IOP Conf. Series: Materials Science and Engineering **319** (2018) 012035 doi:10.1088/1757-899X/319/1/012035

Optimization of Surface Roughness and Wall Thickness in Dieless Incremental Forming Of Aluminum Sheet Using Taguchi

Zamzuri Hamedon[1], Shea Cheng Kuang[1], Hasnulhadi Jaafar[2] and Azmir Azhari[1]
[1]Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, Malaysia
[2]School of Manufacturing Engineering, Universiti Malaysia Perlis, Malaysia
E-mail: zamzuri@ump.edu.my

Abstract. Incremental sheet forming is a versatile sheet metal forming process where a sheet metal is formed into its final shape by a series of localized deformation without a specialised die. However, it still has many shortcomings that need to be overcome such as geometric accuracy, surface roughness, formability, forming speed, and so on. This project focus on minimising the surface roughness of aluminium sheet and improving its thickness uniformity in incremental sheet forming via optimisation of wall angle, feed rate, and step size. Besides, the effect of wall angle, feed rate, and step size to the surface roughness and thickness uniformity of aluminium sheet was investigated in this project. From the results, it was observed that surface roughness and thickness uniformity were inversely varied due to the formation of surface waviness. Increase in feed rate and decrease in step size will produce a lower surface roughness, while uniform thickness reduction was obtained by reducing the wall angle and step size. By using Taguchi analysis, the optimum parameters for minimum surface roughness and uniform thickness reduction of aluminium sheet were determined. The finding of this project helps to reduce the time in optimising the surface roughness and thickness uniformity in incremental sheet forming.

1. Introduction

Since the number of vehicles increasing over the last two decades, new model with new design are introduce to market more often. The requirement remain to have a faster to market whilst without neglecting the safety issue became crucial. New materials was introduce either for lighter and yet stronger vehicles or fuel efficient vehicles [1]. Continuous researches are carried out in optimizing the design of vehicle to obtain efficient energy vehicle. The used of aluminum and high strength steel became equal important. Hamedon et al study a new method in joining a high strength steel and reported that the fatigue strength of hemming of high strength is stronger compare to the spot welding [2-3]. Although strength and safety are important, manufacturing lighter vehicles is also become a priority to high end car manufacturer. Since the aluminum is most demanding material for lighter vehicle, the quickest and easiest technique in producing body parts of this low volume vehicles is by using incremental sheet forming (ISF).

Incremental sheet forming (ISF) is a versatile sheet metal forming process where a sheet metal is formed into its final shape by a series of localized deformation. Generally, the process can be carried out on a CNC machine, where the perimeter of the sheet metal is clamped in a special blank holder. While the forming tool is attached to the CNC machine, it is usually round-ended with a diameter of 5 to 20mm, moving along a designed tool path and continuously indent the sheet following the contour until the final part is formed. In a typical ISF process, a general round-ended forming tool is moved along the NC controlled tool path, the tool moves downwards, indents the sheet by a specific depth, causing localized deformation in the sheet, then draws a contour on a horizontal plane, and then makes a step downwards, draws the next contour, makes the next step downwards, and so on [4]

Many issues and breakthrough finding were identified by researchers in the ISF. Tool diameter is one of the significant process parameters in ISF as it will not only affects the formability but also the surface finish of the sheet. Duflou et al showed that increase in tool diameter will increase the required force for forming [5]. Kim and Park found that increasing of tool diameter will increase the forming depth due to increase of contact zone [6]. However Park and Kim's [7] work showed that crack is easily occurred due to biaxial mode of deformation. Oleksik's work revealed that smaller tool diameter along with larger vertical step size will increase the maximum thickness reduction of the sheet metal [8]. Moreover, Malwad and Nandedkar did some experiments to understand to influence of the wall angle and they had observed that larger wall angle will result in a higher thickness reduction [9] . While effect of feed rate was studied by Hamilton and Jeswiet and reported at the feed rate lower than 2540 mm/, characteristic thinning occurred [10]. Beside all above mentioned issued, Echrif and Hrairi suggested a smaller step size will gave surface waviness and very smooth surface [11]. Malwad and Nandedkar's reported that surface roughness increased along with the step size [9].

