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STUDY ON FORMING FORCES OF PARTS PROCESSED BY SINGLE POINT INCREMENTAL FORMING WITH DUMMY SHEET

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ABSTRACT

The present paper describes the experimental investigation on influence of process parameters on maximum forming force in Single Point Incremental Forming (SPIF) process using dummy sheet. Process parameters namely dummy sheet thickness, tool size, step size, wall angle and feed rate are selected. Taguchi L_{18} orthogonal array is used to design the experiments. From the analysis of variance (ANOVA) dummy sheet thickness, tool size, step size and wall angle are significant process parameters while feed rate is insignificant. It is found that as dummy sheet thickness, tool size, step size and wall angle increase magnitude of peak forming force increases while there is marginal decrease in forming force as feed rate increases. Predictive model is also developed for forming force. Validation tests are performed in order to check the accuracy of developed model. Optimum set of process parameters is also determined to minimize forming force. Experimental results are in good agreement with results predicted by the developed mathematical model.

Key words: *Single point incremental forming, SPIF; Dummy sheet, Forming force, Wall Angle and Step size*

1. Introduction

Single point incremental forming (SPIF) is one of the innovative and emerging advanced sheet metal forming process for production of sheet metal parts. It has various benefits over conventional sheet metal forming process. Sheet metal parts are made using a press tool and design of such press tools is very complex which requires specialized procedure. Design and manufacturing of press tool setup is time consuming and very costly; and hence it is justified only if the press tool is used for mass production [1]. Further, each press tool is designed only for a specific sheet metal part. But using SPIF process any complex shape can be made on the same fixture setup without investing time and resources on design and fabrication of new press tools. It is also known as die-less forming process, as there is no requirement of new dedicated punch and die system for every new geometry to be formed. Thus, this process offers short lead time, high flexibility and is economical in case of small batch production for sheet metal parts like customised or patient specific medical implants, aeronautics and automobile components [2]. It is one of the emerging sheet metal prototyping process with very less machine and tool cost [3]. In SPIF process first CAD model of desired part is prepared in CAD software and thereafter tool path is generated using a CAM software and is fed into controller of CNC machine. Generally, hemispherical ended forming tool is used to deform sheet metal parts. The sheet is held between backing plate and clamping plate (sometimes also called as blank holder) along its periphery. Now the motion of forming tool is synchronised with tool path program and accordingly the deformation of sheet metal into desired part shape takes place [6-7]. But due to some limitations of SPIF process mainly poor surface finish, uneven thickness distribution and high forming time, it is not accepted by sheet metal industries. As reported in literature [4-5] that when SPIF process is performed with dummy sheet placed at top of main/target sheet, surface finish improves. This is so because all the tool marks caused due to high feed rate and spindle rotational speeds, are faced by dummy sheet. This results in relatively smother surface of target sheet. In this process, deformation of both dummy and target sheet takes place simultaneously. Virtual tool size is responsible for deformation of main/target sheet [4]. The virtual increase in tool size on target sheet is due to the thickness of dummy sheet. Because of the incremental nature of the process, forming force required is less. In this process blank is held between the blank holder and the backing plate and tool (or punch) is allowed to move with a small increment in negative z-direction. Figure 1 (a) depicts the layout of SPIF process with dummy sheet placed at the top of main/target sheet and Figure 1 (b)

