IOP Conf. Series: Materials Science and Engineering **257** (2017) 012006 doi:10.1088/1757-899X/257/1/012006

Parameter optimization and stretch enhancement of AISI 316 sheet using rapid prototyping technique

M Moayedfar[1, 2, 3, *], A M Rani[1, 2], H Hanaei[1], A Ahmad[3] and A Tale[4]

[1] Department of Mechanical Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskanadar, Perak Darul Ridzuan, Malaysia
[2] Centre of Intelligent Signal and Imaging Research, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskanadar, Perak Darul Ridzuan, Malaysia
[3] Faculty of Engineering and Technology, DRB-HICOM University of Automotive Malaysia, 26607 Pekan, Pahang Darul Makmur, Malaysia
[4] Wind Energy Technology Institute, Flensburg University of Applied Sciences, Flensburg, Germany

*Corresponding author: majid@dhu.edu.my

Abstract Incremental sheet forming is a flexible manufacturing process which uses the indenter point-to-point force to shape the sheet metal workpiece into manufactured parts in batch production series. However, the problem sometimes arising from this process is the low plastic point in the stress-strain diagram of the material which leads the low stretching amount before ultra-tensile strain point. Hence, a set of experiments is designed to find the optimum forming parameters in this process for optimum sheet thickness distribution while both sides of the sheet are considered for the surface quality improvement. A five-axis high-speed CNC milling machine is employed to deliver the proper motion based on the programming system while the clamping system for holding the sheet metal was a blank mould. Finally, an electron microscope and roughness machine are utilized to evaluate the surface structure of final parts, illustrate any defect may cause during the forming process and examine the roughness of the final part surface accordingly. The best interaction between parameters is obtained with the optimum values which lead the maximum sheet thickness distribution of 4.211e-01 logarithmic elongation when the depth was 24mm with respect to the design. This study demonstrates that this rapid forming method offers an alternative solution for surface quality improvement of 65% avoiding the low probability of cracks and low probability of crystal structure changes.

1. Introduction

There have been significant developments over the past decades regarding the availability of proper metals and metal alloys for sheet metal parts in low and batch production series. Different forming methods are often used by sheet metal industry which is mostly founded on the application of dies and punches with the correct dimensions of the final part to be planned. Generally, these manufacturing processes are employed for mass production series because the cost of the dies will be shared among the products. Nevertheless, the formal approaches based on dies, such as drawing or stamping are not useable

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

if a small amount of product is needed and, consequently, due to the meeting of demands levied by the short and batch series production industries, new manufacturing techniques have to be established. The incremental sheet forming (ISF) process has encountered to be a trustworthy solution among the different possibilities. This technique is built on the shaping of a metal sheet via a computer numerical controlling (CNC) tool or indenter which deforms the blank sheet plastically with respect to the preferred design [1-3]. The major factors affecting localised deformation were found to contact stress and shear mechanisms [4].

The current forming process of sheet metal parts suffers from the mechanical defects such as cracks and non-homogenize sheet distribution which cause fatigue, sheet failure and inaccuracy [5, 6]. Moreover, based on the Micari et al. (2007) explanation, some basic issues related to ISF exist. Their study demonstrated that geometric accuracy can be thought as one of the major limitations of ISF, which can be recompensed through toolpath optimisation [7]. Hence, this study aims to find the minimum defect and maximum surface quality (SQ) of the sheet metal parts using optimum forming parameters in ISF process.

One of the important parameters is spindle speed, which affects friction and consequently surface quality [1]. Some other parameters, which are mentioned in Hussain et al. (2011), include sheet thickness, tool radius, width step, and wall angle. The effective combination of these parameters will produce a highly significant and efficient result. Their study showed that the small radius of the tool combined with a lower width step caused a reduction in profile error, especially when a large wall angle was considered [8]. However, Attanasio et al. (2008) believed that step down (that is a changed form of depth of cut in milling process) also is influential in this process [8, 9]. Both works were used a longstanding version of the design of experiment method which had not a respond method for the parameters interaction. In another study, Ambrogio et al. (2012) found that the quality of the bottom surface in a hot ISF (Ra 0.234 μm) is almost 20% higher when compared with the one in contact with the punch but more than Hussain et al. (2011) study. This is because of both the lower temperatures (around 200°C) reached on the bottom side, which decreased the oxidation phenomenon and caused the absence of mechanical actions on the sheet [10].

It should be mentioned that based on Duflou et al. (2007), in some cases, sheet strain is directly due to the influence of wall angle [11]. An increase in wall angle would result in a strong part being produced and would also prevent any failures and defects; however, it also limits the design variability in sheet metal parts. Fritzen et al. (2013) explained a different case study, which showed that it is difficult to produce a product with a long 90° wall angle, according to the sine law, as per equation (1) [12].

$$\boldsymbol{t} = \boldsymbol{t_0} \, sin\, \boldsymbol{\theta} \qquad (1)$$

Where $\mathbf{t}$ is the final thickness, $\mathbf{t_0}$ is the initial thickness, and $\boldsymbol{\theta}$ is the wall angle. There are some other processes such as thinning and ironing that make inaccuracy in the final results of experiments compare to the prediction by the Sine low.