Although ISF is considered a promising and feasible technology in forming sheet metal products, many researches are still undergoing to improvise the process such as improving the formability, improving the accuracy, eliminating springback, optimizing surface roughness etc. One of the most common research is the optimization of process parameters [12]. The aim of the project is to optimise the wall angle, feed rate, and step size in the ISF process for aluminium sheet to obtain minimum surface roughness and uniform thickness reduction.

2. Experimental procedures

2.1 Process

Firstly, the part to be formed in ISF process is designed in CAD software (CATIA), with the variance of wall angles in which the optimum one will be determined after the experiment. Then, the tool path will be generated on a CAM platform (CATIA), which is fixed throughout the experiment. The generated G-code for the ISF process will then ready to transfer to the 3-axis CNC milling machine.

The forming tool for ISF process is a mild steel rod, was fabricated using a 3-axis CNC turning machine with a ball end and a diameter of 10 mm which is kept constant for all experiments. Figure 1 shows the forming tool of ISF with rough surface to increase the friction between arbour and tool thus preventing slip during the process. Sheet material is aluminum 6061.

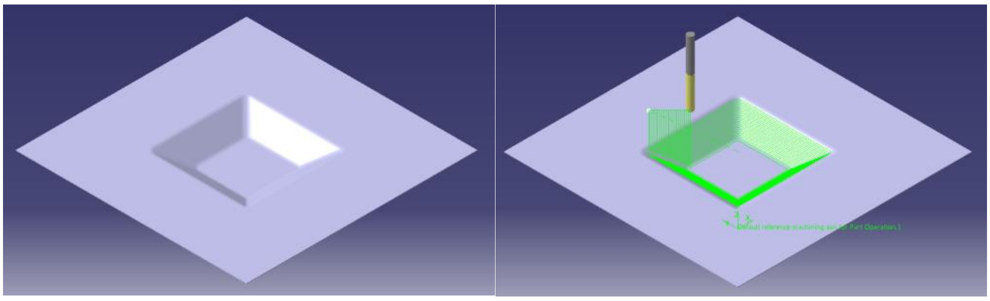
Figure 1: Forming tool for ISF

IOP Conf. Series: Materials Science and Engineering **319** (2018) 012035 doi:10.1088/1757-899X/319/1/012035

2.2 Experimental setup

The jigs for the ISF process is fabricated using mild steel rectangular hollow bars by welding each of it into a square shape. The entire ISF experiment was carried out on a 3 axis CNC milling machine. Figure 2 shows the experimental setup with complete structure of the jigs and set up on the CNC machine.

Figure 2: Experiment setup for ISF on CNC milling machine



(a) (b)

Figure 3: (a) Pyramid frustum shape, (b) Tool path generation in CATIA

In this experiment, wall angle, feed rate, and step size are going to be investigated with 3 levels each. Table 1 shows the experimental setting for each process parameter, and Table 2 shows the different combinations of every process parameters carry out in this experiment. Figure 3(a) shows the shape of aluminium sheet going to form in ISF, which is a pyramid frustum. The forming depth is fixed at 24 mm throughout the experiment. While Figure 3(b) shows proposed shape and tool path of ISF generated in CATIA which is inward helical along the contour only. Spindle speed was kept constant at 1500 rpm.

Table 1: Process parameters and level descriptions

Parameters	**Level 1**	**Level 2**	**Level 3**
Wall Angle	35º	45º	55º
Feed Rate (mm/min)	700	900	1100
Step Size (mm)	0.25	0.50	1.00

Table 2: Design of experiment plan

Experiment	Wall Angle	Feed Rate (mm/min)	Step Size (mm)
1	35º	700	0.25
2	35º	900	0.50
3	35º	1100	1.00
4	45º	700	0.50
5	45º	900	1.00
6	45º	1100	0.25
7	55º	700	1.00
8	55º	900	0.25
9	55º	1100	0.50

3. Results

The formed aluminium sheets were analysed for average surface roughness on four sides of internal slopes and four different radius size of internal corner. Meanwhile, the average thickness reduction of the sheet was measured and compare with the result obtained from the sine law, the uniformity of thickness reduction was investigated as well. The respective areas to be analysed were labelled as shown in Figure 4.

