of pillow defect of stainless-steel sheets in SPIF via experiments. Bend severity is the ratio of sheet thickness to forming tool diameter. A series of forming SPIF experiments are carried out on both stainless steels, including grades SS304 and SS316L, to form parts with varying forming wall angles. Forming tools with different shapes are utilized, including hemispherical and flat end tools. The control solution of pillow defect of stainless-steel sheets is analyzed and explored by physical results. Hence, our study advances the in-depth understanding of formation of pillow defect of stainless-steel sheets and further drives the development of single point incremental forming technology.

1. Introduction

Single point incremental forming technology is a die-less sheet forming process in which a hemispherical or flat end tool moves along a computer numerical control toolpath to incrementally deform a sheet on the same robot to obtain various geometries without any forming dies. As a result, it is extensively utilized to prototype and run small or medium-volume manufacturing at a low cost [1]. A common undesirable outcome during the SPIF process is the early formation of pillow defect which reduces formability. The pillow formation on aluminum alloys has been studied. Isidore et al [2] investigated to reduce pillow height by varying the shape and diameter of the forming tool through numerical simulations and experiments on aluminum sheets. The results showed that pillow height was decreased by using a flat forming tool and increasing the forming tool diameter. Najm and Paniti [3] experimented the use of flat end tools on aluminum sheets and their results proved the effectiveness of flat end tools in reducing pillow height.

However, there is limited knowledge on reducing pillow formation of stainless-steel sheets. Therefore, this research aims to systematically investigate the influences of bend severity, forming tool shape, forming wall angle and stepdown size on the formation of pillow defect on stainless steel sheets.

2. Physical experiments

A series of experiments are conducted by clamping the flat metal sheet onto the frame and the robotic arm follows the toolpath to incrementally form the desired part in SPIF process, as depicted in **Fig. 1**. Forming feed rate is 2000mm/min. Mineral oil is utilized to reduce friction between forming sheet and tool. Eight different forming tools with varying tool diameters and shapes are used to deform sixteen different thick SS304 and SS316L sheets into four desired components. Details are introduced below.

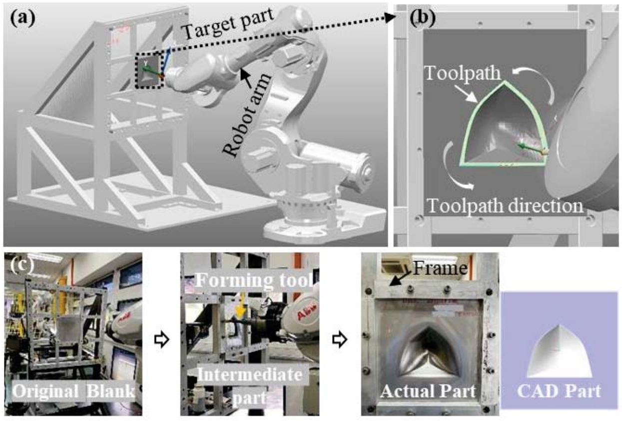
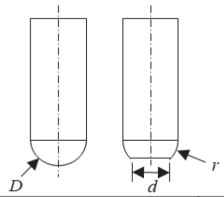


Fig.1 SPIF process: (a) SPIF experimental setup; (b) Toolpath guiding robotic arm; and (c) Forming part via SPIF process.

2.1 Forming tools

Introducing a flat end tool [4] and increasing tool diameter [5] have been shown positive results in mitigating pillow defect on aluminum alloy sheets in SPIF. In this research, **Fig. 2** illustrates eight forming tools with different shapes and dimensions. Hemispherical end tool is common in SPIF technology, while flat end tool is implemented to determine if it could generate results comparable to those employing stainless-steel sheets. The diameters of SKD11 tool are 5 and 15mm. The diameters of carbide tool include 5, 10, 15 and 30mm.



D	Diameter of the tool end
r	Radius of the tool end
d	Flat end diameter of the tool end

Forming tool Shape	*D* (mm)	*r* (mm)	*d* (mm)	Material
Hemispherical End	5	NA	NA	SKD11
	15			
Flat End	15	4.5	6	
Hemispherical End	5	NA	NA	Carbide
	10			
	15			
	30			
Flat End	30	9.0	12	

Fig. 2 Eight forming tools.

2.2 Forming wall angle

It is important to take into account the forming wall angle since too steep of an angle could lead to material fracture and too shallow of an angle could result in pillow development [5]. **Fig. 3** shows four designed components with the forming wall angles of 25° and 45°.