It is assumed that formability can be enhanced with forming speed because of heating effects. In Ham and Jeswiet (2006), an investigation related to the formability of aluminium AA3003 sheets in ISF was carried out through several experiments. The friction heat at the contact zone was high, as the rotational speeds for tool setups were high and thus, it was concluded that formability can be improved with a higher rotational speed. Additionally, the reduction in feed rate also improved blank formability [13]. Another study produced a dome geometry to describe the effect of spindle speed on the formability of St 37-2 steel. The results demonstrated that the tool rotational speed has an impact on formability and that when tool rotational speed is raised, formability will be reduced [14]. Besides that, the tool feed rate has a low impact on formability, as the results demonstrate reduced formability with an increase in feed rate. However, a year before this study, Hussain et al. (2008) conducted a cold incremental forming process to investigate the impacts of various features related to the formability (maximum wall angle) of a commercially pure titanium sheet. It was observed that, against the result of Rattanachan (2009), a raise in the feed rate reduced formability, and hence, the connection between feed rate and maximum wall angle followed a quadratic curve [15].

It should be mentioned that based on Nimbalkar et al. (2013), the forming process achieved higher feed rates compared to typical machining feeds. Due to the fact that the tool is hemispherical, no concern exists, related to the amount of material cut per tooth (flute) for each revolution; a critical factor in determining feed rates in conventional milling [16]. In addition, they noted that step-down regulates the z-axis increments. For some of the cases, an adjusted step-down for various wall angles was utilised for maintaining a constant traverse distance over the metal surface during the manufacture of a range of pyramids and cones with various wall angles. The case became very complex when complicated geometry was involved with various wall angles at diverse locations. Normally, in this case, a constant diameter forming tool with a standardised step-down would be used. The step-down also regulates the surface quality. Consequently, the optimum parameters can have a significant influence on the surface quality, and sheet thickness distribution value of the final part.

2. Methodology

In order to determine the optimum value for each of the forming parameters, an experimental study was designed. This set of experiments was combined with the numerical simulation to reduce the time, tool and sheet material waste. For this purpose, the Design-Expert® (State-Ease Corporation) software was employed to design the experiments for a better interaction between the parameters as the input data and the sheet thickness distribution (STD) value as the output factor. Hence, the parameters were inserted in the software environment and the Response Surface Method (RSM) with central composite design (CCD) technique was applied. There were some possibilities of using the DOE method for this study but CCD that finds the optimal levels of the design variables by adding a few more experiments to the Full Factorial design let to it being selected. Table 1 presents the range of input data for the software for creating the set of experiments in this study. Based on the Hussain et al. (2011) and Attanasio et al. (2008), the minimum and maximum values for each parameter were selected and inserted into the software.

Table 1. The range of forming parameters inserted to the DOE.

Parameter	Range of Variables
Feed Rate	10-200 mm/min
Spindle Speed	50-200 rpm
Step down	0.1-0.7 mm
Width Step	1-4 mm

The width step was based on a percentage of the tool diameter and was selected from 1 to 4 millimetres since the tool diameter is considered to be 10 mm for this study. In regard to some inapplicable values suggested by the software, for example, -0.1 mm for depth step (or DOC), the Alpha function was activated to bring in real values and reduce the negative values since all the applied variables should be more than zero in these experiments. Finally, the output data was created and then transferred to Microsoft Excel®.

The experiment for applying ISF on AISI 316L is adopted from previous work [17] which was clamping the metal sheet alloy from the edges and fix on the table of CNC milling machine using complete clamping system. This clamping includes a main part which is a cylindrical shape and a lid with 6 screws to fix the metal sheet. Toolpath also generated from computer-aided manufacturing (CAM) system and then modified with optimized parameters for ISF process. Tool trajectory applied in combination of manual and software programming as the “combined programming system” to increase the time efficiency and also reduce the amount of scratch [17, 18]. The frustum of a pyramid design include surfaces, edges and fillets used with a 24mm depth and the lubricant also flow on the surface of sheet reducing friction which causes the high temperature on the contact area, between the tool and sheet metal. Since the temperature is the main cause of the shear failure in this process, it will control sequent. After some cycles of the process, one sink will be created where the lubricant liquid flow inside it, hence, the heat will rise up to 80 ºC when the tool is inside the pool of oil and stay steady until the end of the experiment as it is shown in Moayedfar (2014) work.

The pressure direction defined as Zhu et al. (2012) study, which explained that an optimized tool approach angle on the surface of sheet metal can effect on the depth of drawing [19]. In this case, 5 axes CNC milling machine is employed to make the motion similar to a robot actuator and then, shape the metal sheet alloy incrementally. Figure 1 shows the installed set of tool and clamp on the CNC machine. Toolpath also is directly taken from the CAM systems for the part to be formed.