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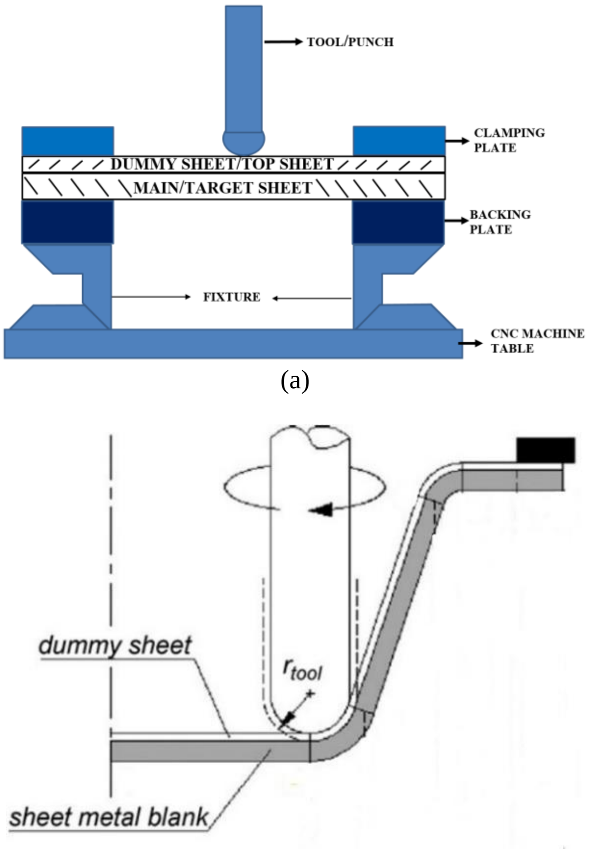
shows the schematic representation of deformation of target sheet via virtual increase in tool size.



(a)

(b)

Fig. 1. (a) Layout of SPIF process with dummy sheet; (b) Schematic representation of deformation of target sheet via virtual tool size [4]

Worldwide researchers have made research efforts in studying deformation mechanics and forming forces in SPIF process. For example, Duflou et al. [8] investigated the influence of tool size, step size and wall angle on forming force. It was concluded that forming forces increases as step size, tool size and wall angle increases. Forming forces was found to be directly proportional to step size. Result obtained with wall angle 60° shows a drop in the force required to deform the sheet metal. This was explained by localised necking, which is usually present in parts that have wall angles near the maximum achievable with a conventional top down single point incremental forming tool path. Formed part which gets fractured will show this same peak and subsequent drop in force magnitude but will develop tears before reaching a minimum force level and slowly increasing again. Part failure prediction may be possible using this rapid drop in force as an indicator.

Ambrogio et al. [9] found that the force gradient after the peak can be effectively considered as a critical indicator to detect and prevent fracture/failure of formed part. Duflou et al. [10] studied the influence of tool diameter, step size, wall angle and thickness of sheet metal on forming forces. It was concluded that by increasing the vertical step size, tool diameter, wall angle or sheet thickness, the force increases. Durante et al. [11] conducted a study on the influence of tool rotation on forming forces and it was pointed out that the rotation has no considerable influence as it reduces the value of the in-plane forces. Petek et al. [12] studied the effect of wall angle, tool rotation, vertical step size, tool diameter and lubrication on forming forces. It was reported that forming forces increase as wall angle, tool diameter and step size increases. Bagudanch et al. [13] presented the influence of various SPIF process parameters on forming forces. The parameters analysed were the tool diameter, the vertical step size and the spindle speed. It is concluded that axial force increases as tool diameter and vertical step size increase. But as spindle speed increases forming force decreases. Bahloul et al. [14] applied their efforts to minimize thinning rate and maximum load force. Initial sheet thickness and wall angle were found to be significant process parameters influencing force and sheet thinning while tool diameter showed more influence on the maximum tool load than in the sheet thinning. The sheet thinning exhibited more sensitivity to the vertical step size than to the tool diameter. Aerens et al. [15] studied the incremental forming of truncated cones with different materials using experimental and statistical analyses. Regression formulae were proposed to predict the triple forming forces including axial, radial, and tangential components from input variables including wall angle, initial thickness, tool diameter, and vertical pitch. They established empirical formulae to predict the forces occurring during the single point incremental forming process. Mirnia and Dariani [16] studied the deformation in SPIF process using upper bound approach. It was considered that the forming forces acting on the tool are in axial, radial, and tangential directions as shown in Figure 2. It was reported that by increasing the tool diameter wall angle and vertical pitch tangential force increases.

Kumar and Gulati [17] studied the influence of sheet thickness, step size, tool diameter, tool shape, spindle speed, wall angle and feed rate on forming forces in SPIF process. It was concluded that forming force increases with increase in sheet thickness, step size, tool diameter, wall angle, spindle speed.