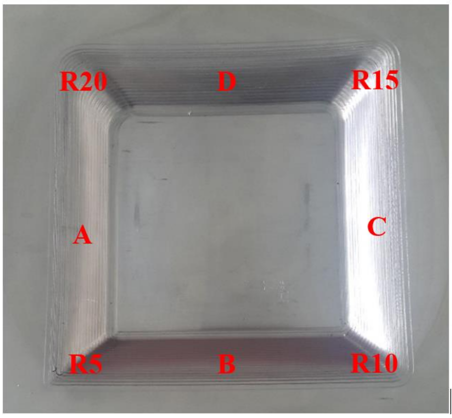


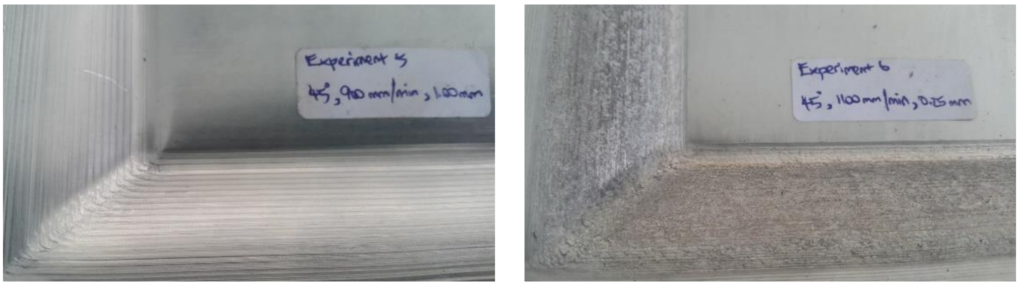
Figure 4: Area for location of measurement taken

Table 3 showed that Experiment 4 has the lowest average surface roughness while Experiment 9 produced the highest average surface roughness. For wall angle of 35º, surface roughness decreased when the feed rate and step size increased. However, the surface roughness increased when the feed rate increased for 45º and 55º of wall angle. Figure 5 shown surface conditions of aluminium sheet for different parameters from experiment 5 and experiment 6.

Table 3: Summary of average surface roughness of aluminium sheet in ISF

Experiment	1	2	3	***4***	5	6	7	8	***9***
Average Surface Roughness (μm)	6.966	6.315	5.126	***2.333***	3.062	6.578	2.772	5.757	***7.178***

IOP Conf. Series: Materials Science and Engineering **319** (2018) 012035 doi:10.1088/1757-899X/319/1/012035



(a) (b)

Figure 5: Surface of aluminium sheet for different parameters (a) experiment 5 and (b) experiment 6

Table 4: Summary of thickness reduction of aluminium sheet in ISF

Experiment	Thickness Reduction (mm)					Standard Deviation
	Area A	Area B	Area C	Area D	Average	
1	0.8322	0.8265	0.8300	0.8254	0.8285	0.0031
2	0.8355	0.8495	0.8616	0.8584	0.8513	0.0117
3	0.8970	0.8691	0.8639	0.8384	0.8671	0.0240
4	0.7337	0.6900	0.7299	0.6965	0.7125	0.0225
5	0.7400	0.6959	0.7440	0.7373	0.7293	0.0224
6	0.7300	0.7379	0.7228	0.7179	0.7272	0.0087
7	0.6084	0.6152	0.5779	0.5762	0.5944	0.0203
8	0.6185	0.5731	0.5648	0.5712	0.5819	0.0247
9	0.5698	0.5644	0.5898	0.6112	0.5838	0.0213

Table 4 shows the standard deviation of average thickness reduction of aluminium sheet for each experiment. A smaller value of standard deviation indicates that the thickness from each area are closer to the mean, which means that the thickness reduction is more uniform.

3.1 Parameters Optimisation for Surface Roughness

In order to minimise the surface roughness of aluminium sheet in ISF, optimisation of parameters was done from the results of the 9 experiments using Minitab software, response graphs for means and S/N ratios were generated. Figure 6 displayed the response graph for S/N ratios and means for surface roughness of aluminium sheet. Generally, a smaller-is-better S/N ratio.