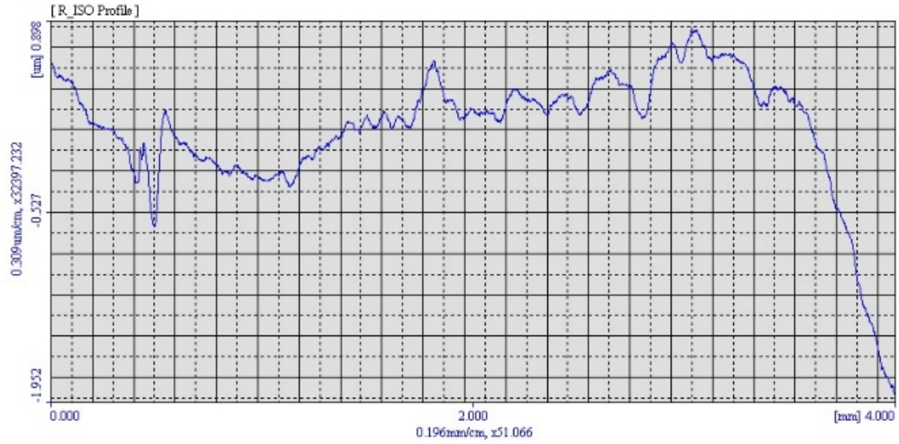
Figure 1. Setup of ISF process on the CNC milling machine table [17].

In order to find the morphology of the sheet metal surface, the Field Emission Scanning Electron Microscope (FESEM) is employed to capture the surface structure of sheet material before and after the process and also the behind side of sheet metal after the process since that side will be the outer side of the implant (The inner side will contact directly with bone surface). Finally, roughness test machine was employed to magnifier the surface roughness of the sheet metal to detect a number of scratches introduced by the indenter during the process in all three mentioned surfaces.

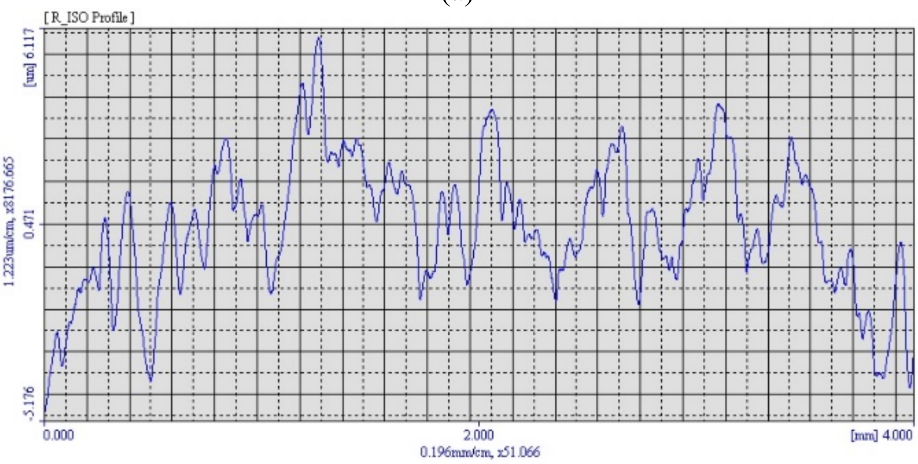
3. Results and discussion

There were only 22 samples out of 30 samples suggested by DOE that provide the complete sheet stretching to the final depth design. In the other 8 samples, UTS were appeared before shaping the complete pyramid. Therefore, those samples considered as the failed tests and did not use in the characterization. However, 22 samples are examined in roughness test and surface morphology determination even those with low surface quality which could be detected visually.

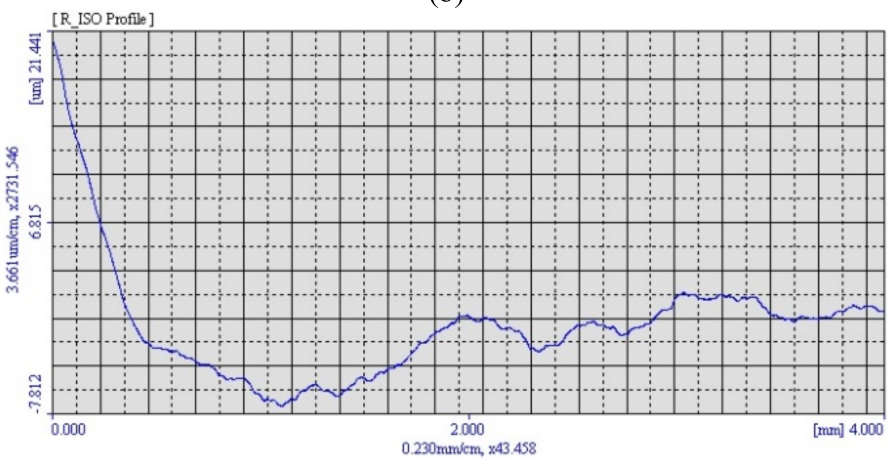
The roughness test is employed to determine the surface quality of samples in three different sides of the raw material, the contact surface and backside surface. The results of tests illustrated the optimum set of parameters for the forming process. Then, respond for all 22 samples sent to the DOE for analysing and defining the parameters interaction. Figure 2 shows the best sample regarding the SQ of the contact surface in roughness test compare with the other surfaces and STD of 4.211e-01 (LE). As can be seen in figure 2 (a), the raw material SQ is Ra 0.359 µm while the contact surface as shown in figure 2 (b) has Ra 3.073 µm. Figure 2 (c) also illuminate the roughness of Ra 1.590 µm for the sheet backside of the part.



(a)



(b)



(c)

Figure 2. Roughness test of the best sample. (a) Raw material, (b) contact surface, (c) back-side surface.