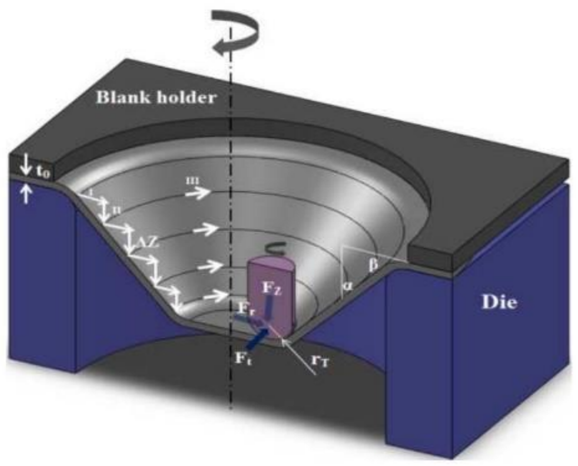


Fig. 2. Forming forces during SPIF process [16]

The major advantage of SPIF process is the low forming forces because of incremental deformation characteristics. But when SPIF process is performed with dummy sheet at the top of target sheet there is rise in magnitude of forming forces. This is because of increase in cumulative thickness of sheet (dummy sheet together with target sheet) and as sheet thickness increases forming forces increases. Thus, it is very important to study the forming forces in SPIF process using dummy sheet. As two sheets are deformed simultaneously the force will be higher and requires further investigation. Generally forming force is a limiting factor for the selection of machinery. In other words, structures of the machine (including spindle, frames, holding devices and joints) should be strong and robust enough to withstand such magnitude of forming forces and also able to deform raw sheet metal [18]. It also helps in prediction of material failure i.e. the probability of occurrence of crack can be predicted in SPIF process by keeping online track of maximum force and carefully observing its trend [19]. Also, no research efforts have been made to study the forming force in SPIF process with dummy sheet. So, the objective of the present work is to investigate the influence of process parameters on forming force and estimate the optimum combination of process parameters for minimum forming force in SPIF process using dummy sheet. For the present work five process parameters namely dummy sheet thickness, tool size, step size, wall angle and feed rate are considered. Taguchi L_{18} orthogonal array (OA) was used to study the influence of process parameters on forming force. For the present work Taguchi L_{18} orthogonal array suggests 18 experimental runs with all possible combination of process parameters. On the other hand, design of experiments strategy such as full factorial etc. suggests 243 number of experimental runs (with 5 process parameters each with 3 levels) resulting more data to handle and analyse which increases the probability of human error.

1.1 Selection of process parameters

In the present study, five process parameters namely dummy sheet thickness, tool size, step size, wall angle and feed rate are considered. The process parameters are selected on the basis of available experimental setup, reviewed literature and their influence on forming force. As also reported by Kumar et al., [28] that most investigated process parameters influencing forming force are step size followed by tool diameter, wall angle, sheet thickness, spindle speed and feed rate. Spindle speed is not considered in the present study because it creates unnecessary vibrations during forming operation and deteriorate the surface characteristics of formed part.

2. Experimental plan

In the present work influence of dummy sheet thickness, tool size, step size, wall angle and feed rate on forming force is studied. Two levels of dummy sheet thickness and three levels of other process parameters are taken. Table 1 shows the process parameters with their levels. Table 2 represents the values of parameters held constant for experimental investigation. Experiments are designed according to Taguchi L_{18} OA. Total 18 experiments were conducted. Experimental setup (Figure 3) consists of conventional three axis CNC milling machine and a milling tool dynamometer which is mounted on CNC machine table. The CNC machine tool is of M/s Batliboi product with model "DART" having a Siemens controller (Sinumerik 802-D) while the make of dynamometer unit is "M/s Syscon Instruments Private Ltd, Bangalore" with model "SPL". A data acquisition (DAQ) software is used to record the value of forming force in 3 axial directions.

Table 1 Process parameters and their level

Sl. No.	Parameters	Unit	Level 1	Level 2	Level 3
1	Wall angle	degree	40	55	70
2	Step size	mm	0.4	0.7	1
3	Tool size	mm	6	9	12
4	Feed rate	mm/min	1500	3000	4500
5	Dummysheet thickness	mm	0.71	0.91	-NA-

For the present experimental investigation three tools hemispherical ended (HSS M-2 grade-HC) of diameter 12 mm, 9 mm and 6 mm are used.