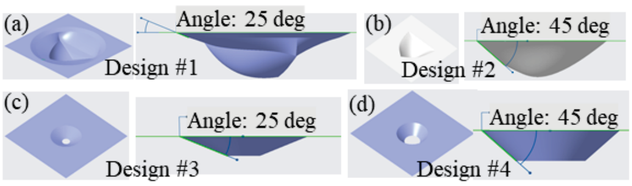


Fig. 3 Four designed components: (a) and (c) Wall angle of 25°; (b) and (d) Wall angle of 45°.

2.3 Material property

Pillow defect can easily happen during SPIF process, which causes stainless steel sheets are more difficult to deform than aluminum alloys. Due to their widespread use, SS304 and SS316L sheets are chosen as the research material in this study in order to expand the applicability of SPIF technique. **Table 1** displays sixteen samples using different thick SS304 and SS316L sheets. All the original sheets have the length and width of 335mm. **Fig. 4** shows their engineering stress and strain relationships. Compared to SS316L, SS304 material has a slightly greater ultimate stress. However, when SS304 material is annealed at 1040°C for 1 hour, the hardness value 203HV of annealed SS304 material is very close to the hardness value 200HV of SS316L material and is lower than the hardness value 235HV of SS304 material.

Table 1 sixteen samples using different thick SS304 and SS316L.

Sample name	Raw material	Raw material thickness (mm)
Sample #1	SS316L	1
Sample #2		
Sample #3		
Sample #4		
Sample #5		
Sample #6	Annealed SS304	2
Sample #7	SS304	
Sample #8	Annealed SS304	
Sample #9	SS316L	0.5
Sample #10		
Sample #11		
Sample #12		
Sample #13		
Sample #14		
Sample #15	SS304	1
Sample #16		

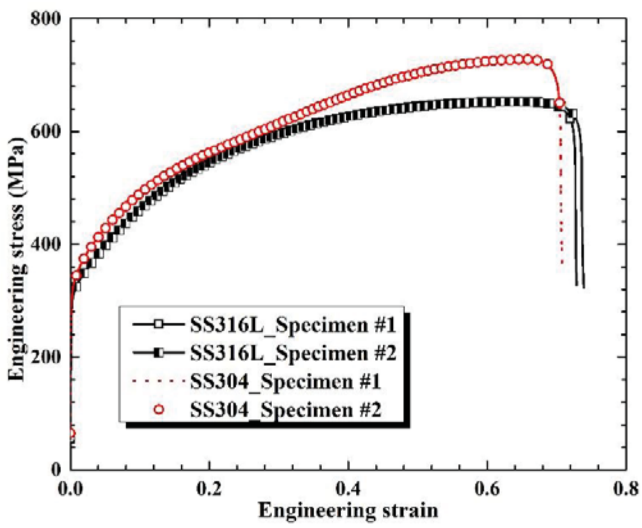


Fig. 4 Engineering stress and strain curves.

3. Experiment results

3.1 Influence of bend severity on pillow formation

During the SPIF procedure, pillow defect is easily created at the sheet center, as depicted in **Fig. 5** below.

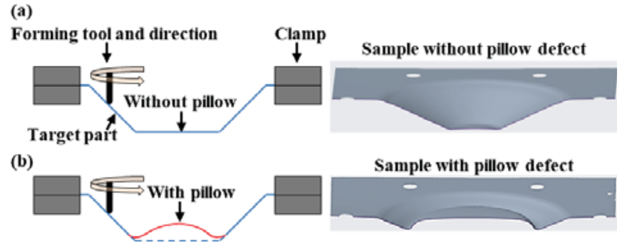


Fig. 5 Illustration of pillow formation during SPIF process.

Bend severity is the relationship between sheet thickness and tool diameter as a ratio, *t/D*. Seven samples are formed using SPIF process and thereafter laser scanned to investigate the effect of bend severity on pillow formation, as shown in **Fig. 6**.

The experimental results show that a higher bend severity value leads to pillow formation, while a lower bend severity ratio reduces the pillow height. In **Fig.6(a)**, the design, material, thickness and stepdown size are all consistent. However, by increasing the tool diameter and effectively decreasing the bend severity ratio, it is deduced that the pillow formation will not be present from a ratio of 0.033 and below. Similarly, **Fig. 6(b)** shows that pillow formation is not present from a ratio of 0.1 and below. In **Fig.6(c)**, it is noticed that pillow formation occurs at a higher bend severity ratio on an annealed sheet but does not occur when the bend severity ratio decreases despite forming on the raw material.