As it shown, the surface quality of the contact surface 10 times is lower than the raw material but the back-side surface is around four times lower than the base material. Consequently, the amount of scratch in ISF is the big challenge in SQ of final parts that can be minimize via proper forming parameters. However, the back-side surface can be applied in this method as the final part. For instance, the outer side of the pyramid can be considered as the final part which is carrying a better SQ.

Parts are collected to characterise with FESEM resolution of 4 nm at 0.1 kV. The surface of parts is considered and presented in figure 3. As can be seen in figure 3 (a), the surface area of AISI 316L is for blank metal sheet alloy which is presented from steel company after tension reduction process. The final mechanical work on these sort of sheet alloys is cold rolling so the surface quality will be improved. Figure 3 (b) illustrates that there was some forming process on sheet metal that changes the surface morphology. There are some scratches on the surface of sheet metal made by the tool that reduce the surface quality of the final part. Hoverer, this amount is not considerable in sheet metal forming processes using stretching such deep drawing.

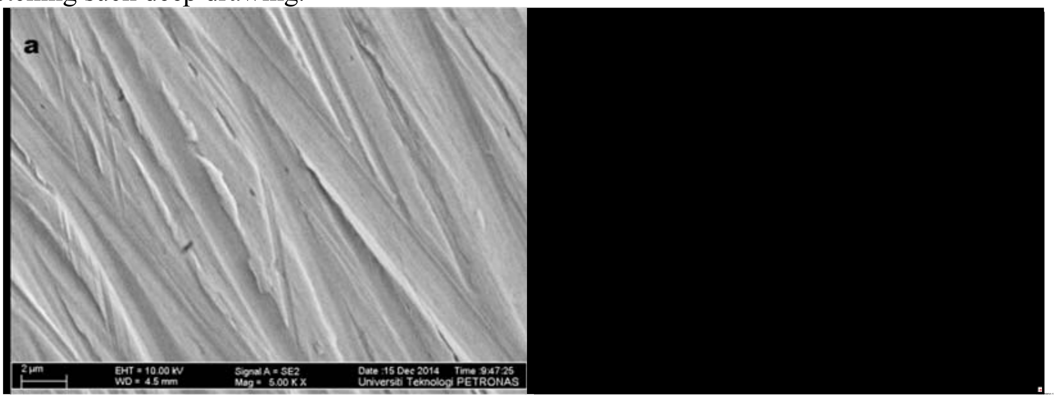


Figure 3. (a) Row material. (b) Sheet part after ISF process.

The back side of the sheet part after forming has more appropriate surface quality regarding the lower amount of scratches. Furthermore, the defects of ironing process and tool scratch that may effect on surface quality has few influences on the back-side surface. Figure 4 shows the similarity of the back side of sheet part with the surface of raw material. The amount of disorganization is lower, and also due to some work hardening on the sheet surface, the quality is increased. In general, the strength of part will be increased while the surface quality will remain almost the same.

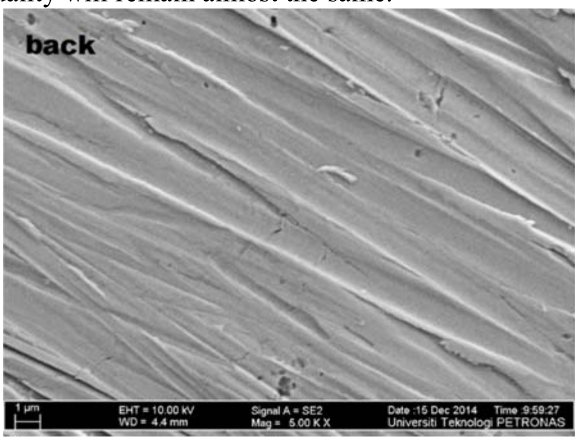
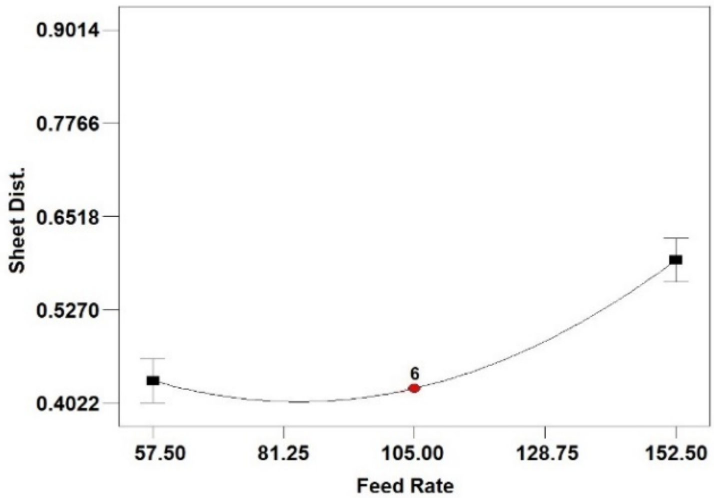


