An Experimental Investigation of Some Relevant Process Parameters Affecting Formed Thickness in ISMF Process

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Abstract

In this paper, a systematic approach to investigate the effect of some relevant process parameters on thickness variation aspect in incremental sheet metal forming (ISMF) process has been studied. The thickness variation aspect was investigated by disclosing the effects of four discrete process parameters: number of forming passes χ_1, typology of forming speed χ_2, direction of tool travel relative to the rolling direction χ_3, and typology of tool path χ_4. The proposed systematic approach utilizes design of experiment (DOE) and analysis of variance (ANOVA) as a base to study the effects of four process parameters and different influential combinations. The analyses results have shown that number of forming passes χ_1, and direction of tool travel relative to the rolling direction χ_3 have greatest effect on the thickness variation. It is demonstrated that the response table and response graph, main effect plot, analysis of variance ANOVA and predictive model generation are powerful systematic procedure to disclose the impacts of the process parameters on the thickness variation.

Keywords: incremental sheet metal forming ISMF, design of experiment DOE, analysis of variance ANOVA, response table, response graph, multiple regression.

الدراسة العملية لبعض العوامل المؤثرة على سمك التشكيل في عملية التشكيل التزايدية للصفائح المعدنية

الخلاصة

يهدف البحث الحالي إلى دراسة تأثير بعض العوامل المؤثرة على اختلاف السمك في عمليات تشكيل الصفائح التزايدية. العوامل التي تم دراستها هي: عدد مراحل التشكيل χ_1 , نوع سرعة التشكيل χ_2 , اتجاه حركة عدة التشكيل بالنسبة إلى اتجاه الدلفنة χ_3, ونوع مسار العدة χ_4. دراسة تأثير هذه العوامل الأربعة وتداخلاتها على اختلاف السمك تم بالاعتماد على طريقة تصميم التجارب DOE وطريقة تحليل التباين ANOVA. من خلال تحليل النتائج تم التوصل إلى أن عدد مراحل التشكيل و اتجاه حركة عدة التشكيل بالنسبة إلى اتجاه الدلفنة لهما التأثير الأعظم على اختلاف السمك. كذلك أثبتت الدراسة إن جدول الاستجابة, مخطط الاستجابة, مخطط التأثير الرئيسي, تحليل التباين, ومعادلات التنبوء بالسمك هي أدوات وأساليب متميزة للكشف عن مدى تأثير العوامل المدروسة على اختلاف السمك.

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Nomenclature

χ_1	Control Factor
Adj R^2	Adjusted Coefficient of Multiple regression
AIP_ATP	Adaptive Iso-Parametric Tool Path
CF	Constant Forming Speed
df	Degree of Freedom
DP	Double Pass Forming
E	Percentage Error
F_C	Calculated Fisher-Ratio
FS	Forming Speed [mm/min]
F_T	Tabulated Fisher-Ratio
i	Rank Order
IP_ATP	Iso-Parametric Tool Path
K_r	Number of Carriers
L	Length of Linear Segment [mm]
n	Sources of Variations
PCAD	Points of CAD Model
P_i	Probability
P-value	Probability for Significance
r	Correlation Coefficient
R^2	Coefficient of Multiple regression
RD	Rolling Direction
SF	Scaling Factor [mm]
SP	Single Pass Forming
SSE	Error Some of Square
SST	Total Sum of Square
t	Measured Sheet Thickness [mm]
T	Forming Time [min]
SST	Total Sum of Square
t	Measured Sheet Thickness [mm]
T	Forming Time [min]
TD	Transverse Direction
TF	Translation Factor [mm]
t_p	Predicted Sheet Thickness [mm]
VF	Variable Forming Speed