Table 2 Values of process parameter held constant

Parameter	Unit	Value
Tool path type	NA	Contoured
Spindle speed	rpm	0
Target Sheet thickness	mm	0.91
Top diameter of cone	mm	130
Tool material	NA	HSS
Max. forming depth	mm	48 mm

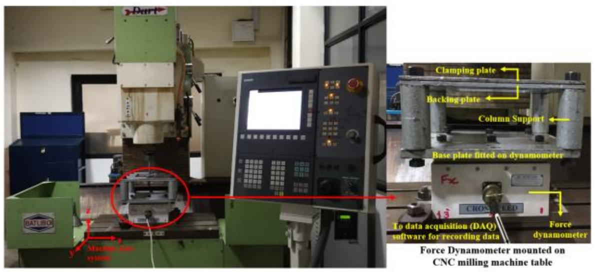
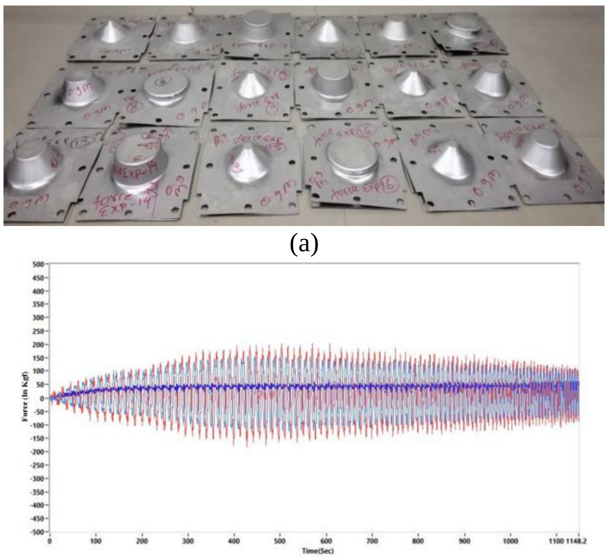


Fig. 3. Experimental setup for SPIF using dummy sheet

3. Results and Discussion

With respective experimental run order (Taguchi L-18 OA), the value of forming force is measured and maximum or peak value of forming force is selected as response. Table 3 shows measured value of forming force with respective experimental run order. Figure 4 depicts (a) Parts formed by SPIF process with dummy sheet as per experimental run order (b) Forming force value obtained from force dynamometer. Figure 5 shows the Normal probability Plot. Figure 6 shows the main effect plot for forming force. From the ANOVA table (Table 4) it is found that dummy sheet thickness (t_d), tool size (d_t), step size (s) and wall angle (w) are found to be significant process parameters influencing forming force. Feed rate (f) is found to be insignificant. As dummy sheet thickness (t_d) increases the maximum value of forming force increases. This is due to the fact that more sheet metal is available for deformation per loop (i.e. more sheet metal is subjected to forming operation per loop). So, more resistance to deformation is offered by material. Thus, more energy (in terms of forming force) is required to deform the sheet metal. As tool size (d_t) increases forming forces increases. It is because the zone of contact between tool and sheet metal blank increases. With higher tool size the forces are distributed relatively over a larger area. This increases the area on which force is concentrated and due to this increase in area of contact between tool and the sheet takes place i.e. more sheet metal is subjected to deformation. Since more area of sheet metal is subjected to the deformation per loop, the energy (in terms of forming forces) required for deformation increases.


(a)

(b)

Fig.4 (a) Parts formed by SPIF using dummy sheet as per experimental run order; (b) Force trend recorded by dynamometer's data acquisition (DAQ) software