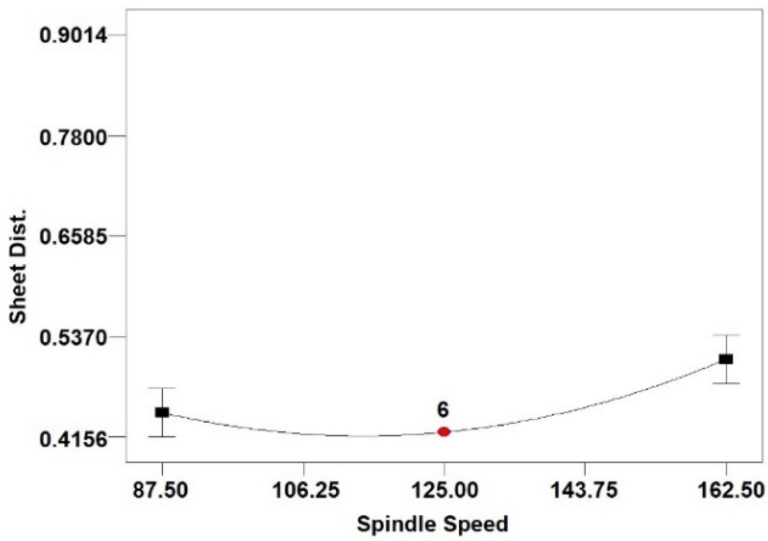
Figure 4. Back side of the sheet metal after ISF process.

The roughness test machine is employed to determine the roughness of the surfaces in this study. Among the all the samples. It should be mentioned that the temperature did not have a significant effect on the process since the cooling liquid is flowing on the surface of the metal sheet. Therefore, the effect of temperature is not considered in this study.

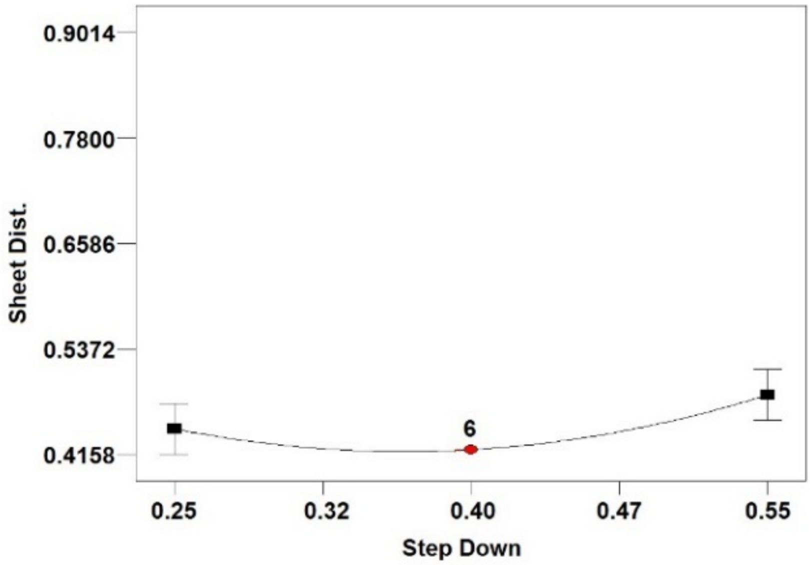
In this study, the influence of four parameters feed rate, spindle speed, step down, and width step versus the sheet stretching that is the representative of the sheet thickness distribution was examined via DOE. The Design of Experiment used in this respond method illustrates that some of the parameters such as feed rate and width step have a significant influence on STD compared to the other parameters. Figure 5 shows the behaviour of these four parameters versus STD during the experiment, where the (a) is the diagram of variation for feed rate, (b) spindle speed, (c) step down, and (d) width step.



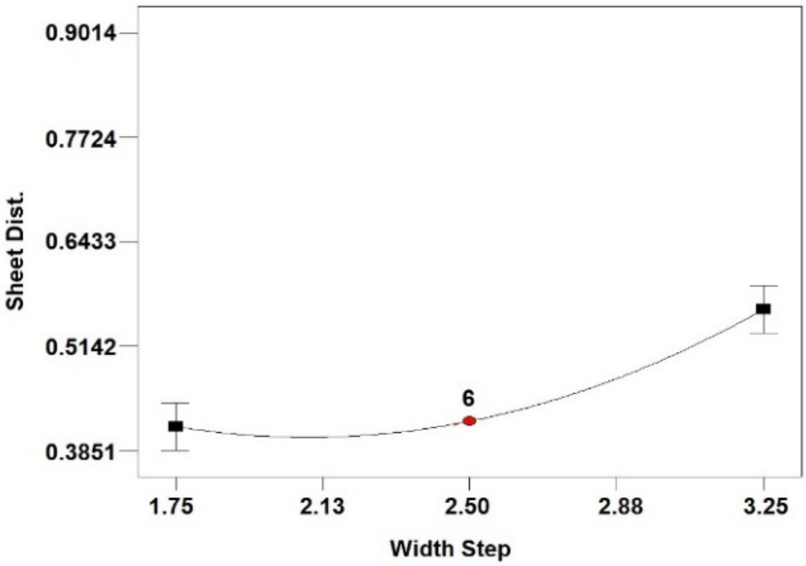
(a)



(b)



(c)



(d)

Figure 5. The interaction between effective parameters versus STD. (a) feed rate, (b) spindle speed, (c) step down, and (d) width step

As can be observed from the results, the feed rate is the most influential parameter in this study. Moreover, step width also showed a considerable effect on the amount of STD in this analysis, while the spindle speed and step down played a less important role in the forming process. The influence of step down just appeared once in a cycle, and the spindle speed effect could be minimised using a proper lubricant to reduce friction. However, high values of feed rate increased the friction and vibration of the process, which are the two major defects of ISF. In addition, a width step of more than 20% of the tool diameter increased the risk of sheet failure due to the huge pressure on the surface of the sheet metal, which changes the process from stretching to chipping. This defect was accrued throughout the experimental investigation, as shown in figure 6.