1.Introduction

Due to the recent diversification of the customer's demand and fast development of the manufacturing automation technology, new manufacturing methods for a small-size production need to be developed. By the early nineties research efforts succeeded in the development of a new non-conventional sheet metal forming process, namely Incremental Sheet Metal Forming (ISMF), as a new promising technology [1]. ISMF process utilizes the ordinary CNC milling machine to realize the intended shapes. The process characteristics and deformation modes for such a non-conventional manufacturing process are different from the conventional manufacturing processes due to the absence of direct contact between the raw material and the "former", and the dedicated tools are dispensed with. Some research efforts have been directed towards the ISMF process. Dai et al. [2] analyzed the axially symmetric incremental forming under ideal situation. The flow of metal has been controlled assuming even

deformation that makes the distribution of the strain in the final formed specimen even. Investigation of wall thickness uniformity was undertaken by Kim and Yang [3], using an experimentally double-pass forming method to improve the formability in the ISMF process. A systematic investigation as an attempt to approximate the ISMF deformation analysis was made by Iseki [4] based on the strip method. To be able to understand the physical phenomena involved in ISMF technique, the process of this technique was studied by Pohlak [5]. The study utilizes both types of 2D and 3D finite element analyses on the incremental sheet metal forming without support (negative ISMF) and the incremental sheet metal forming with support (positive ISMF). Ambrogio et al. [6] proposed a preliminary study to integrate numerical/ experimental procedure to limit the shape defects between the obtained geometry and the desired one. Hussain and Gao [7] presented a viable method to test the thinning limits of sheet metal in negative incremental sheet metal forming using Cosine's law of thickness distribution. An experimental incipient study of the effects of some ISMF process parameters was undertaken by Kopac and Kampus [8]. The assessment of the sheet metal formability was assumed to obey plane stress state. The tool trajectory, lubrication and final shapes were experimentally tested. Cerro et al. [9] showed a preliminary results obtained with experimental tests and a simple finite element model has been carried out with finite element analysis package ABAQUS. An attempt to improve the surface quality and thickness distribution was undertaken by Attanasio et al. [10]. The work dealt with the optimization of the tool path in two point incremental sheet metal forming process. Filice et al. [11] developed the on-line control of incremental sheet metal forming process by measuring the induced forces between the sheet and the punch. Ambrogio et al. [12] developed a new failure prevention algorithm applied to the negative incremental sheet forming process. A rigorous investigation of the ability to from complex parts using die, which reproduces the part geometry is presented by E. Ceretti et al. [13]. The die is mounted on the table of the CNC machine and the moving punch deforms the sheet up to the die in order to assure the correctness of the geometry and dimensions of the part produced. G.Ambrogio et al.[14] advance their previous work to disclose the ability of ISF technique to achieve a high- customized ankle support with a good measured discrepancy, with respect to the designed surface lower than 1mm.

Although the incremental sheet metal forming process is simple and relatively easy to control the tool movement by utilizing CNC milling machines, the numerous process parameters enclosing the forming process make the ISMF an area of debate. In this work, an experimental campaign has been developed to investigate the effect of the four discrete process parameters on the thickness variation. Each process parameters has been studied based on two levels.

2. Incremental sheet metal forming by CNC milling machine

The incremental sheet metal forming technology utilities the well-known CNC milling machine-tool, where the cutting tool "cutter" is dispensed a cylindrical tool of hemispherical head allowing it to follow any required contour on the blank sheet without any dedicated die. So, the forming forces are concentrated in small limited area and the required shape is "sculptured" by controlling the tool motion over the blank. This technology is termed as incremental sheet forming since the blank is not subjected to a fully plastic deformation during tool movements.

The incremental sheet metal forming does not require expensive tools for manufacturing of complex-shaped parts and the forming equipment is suitable for large variety of products without matched tool or expensive investments. The process starts from a flat sheet metal blank, fixed on a sufficiently stiff base frame mounted on the table of a CNC vertical milling machine. An example is shown in Fig. 1, where a hemispherical tool imposes some plastic deformation on the sheet in a CNC milling machine.

3. Parametric study

The effects of the four chosen control variables (number of forming passes $\chi 1$, typology of forming speed $\chi 2$, direction of tool travel relative to the rolling direction $\chi 3$, and typology of tool path $\chi 4$) on the formed thickness in the negative incremental sheet metal forming process are investigated according to the following scheme:

1. identifying the important control factors and their levels that are expected to influence the formed thickness; using the design of experiment (DOE) method to develop the design matrix;
2. conducting the experiments according to the developed design matrix;
3. analyzing the results using: response graph; main effect plot; normal probability plot; analysis of variance (ANOVA) and predictive model generation.

3.1 Identifying the important control factors and their levels

Table 1 shows the four chosen control factors and their levels.