Table 3 Experimental run order with measured response

Ex. No.	Dummy Sheet thickness (mm)	Tool Size (mm)	Step Size (mm)	Wall Angle (Degree)	Feed Rate (mm/min)	Peak Forming Force (N)
1	0.71	6	0.4	40	1500	1981.62
2	0.71	6	0.7	55	3000	2540.79
3	0.71	6	1	70	4500	2844.9
4	0.71	9	0.4	40	3000	2354.4
5	0.71	9	0.7	55	4500	3080.34
6	0.71	9	1	70	1500	3492.36
7	0.71	12	0.4	55	1500	3021.48
8	0.71	12	0.7	70	3000	3462.93
9	0.71	12	1	40	4500	2992.05
10	0.91	6	0.4	70	4500	2589.84
11	0.91	6	0.7	40	1500	2521.17
12	0.91	6	1	55	3000	3325.59
13	0.91	9	0.4	55	4500	3050.91
14	0.91	9	0.7	70	1500	3570.84
15	0.91	9	1	40	3000	3256.92
16	0.91	12	0.4	70	3000	3580.65
17	0.91	12	0.7	40	4500	3247.11
18	0.91	12	1	55	1500	4414.5

Further as step size (s) increases forming forces increases. It is because intensity of localized deformation of sheet material increases as step size increases. Also, higher step size intensifies the amount of localized deformation of sheet metal which in turn increases forming forces. (i.e. in a particular loop, deforming 0.4 mm of sheet metal will require less forming force rather than deforming 1 mm of same sheet metal). The tool tries to pierce/indent the sheet metal at high step size. This results in severe localized stretching and straining of sheet metal which is responsible for increasing the forming forces. Similar results are also reported by [12], [20]. As wall angle (w) increases the forming force increases. At large wall angles more forces is required to deform the sheet metal. From the sine law, "$t_f = t_i \times \sin\alpha$", of conventional sheet metal forming process, it is evident that as wall angle increases the final wall thickness (t_f) decreases. As wall angle increases the deformation energy required to deform the sheet metal in order to achieve the required final wall thickness (t_f) (with reference to sine law) increases. This deformation energy is supplied to sheet metal in the form of forming forces. Also, at lower wall angle bending is predominant but at steeper wall angles the sheet is deformed by severe stretching as the localised deformation is very high. Interestingly the rate at which forming forces increases when wall angle is varied from 40º to 55º (i.e. from level 1 to level 2) is higher than the rate at which forming force increases when wall angle is varied from 55º to 70º (i.e. from level 2 to level 3) (Figure 6). Such difference in rate of increase of forming forces can be considered as an indicator of material failure/fracture because the limiting wall angle for the sheet material is very close and the fracture can occur if the wall angle is further increased. As feed rate (f) has no considerable influence on forming force. So high feed rate can be used to reduce forming time as there is no undesired effect of it. In fact, there is nominal decrease in forming forces as feed rate increases which is desirable. This is due to the fact that the frictional heat which is generated due to sliding contact between the tool and sheet metal blank, which soften the material (i.e. the ductility of material has increased).

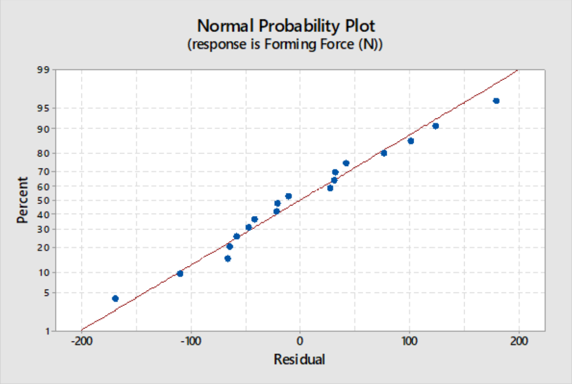


Fig. 5 Normal probability Plot

Thus, less forces are required to deform the sheet metal. The reason why there is nominal decrease in magnitude of forming force is because the contact between the tool and sheet is lubricated. So, the coefficient of friction is reduced. This reduces the frictional heat generated.