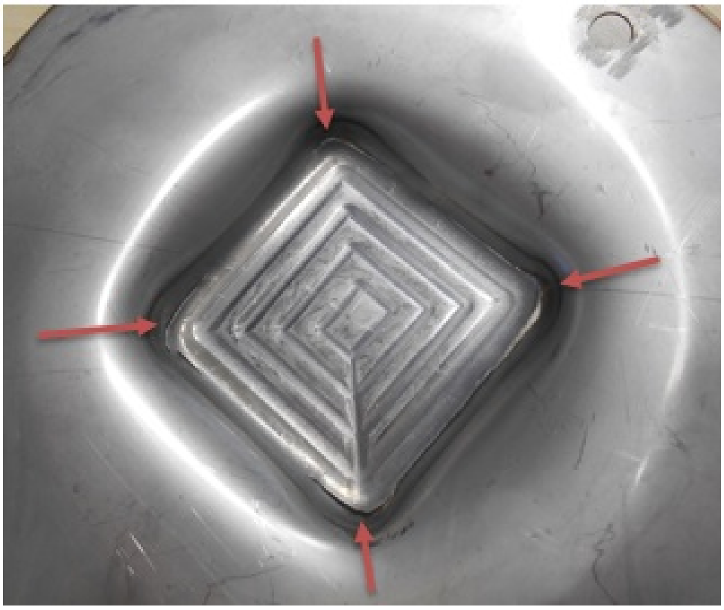


Figure 6. Sheet failure appearing due to large step size

The interaction of the two parameters on the STD was evaluated and shown in 3D diagrams to illustrate the influence of the combined parameters in a particular time. Figure 7 illustrates the influence of these significant parameters including feed rate and spindle speed, on the ISF process.

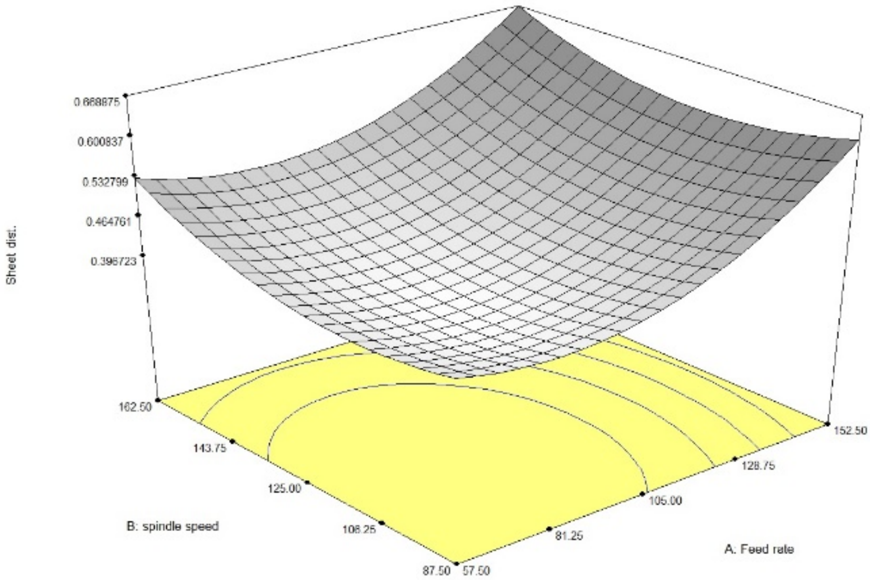


Figure 7. The effect of feed rate and spindle speed on sheet thickness distribution

Both feed rate and spindle speed have a linear effect on the response of the sheet thickness distribution while the combination of the two parameters also yielded a linear response. However, the combination of the parameters increased the amount of sheet stretch up to 0.668875 µm where every single parameter (~ 0532799 µm for spindle speed and 0.600837 µm for feed rate) was not able to increase the sheet stretch up to that point. Figure 7 shows that the combination of both effective parameters when the values are at maximum would cause sheet failure since the high amount of STD in this study is one reason for sheet fracture.

A high feed rate has a significant effect on sheet failure and a large width step increases the risk of sheet fracture. Figure 8 presents the considerable interaction between these parameters versus STD, where the thickness distribution shows a dramatic increase up to the highest point.