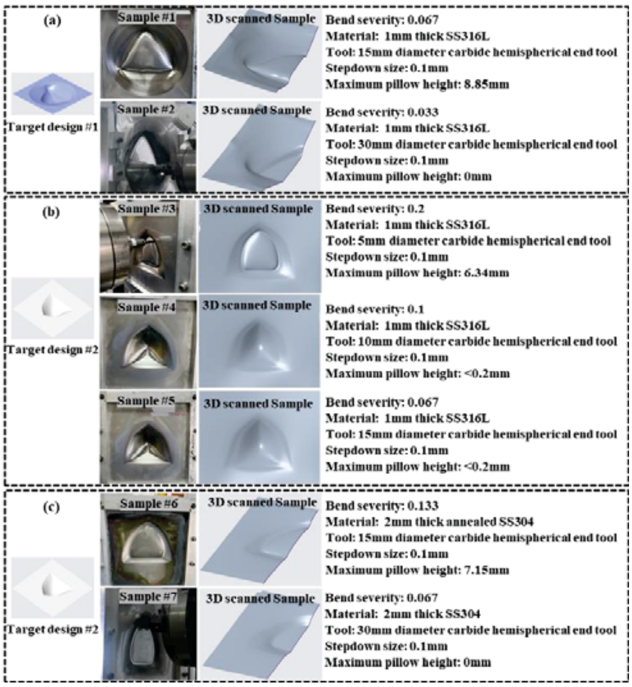


Fig. 6 Effect of bend severity on pillow formation for different samples: (a) Samples #1 and #2; (b) Samples #3 to #5; and (c) Samples #6 and #7.

3.2 Influence of forming tool shape on pillow formation

In contrast to the hemispherical end tool, the flat end tool is found to assist reduce pillow formation in **Fig. 7**. Samples #15 and #16 use same design, forming tool diameter, raw material and material thickness. In **Fig7(a)**, pillow defect is noticed when the hemispherical tool is used with a maximum height of 5.41mm. On the contrary in **Fig.7(b)**, this defect is reduced significantly by using a flat end tool to 0mm. This shows that the flat end tool is a crucial factor in SPIF process to help achieve the desired part without pillow defect.

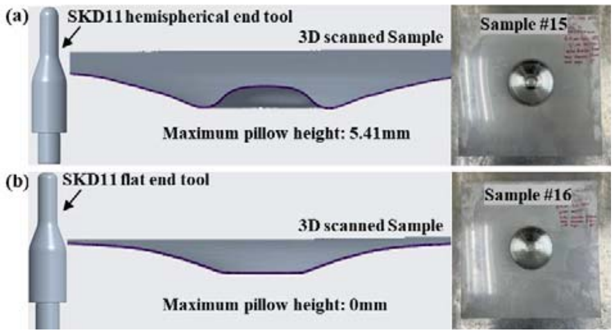


Fig. 7 Effect of forming tool shape on pillow formation for different samples: (a) Samples #15 and (b) Samples #16.

3.3 Influence of forming wall angle on pillow formation

The 0.5mm thick SS316L blank is utilized as the raw material, and Samples #9 and #14 are progressively formed using the SKD11 hemispherical forming tool with a 5mm diameter and 0.05mm stepdown size, as illustrated in **Fig. 8**. The outside and inner diameters of samples #9 and #14 are 120mm and 30mm, respectively. However, their respective forming wall angles are 25° and 45°. It is interesting that changing the forming wall angles produces considerable results and that the pillow defect decreases noticeably as the forming wall angle rises. When comparing the two examples, it can be seen that the truncated cone with the 45° forming wall angle performs better than the one with the 25° forming wall angle.

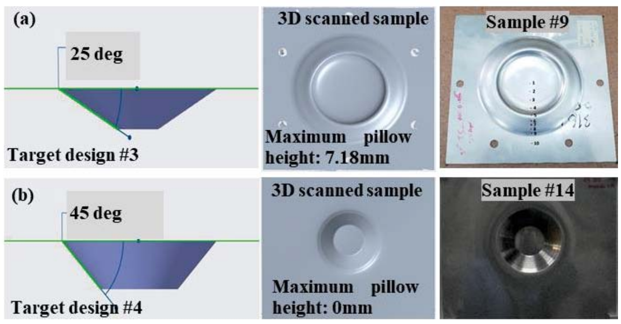


Fig. 8 Effect of forming wall angle on pillow formation for different samples: (a) Samples #9 and (b) Samples #14.

3.4 Influence of stepdown size on pillow formation

Because a greater stepdown size considerably increases processing efficiency, stepdown size is a crucial processing parameter in SPIF technology. This study uses a 0.1mm stepdown size, a 0.5mm thick SS316L blank, and an SKD11 hemispherical forming tool with a diameter of 5mm to incrementally form Samples #10 with a forming wall angle of 25°. Sample #10 has a pillow defect with a maximum pillow height of 6.61mm. Sample #9 is made with a more noticeable pillow defect that is generated in an early period when the stepdown size is decreased to 0.05mm and the other processing settings are left same, as shown in **Fig. 9(a)**. However, Samples #11 has a much lower pillow defect with a maximum pillow height of 0.61mm compared to Sample #9 when a larger SKD11 hemispherical forming tool with a diameter of 15mm is employed and the other processing settings are kept same, as shown in **Fig. 9(b)**. The maximum pillow height values of Samples #12 and #13 do not significantly alter even when the stepdown size is increased.