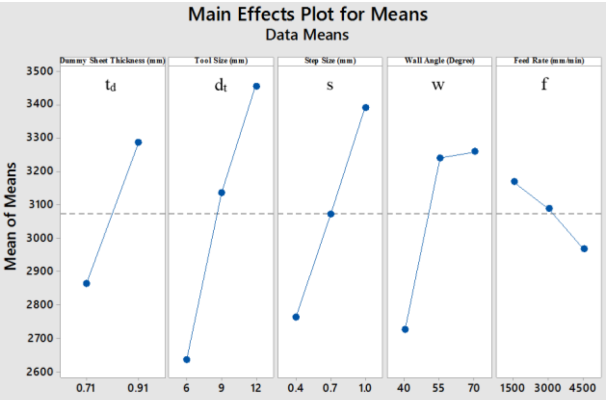
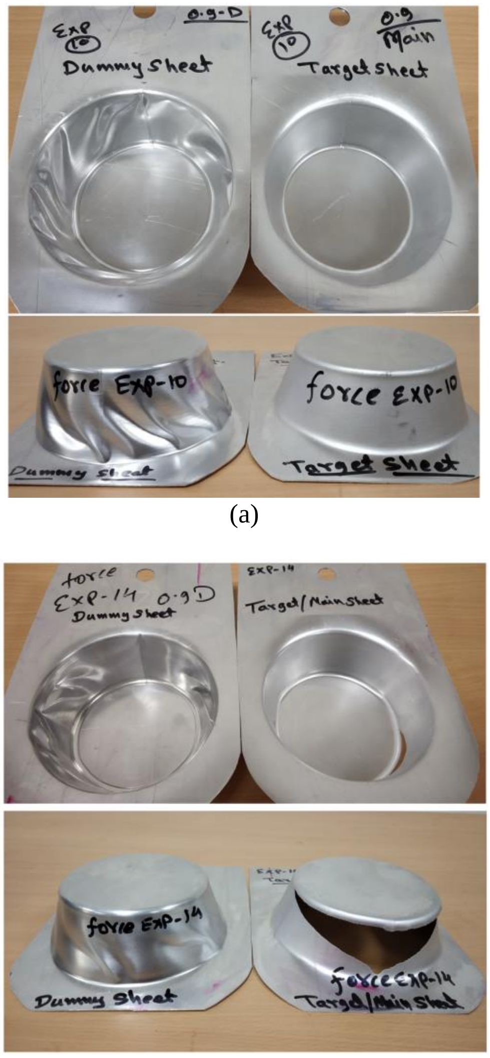


Fig. 6 Main effect plot for forming force

Table 4 ANOVA for forming force

Source	**Degree of Freedom**	**Adj Sum of Squares**	**Adj Mean Square**	**F-Value**	**P-Value**
Dummy Sheet Thickness	1	796600	796600	50.88	0.000
Tool Size	2	2045883	1022942	65.34	0.000
Step Size	2	1170359	585180	37.38	0.000
Wall Angle	2	1092504	546252	34.89	0.000
Feed Rate	2	120905	60452	3.86	0.067
Error	8	125246	15656		
Total	17	5351497			
Model Summary					
R-sq	R-sq (adj)	R-sq (pred)			
97.66%	95.03%	88.15%			

Wall angle of 70º was successfully formed (experiment 10) without failure with SPIF process using dummy sheet. Figure 7 (a) depicts the formed component with wall angle 70º. It is to be noted that dummy sheet suffered with defect known as wrinkling (twisting) of sheet while there is no such defect is present on target sheet. It is somehow associated with flow of material in the direction of tool movement at higher feed. The material of sheet tries to plastically flow in the direction of tool movement at very high feed rate and steeper wall angles. The high feed generates enough frictional heat to soften sheet material. This soften sheet material tries to flow in the direction of tool movement. The inherent moment of inertia i.e. property of sheet metal by which it holds itself along the clamped edges against the movement of tool diminishes at high feed rate and large wall angles. This generally occurs where tool has just lost the contact from the sheet. Such defect is only seen on dummy sheet and defect free forming is observed on target sheet in the present work. Thus, it can be concluded that with the use of dummy sheet not only wear and bulging of sides can be minimized [21] but also wrinkling of target sheet can be eliminated up to major extent. Also, there is no pillow defect observed on target sheet. Figure 7 (b) shows the undesirable effects of large wall angle, high dummy sheet thickness and step size (experiment no. 14). As already discussed, using large wall angle, high value of dummy sheet thickness together with high step size leads severe stretching which requires high magnitude of forming forces. Due to this more thinning of sheet occurs and which ultimately leads to failure of material. It is worth pointing out that the fracture occurs on target sheet but not on dummy sheet. This is because target sheet deforms due to the virtual tool size as shown in the Figure 1 (b). The virtual tool size is always greater than the diameter of forming tool. Thus, failure occur at target sheet and not on dummy sheet due to virtually increased tool size. The possible reason for such type of failure is related to material formability. There is very nominal decrease in formability in SPIF process with dummy sheet [5] and it is a well-known fact that formability in SPIF process is more than conventional sheet metal forming processes [21]. Thus, such small decrease in formability will not cause any problem. Also, formability and forming force in SPIF process can be interrelated. Formability is maximum achievable wall angle/forming depth after which the fracture of sheet occurs. By online monitoring of force, a peak value of forming force occurs after which the fracture occurs. If this peak value of force is controlled then fracture can be delayed up to some extent and formability can be enhanced further. This peak value of forming force depends primarily on mechanical properties of sheet metal and various process parameters used during forming operation. Mechanical properties of sheet metal like strain hardening exponent (n), strength coefficient (K) while process parameters like tool size, step size and wall angle together contribute in peak value of forming forces. If sheet metal has high strain hardening exponent than it means sheet has high formability. Since it corresponds to the value of uniform elongation in engineering stress strain curve on the other hand high strength coefficient means high resistance to deformation [23]. Also, Ambrogio et al. [9] reported that force trend may effectively work as an indicator of material failure. Liu et al. [24] reported that slope of the force curve after the peak value can be identified as a forming failure prediction indicator.