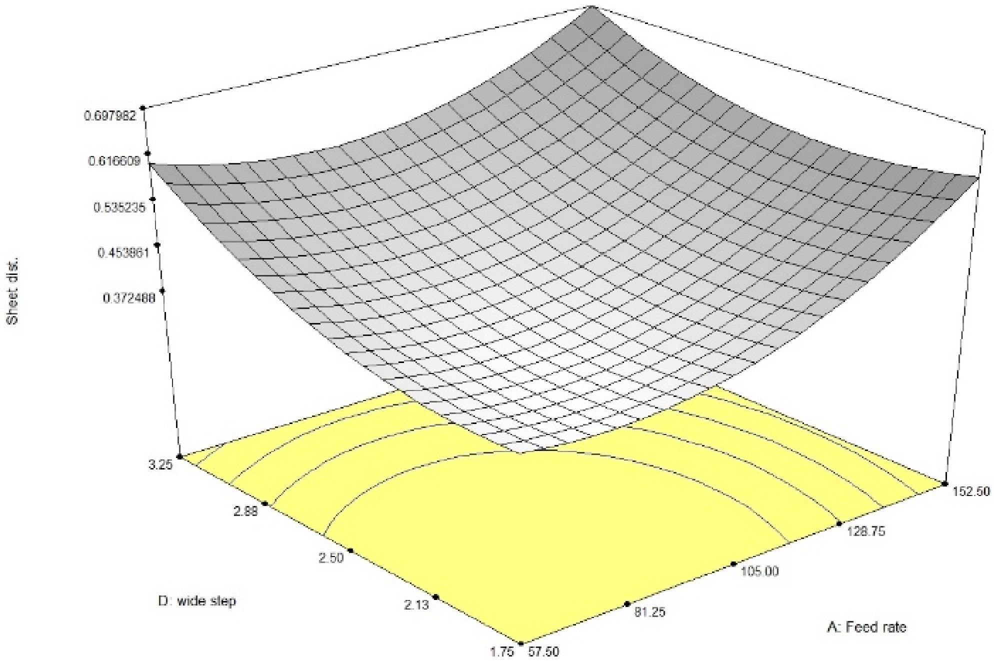


Figure 8. The effect of feed rate and wide step on sheet thickness distribution

As can be seen from figure 8, both factors sharply increased the STD up to ~ 0.697982 µm, whereas in figure 9, the combination of the two parameters of spindle speed and depth of cut increased the STD to ~ 0.585355 µm. Increasing the depth of cut to more than 0.47 together with an increase in spindle speed up to 143.75 would be the optimum condition for this response since the sheet distribution values increased sharply upward as a result.

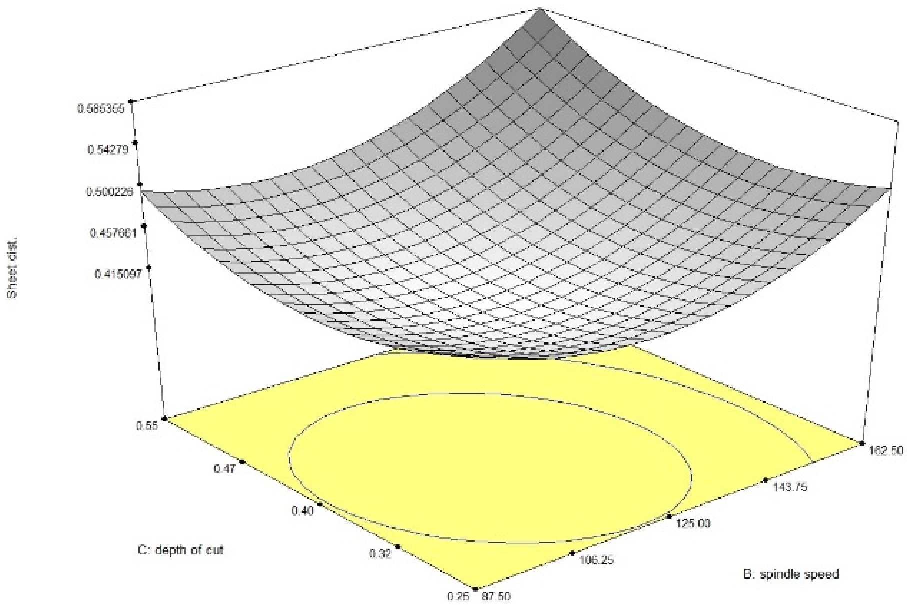


Figure 9. The effect of depth of cut and spindle speed on sheet distribution

However, using low parameters increased the time of production, hence, an optimum amount was obtained from equation (2). This equation was driven based on the parameter response in these experiments where the affected parameters are sheet thickness distribution (STD), feed rate (***A***), spindle speed (***B***), depth of cut (***C***), and (***D***) width step.

$$\boldsymbol{STD} = 0.42 + 0.081 * \boldsymbol{A} + 0.032 * \boldsymbol{B} + 0.020 * \boldsymbol{C} + 0.072 * \boldsymbol{D} + 0.091 * \boldsymbol{A}^2 + 0.056 * \boldsymbol{B}^2 + 0.044 * \boldsymbol{C}^2 + 0.066 * \boldsymbol{D}^2 - 0.012 * \boldsymbol{A} * \boldsymbol{B} + 4.919\boldsymbol{E}\text{-}003 * \boldsymbol{A} * \boldsymbol{C} - 0.033 * \boldsymbol{A} * \boldsymbol{D} + 0.013 * \boldsymbol{B} * \boldsymbol{C} + 4.069\boldsymbol{E}\text{-}003 * \boldsymbol{B} * \boldsymbol{D} - 4.244\boldsymbol{E}\text{-}003 * \boldsymbol{C} * \boldsymbol{D} \quad (2)$$

As stated in equation (2), the effect of feed rate and spindle speed on the STD is higher since the impact factors for these parameters are 0.081 and 0.072, respectively. Based on the analysis by the DOE software (DE®), the R-Squared ($\boldsymbol{R}^2$) value was 0.9521 and the Adjusting $\boldsymbol{R}^2$ value was calculated as 0.9073. Also, the Prediction R-Squared value of 0.7239 was found to be in reasonable agreement with the Adjusting R-Squared value.