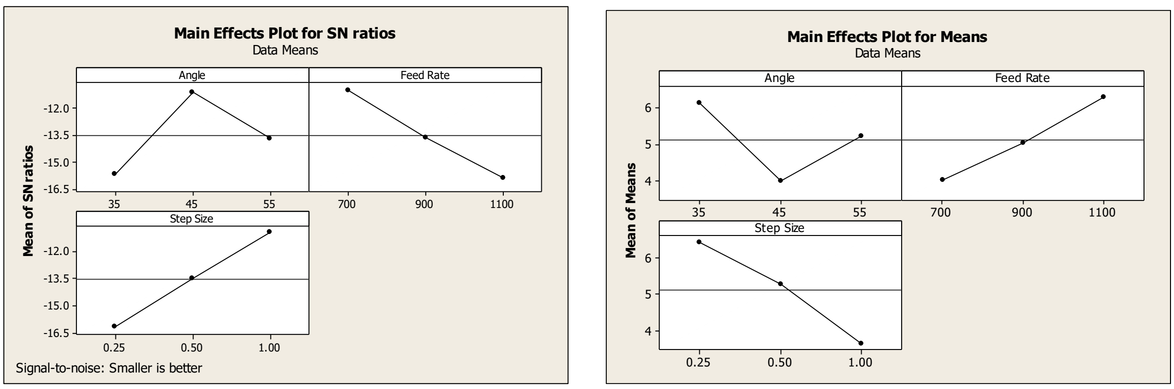


Figure 6: Response graph for S/N ratios and means for surface roughness

3.2 Parameters Optimisation for Uniform Thickness Reduction

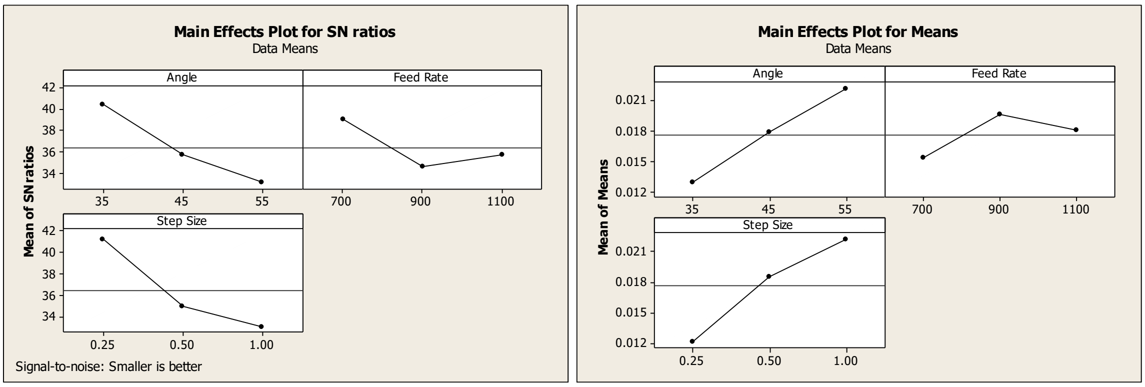


Figure 7: Response graph for S/N ratios and means for thickness uniformity

From the response graph of mean of means (thickness uniformity) as shown in figure 7, increase in wall angle and step size caused the thickness of aluminium sheet less uniform. On the other hand, the thickness uniformity decreased at 900 mm/min and rose at 1100 mm/min.

A confirmation test was carried out to verify the results of parameters optimisation. The optimised parameters for surface roughness and thickness uniformity was summarised in Table 5. However, the optimised parameters for thickness uniformity was exactly same with Experiment 1, therefore a confirmation test was not required. The result of average surface roughness with optimised parameters was revealed in Table 6.

Table 5: Optimised parameters for each outcome

Optimisation	**Angle**	**Feed Rate (mm/min)**	**Step Size (mm)**
Surface Roughness	45º	700	1.00
Thickness Uniformity	35º	700	0.25

Table 6: Comparison of actual surface roughness with the predicted value

Area	**Surface Roughness (µm)**			**Error (%)**
	Prediction	**Actual**	**Difference**	
Overall	2.469	1.705	0.764	30.9437
R5	1.332	0.885	0.447	33.5586
R10	1.525	1.564	0.039	2.5574
R15	1.491	2.290	0.799	53.5882
R20	2.85	2.122	0.728	25.5439

From Table 6, it can be observed that the difference between the predicted and actual surface roughness of aluminium sheet showed a relatively high error percentage except for area R5.