Hence, increasing stepdown size does help reduce pillow defect. However, the reduction in pillow height is more significant when forming tool with a smaller diameter is employed. When a larger forming tool is used, the influence of stepdown size on reducing pillow height is minimal.

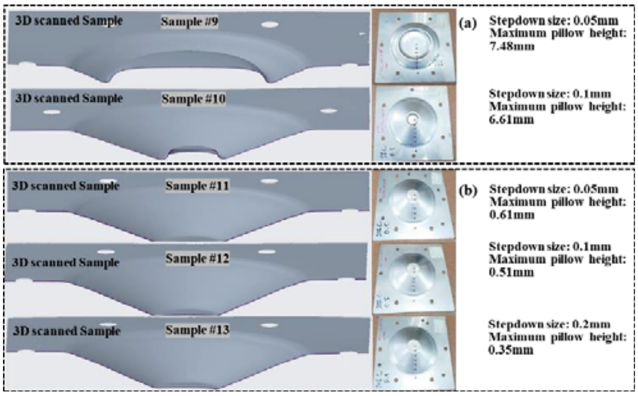


Fig. 9 Effect of stepdown size on pillow formation for different samples: (a) Samples #9 and #10 and (b) Samples #11 to #13.

3.5 Successful application on 2mm thick annealed SS304 sheet

The original Design #2 in **Fig.10(a)** cannot be incrementally formed initially when a 2mm thick SS304 blank, a 0.1mm stepdown size, and a carbide hemispherical forming tool with a diameter of 30mm are used, mainly due to the maximum forming force limitation of the robot in SPIF technology, despite no apparent pillow formation. When the stepdown size and material thickness are held constant in **Fig. 10(b)**, it's interesting to note that Sample #8 almost same as Design #2 can be effectively formed without any pillow formation by raising the part's tip radius, using a carbide flat end forming tool with a 30mm diameter, and annealing a 2mm thick stainless-steel sheet.

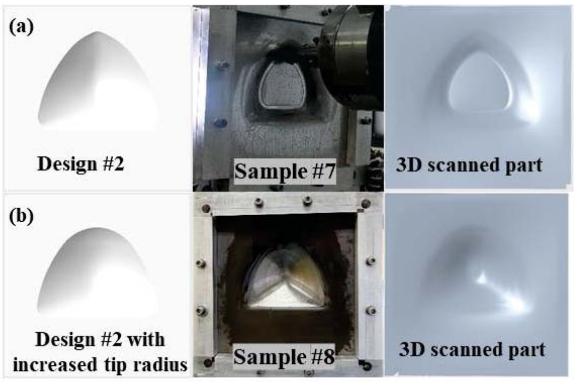


Fig. 10 Application: (a) Sample #7 and (b) Sample #8.

4. Conclusions

This research investigates the influences of bend severity, forming tool shape, forming wall angle and stepdown size on the formation of pillow defect on stainless steel sheets. Through the experimental results obtained, the following conclusions can be made:

(1) Increasing the forming tool diameter will assist reduce the formation of pillow defect.
(2) Implementing a flat end forming tool decreases pillow defect.
(3) Increasing the forming wall angle of the part impedes pillow formation.
(4) Decreasing the bend severity ratio prevents pillow formation.
(5) Stepdown size has a substantial impact on pillow formation when a small forming tool is employed. However, the effect of stepdown size on lowering pillow height is only marginally significant when a larger forming tool is employed.
(6) A complicated trihedral component without pillow defect is successfully formed using 2mm thick annealed SS304 blank via single point incremental forming technology.

ACKNOWLEDGEMENT

This work was completed as part of the development of Robotic Incremental Sheet Forming system implemented at Metal and Ceramic Forming Group (MCG) at Singapore Institute of Manufacturing Technology, A*STAR Research Entities. The project was financially supported by RIE2020 Advanced Manufacturing and Engineering (AME) Industry Alignment Fund – Pre-Positioning (IAF-PP), under the research program A1896a0034: Manufacturing of Lightweight Freeform Shell, Sandwich, and Hybrid Cellular Structures for Aerospace Component Manufacturing and Repair. The authors would like to also acknowledge the collaboration and engineering support from TTJ Design and Engineering Pte Ltd.

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