(a)

(b)

Fig. 7 (a) Formed component with wall angle 70 degree; (b) Undesirable effect of large wall angle, high dummy sheet thickness and step size

With online monitoring of forming force fracture can be detected and delayed by proper adjustment of parameters there by enhancing formability. Further from the analysis of formed part processed by SPIF process it can be pointed that there is a critical region at which the wall thickness of formed part is minimum. This region is known as thinning region (sometimes called as thinning band) [25-26]. Formability in SPIF process is also associated with thinning region of formed part. The thinning band generally occurs after initial bending region. It is one of the main reasons for fracture. It is predominant at steeper wall angles. This is due to the fact that stretching intensifies at higher wall angles also SPIF process does not follow sine law of conventional sheet metal forming process. Kumar and Gulati [17] reported that as wall angle increases forming forces increases. Similar trends have been observed in present investigation. Thinning can only be controlled by adjusting and proper selection of process parameters. Once the parameters are finalised and the forming operation is started then there is no control over thinning which ultimately leads to fracture. But with online monitoring of peak force the fracture/failure can be detected and suitable counter measures can be taken to delay the fracture/failure.

4. Predictive Model for Forming Force

A predictive mathematical model is developed to represent the peak or maximum forming force in terms of actual factors and given by equation

$$\textbf{Forming force} = -1362 + (2104\times t_d) + (136.5\times d_t) + (1041\times s) + (17.71\times w) - (0.0665\times f) \qquad (1)$$

Where t_d = dummy sheet thickness; d_t = tool size; s; step size, w = wall angle; f = feed rate. The predicted values are in good agreement with measured experimental values as the error is within acceptable range. Confirmation test are performed in order to verify suitability of developed mathematical model. Some random levels of process parameters are taken within range of design space and with these levels different combinations are made. Confirmation experiments are performed and the results are given in Table 5. The maximum percentage error between predicted and obtained is within acceptable range. Thus, obtained results through experiments are in good agreement with values predicted by developed model.

Table 5: Confirmation Experiments and Results

Test. No.	t_d	d_t	s	w	f	Predicted forming force	Obtained forming force	% error
1	0.71	6	0.5	45	1800	2148.59	2214.8	2.99
2	0.71	9	0.85	50	2000	2997.69	3175.2	5.59
3	0.91	12	0.6	60	3500	3625.14	4165	12.96
4	0.91	9	0.9	65	4000	3603.19	3880.8	7.15

5. Optimum process Parameters for Forming Force

For optimal combination of forming parameters, best level for each process parameter was found according to the highest S/N ratio in the levels of that process parameter. The levels and S/N ratios for the factors giving the lowest forming forces are given in Table 6. For estimation of optimum forming force Equation (2) is used [27]. It is as follows:

$$\boldsymbol{\mu_{FF,opt} = t_{d1} + d_{t1} + s_1 + w_1 - (3\times\mu_{FF,avg})} \qquad (2)$$