4. Discussions

Durante et al had proposed that the presence or absence of tool rotation will affects the value of surface roughness within the range of 10% [13]. Initially, these experiments was intended to carry out with a spindle speed of 1500 rpm as suggested by Echrif and Hrairi where they produced the best result for surface roughness [11]. Unfortunately, major scratching was found on the surface of the aluminium sheet with the indicated spindle speed in these experiments, causing undesirable surface finish to be produced. Therefore, the surface roughness test was neglected. In order to eliminate or reduce the unwanted scratches on the aluminium sheet surface, tool rotation was disabled for all experiments. In addition, lubricant was applied to the tip of forming tool in the beginning of each experiment. The scratches were greatly reduced and better surface finish was produced. It was believed that tool rotation generated more friction and surface contact between the tool and sheet, moreover no lubrication was involved, and hence it caused rough scratching to occur along the sheet.

The thickness uniformity of aluminium sheet was measured in term of standard deviation of the thickness, where a lower value indicates that the thicknesses are closer to the mean, therefore it means a more uniform thickness. It was observed from the analysis of results that increasing of step size and wall angle will reduce the thickness uniformity, where the former parameter influenced the most to the thickness uniformity followed by the latter one. Besides that, the results clearly revealed that the surface roughness and thickness uniformity were varied inversely. This finding has proved that better surface roughness does not come along with uniform thickness reduction, which can be explained by the effect of surface waviness as proposed by Echrif and Hrairi [11]. In addition, step size played an important role in the formation of surface waviness. The gap of punch between the paths which did not contact the sheet area is not deformed during ISF. A lower step size will reduce the size of the surface waviness and lead to better surface roughness, but the number of non-deformed area will increased, which caused the sheet thickness to be less uniform. On the other hand, forming tool with larger diameter can help to decrease the size of surface waviness.

5. Conclusions

In this project, the optimised parameters for minimum surface roughness and uniform thickness reduction in ISF has been determined via Taguchi analysis. From the design of experiments, the optimum parameters for minimum surface roughness was 45º wall angle, 700 mm/min feed rate, and 1.00 mm step size. On the other hand, uniform thickness of aluminium sheet was optimised at 35º wall angle, 700 mm/min feed rate, and 0.25 mm step size. Besides that, the effect of each parameters to the surface roughness and thickness uniformity has been investigated. Increase in step size and decrease in feed rate will improve the surface roughness of aluminium sheet in ISF. While decrease in wall angle and step size will produce a sheet with better thickness uniformity. Further analysis carried out using ANOVA, (not discussed in this paper) showed that the step size was the most significant parameter to both the surface roughness and thickness uniformity of aluminium sheet.

Acknowledgement

This work was supported by the Universiti Malaysia Pahang Research Grant Scheme RDU1703214. The authors would also like to acknowledge the assistance provided by Faculty of Manufacturing Engineering of UMP.

References

[1] Z Hamedon, K Mori, Y Abe (2014), Journal of Materials Processing Technology, 214, 945-950
[2] Z Hamedon, K Mori, Y Abe (2015). Applied Mechanics and Materials 773, 282-286
[3] Z Hamedon, K Mori, Y Abe, (2014). Procedia Engineering 81, 2074-2079
[4] Pohlak M, Majak J, & Küttner R. (2007). Proceedings of the Estonian Academy of Sciences (Engineering), 13(2), 129–138.
[5] Duflou, J, Tunçkol Y, Szekeres A, & Vanherck P. (2007). Journal of Materials Processing Technology, 189(1-3), 65–72.
[6] Kim Y H, & Park J J. (2002). Journal of Materials Processing Technology, 130-131(3), 42–46.
[7] Park J-J, & Kim Y-H. (2003). Journal of Materials Processing Technology, 140(1-3), 447–453.
[8] Oleksik V. (2014). Procedia Engineering, 81, 2280–2285.
[9] Malwad D S, & Nandedkar V M. (2014). Procedia Materials Science, 6 (Icmpc), 1505–1510.

[10] Hamilton K, & Jeswiet J. (2010). CIRP Annals - Manufacturing Technology, 59(1), 311–314.
[11] Echrif SBM, Hrairi M. (2011). Materials and Manufacturing Processes 26 (11), 1404-1414
[12] S A Bagaber, A R Yusoff. (2017). Journal of Cleaner Production, 157, 30-46
[13] Durante M, Formisano A, Langella A, & Capece Minutolo F M. (2009). Journal of Materials Processing Technology, 209(9), 4621–4626.