4. Conclusions

A new prototyping method of production is in need to employ for batch and low production series in rapid forming techniques. Hence, incremental sheet forming as a potential process is presented to increase the variety of sheet metal parts. However, this process suffers from some drawback such as low surface quality and the high possibility of sheet failure. Hence, in this study, a set of experiment is designed and applied to determine the significant effective parameters in this sheet forming process and also find the optimum values of the parameters with respect to the maximum sheet thickness distribution and higher surface quality than current studies. For this purpose, the result of experiments is characterized via utilising of roughness test and the FESEM test. Then, the respond of the each set of parameters is applied in DOE to obtain the optimum forming parameters and their interaction. Consequently, the data presented in this study shows a range of optimized parameters in 24 mm pyramid design shape for ISF method with adequate surface quality (Ra 3.073 μm for contact surface) Ra 1.590 μm for back-side surface up to 35%

higher than the current research based on the graphs generated by surface roughness machine. Furthermore, the results illuminate that the ISF will not be the cause of crack and crystal structure defects on the final parts, and also presented as a low defect process for sheet metal accessories and parts production.

Acknowledgement
The authors are thankful to the Ministry of Higher Education, Malaysia (MOHE) for supporting this research via FRGS/1/2014/TK01/UTP/02/8 research grant.

References

[1] Jeswiet J, Micari F, Hirt G, Bramley A, Duflou J and Allwood J 2005 Asymmetric single point incremental forming of sheet metal *CIRP Annals-Manufacturing Technology* **54** 88-114
[2] Jackson K and Allwood J 2009 The mechanics of incremental sheet forming *Journal of materials processing technology* **209** 1158-74
[3] Allwood J M, Braun D and Music O 2010 The effect of partially cut-out blanks on geometric accuracy in incremental sheet forming *Journal of Materials Processing Technology* **210** 1501-10
[4] Emmens W and Van den Boogaard A 2009 Incremental forming by continuous bending under tension—an experimental investigation *Journal of Materials Processing Technology* **209** 5456-63
[5] Schaeffer L, Castelan J, Gruber V, Daleffe A and Marcelino R 2009 Development of customized products through the use of incremental sheet forming for medical orthopaedic applications. In: *3rd International Conference on Integrity, Reliability and Failure,* pp 65-6
[6] Shapiro F 2008 Bone development and its relation to fracture repair. The role of mesenchymal osteoblasts and surface osteoblasts *Eur Cell Mater* **15** 53-76
[7] Micari F, Ambrogio G and Filice L 2007 Shape and dimensional accuracy in single point incremental forming: state of the art and future trends *Journal of Materials Processing Technology* **191** 390-5
[8] Hussain G, Lin G and Hayat N 2011 Improving profile accuracy in SPIF process through statistical optimization of forming parameters *Journal of Mechanical Science and Technology* **25** 177-82
[9] Attanasio A, Ceretti E, Giardini C and Mazzoni L 2008 Asymmetric two points incremental forming: improving surface quality and geometric accuracy by tool path optimization *Journal of Materials Processing Technology* **197** 59-67
[10] Ambrogio G, Filice L and Gagliardi F 2012 Formability of lightweight alloys by hot incremental sheet forming *Materials & Design* **34** 501-8
[11] Duflou J, Callebaut B, Verbert J and De Baerdemaeker H 2007 Laser assisted incremental forming: formability and accuracy improvement *CIRP Annals-Manufacturing Technology* **56** 273-6
[12] Fritzen D, Daleffe A, Castelan J and Schaeffer L 2013 Brass 70/30 and Incremental Sheet Forming Process. In: *Key Engineering Materials*: Trans Tech Publ) pp 1419-31
[13] Ham M and Jeswiet J 2006 Single point incremental forming and the forming criteria for AA3003 *CIRP Annals-Manufacturing Technology* **55** 241-4
[14] Rattanachan K and Chungchoo C 2009 Formability in single point incremental forming of dome geometry *AIJSTPME* **2** 57-63
[15] Hussain G, Gao L and Zhang Z 2008 Formability evaluation of a pure titanium sheet in the cold incremental forming process *The International Journal of Advanced Manufacturing Technology* **37** 920-6
[16] Nimbalkar D and Nandedkar V 2013 Review of incremental forming of sheet metal components *Int J Eng Res Appl* **3** 39-51

IOP Conf. Series: Materials Science and Engineering **257** (2017) 012006 doi:10.1088/1757-899X/257/1/012006

[17] Moayedfar M, Leman Z and Baharudin B 2014 Incremental Sheet Forming (ISF) of AISI 316 Stainless Steel Sheet Using CNC Milling Machine. In: *Advanced Materials Research*: Trans Tech Publ) pp 322-7

[18] Moayedfar M, Rani A M B A, Salehi P and Tad V V L N R 2014 Comparative Study between Programming Systems for Incremental Sheet Forming Process. In: *MATEC Web of Conferences*: EDP Sciences) p 04009

[19] Zhu H, Li N and Liu Z 2012 The effect of pressing direction on the 5-axis CNC incremental forming quality *International journal of material forming* **5** 227-33