$\mu_{FF,opt}$ = 1764.72 N

Where, t_{d1} is value of dummy sheet thickness at level 1 i.e. 0.71mm, d_{t1} is value of tool size at level 1 i.e. 6 mm, s_1 is value of step size at level 1 i.e. 0.4 mm, w_1 is value of wall angle at level 1 i.e. 40° and $\mu_{FF,opt}$ is value of average forming force i.e. 3073.8 N. The confidence intervals (95%) of confirmation experiments (CI_{CE}) are calculated using

$$CI_{CE} = \sqrt{F_{\alpha(1,f_e)} V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \qquad (3)$$

Where, $\mathbf{F\alpha_{(1,\,fe)}}$ = The F-ratio at the confidence level of (1-α) against DoF 1 = 5.32; $\mathbf{f_e}$ = Error degree of freedom = 8; **R** = Sample size for conformation experiments = 3; $\mathbf{V_e}$ = Error variance = 15656; $\mathbf{N_t}$ = Number of trails = 54; **DoF** = Total degrees of freedom associated in the estimate of mean response = 9; $\mathbf{n_{eff}}$ = $N_t/(1+DoF)$ = 5.4. After substituting these values in equation (3) the CI_{CE} is found to be ±207.109**.** The predicted mean of forming force is $\mu_{FF,opt}$ = 1764.72 N. The 95% of predicted optimal forming force is =

$(\mu_{FF,opt} - CI_{CE}) < (\mu_{FF,opt}) < (\mu_{FF,opt} + CI_{CE})$

i.e.
$(1764.72–207.11)<(\mu_{FF,opt}=1764.72)<(1764.72+207.11)$

Which gives $1557.61 < (\mu_{FF,opt} = 1764.72) < 1971.83$

The optimum forming force obtained from equation (2) was compared with value obtained from equation (1) and with confirmation experiment at optimal setting of process parameters. The comparison is given in Table 7. The value of forming force obtained through experiment i.e. 1967.85 N at optimum setting of process parameters lies within the range of C.I. of predicted optimal values

Table 6 Optimum set of process parameters

Parameter	**S/N ratio**	**level**	**Corresponding Forming force (N)**	**Value**	**Avg. forming force $\mu_{FF,avg}$**
(t_d)	-69.01	Level **1** t_{d1})	2863.43 N	0.71mm	3073.8 N
(d_t)	-68.30	Level **1** d_{t1})	2633.99 N	6 mm	
(s)	-68.66	Level **1** (s_1)	2763.15 N	0.4 mm	
(w)	-68.56	Level **1**(w_1)	2725.55 N	40º	

Table 7 Comparison of optimum forming force

Forming force	**Value N)**
From equation (1)	1776.39
From equation (2)	1764.72
Obtained through experiment	1967.85

6. Conclusion

In the present experimental investigation influence of process parameters on forming force is studied in SPIF process using dummy sheet. The process parameters namely dummy sheet thickness, step size, tool size, wall angle and feed rate on forming force were considered for study. Experiments are performed as per Taguchi L18 Orthogonal array design plan. Following conclusions are drawn from the experimental analysis:

(i) There is considerable influence of dummy sheet thickness, tool size, step size and wall angle on forming force.

(ii) As dummy sheet thickness, tool size, step size and wall angle increases forming force increases.

(iii) Feed rate is insignificant parameter. Thus, higher feed rate can be used to reduce the forming time.

Further, mathematical model for predicting forming force is developed. The results obtained with the model are found to be in good agreement with experimental results.

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Nomenclature

Symbol	Meaning	Unit
t_d	Dummy sheet thickness	mm
d_t	Tool size	mm
s	Step size	mm
w	Wall angle	degree
f	Feed rate	mm/min
$\mu_{FF,avg}$	Avg. forming force	N
$\mu_{FF,opt}$	Optimal forming force	N
Dof	Degree of freedom	--
CI_{CE}	Confidence interval	--
f_e	Error degree of freedom	--
N_t	Number of trails	--
R	Sample size for confirmation experiments	--
V_e	Error variance	--
OA	Orthogonal array	--