3.2 Design of Experiments DOE

The design of experiment DOE is an effective approach to optimize the throughput in various manufacturing-related processes [15]. The main merit of the DOE is that the cost of experimentation can be reduced considerably [16]. The full factorial design of experiments FFD is used in this paper, accordingly, 16 experiments must be conducted to cover all the control factors (2^4=16; four control factors, and two levels for each factor) [15].Table 1 shows the four control factors and their levels that will bee experimentally adopted. Table 2 shows the devoted design matrix based on the 2^4 FFD.

3.2 Conduction the Experiments

The oyster-like shape is the nominated CAD model as shown in Fig.2. The tool path for each part is generated using MATLAB programming system, and then post-processed to generate the required G-code utilizing the UG-NX5 Programming system as shown in

Fig.3. The 16 experiments listed in Table 1 are conducted on the XK714B series CNC milling machine (see previous Fig.1). The following explanations highlight some notes about the control factors:

1- Number of forming passes

In single pass forming, the forming tool follows the model in one pass from the start to finish without ceasing the forming process. In order to improve the accuracy of the formed part, a double pass forming is proposed, where the forming tool follows two different CAD models or two shapes to realize the required part. The first shape that the tool follows is termed intermediate shape; the second shape is the required CAD model. The intermediate shape IS is constructed using the 3D transformation technique utilizing scaling and translation technique as follows (see Fig. 3):

$$\dot{P}_i^{IS} = \dot{P}_i^{CAD} \times SF + j \cdot TFi \quad \ldots(1)$$

Where PIS , PCAD is the coordinates of the intermediate shape and CAD model respectively, SF is the scaling factor (SF<1), TF is the translation factor (distance between the two centers C1and C2) , i may be x or y or z, j=1 when i=x or y and j=0 when i=z. The size of the intermediate shape is decided to be half CAD model, therefore (SF=0.5). Figure 4 shows the IPATP used to form the required desired shape (DS) and intermediate shape (IS).

2- Typology of Forming Speed

Both IPATP and AIPATP depend on digitization of the whole surface to a large number of linear segments. Altogether, the lengths of linear segments are different. When the forming process is based on constant forming speed for the entire surface, the forming time will be different from segment to another. Accordingly, the smaller the linear segment, the shorter the forming time is and greater strain rate would be result and vise versa. Accordingly the part will be subjected to a non- uniform strain field. In view of this result, the variable feed rate forming concept is proposed where each linear segment has its own feed rate which is different from the other segments. Therefore, the forming time of all linear segments will be the same resulting in uniform strain rate field. Accordingly, the FS of each linear segment (FSi) can be calculated as follows:

$$FS_1 = \frac{L1}{T1}; FS_2 = \frac{L2}{T2} \quad \ldots. (2)$$

$$\therefore FS_2 = \frac{L2}{L1} FS_1 \quad \ldots. (3)$$

or generally;

$$FS_i = \frac{Li}{L_{\max}} FS_{\max} \quad \ldots. (4)$$

Where FSi , FSmax is the forming speed of the ith segment and maximum forming speed, Li, Lmax is the length of ith segment and the length of the longest linear segment, and T is the forming time.

3-Direction of Tool Travel

Two types of tool motion are discussed; rolling direction (RD) when the forward direction FD is parallel to the RD. On the other hand, when the FD is perpendicular to the RD, this motion is termed TD. Fig.5 shows the two types of tool paths directions relative to the rolling direction.

4-Typology of Tool Path

The tool path in Iso-parametric tool path IPATP is generated based on digitization of the whole surface based on constant increment regardless of the degree of the surface complexity. On the other hand, tool path in adaptive Iso-parametric tool path AIPATP is generated based on digitization of the whole surface based on variable increment according to the local curvature variation of the surface. Each conducted part has been cut-out using electric discharge machine as shown in Fig.6.a.

3.3 Analysis of Factors Influencing Thickness Variation

The variation in the formed thickness is analyzed based on five different statistical criterions: (i) general response table and estimated effect graph, (ii) main effect plot, (iii) normal probability table and normal probability plot, (iv) analysis of variance and (v) regression analysis.

3.3.1General Response Table and Response Graph

Table 3 shows the general response table of the 16 trails. Based on the results of this table, the estimated effect graph is plotted as shown in Fig.7. The response graph highlights that the number of forming passes (χ1) is the most influential factor affecting the measured thickness followed by the direction of tool travel (χ3), type of tool path (χ4) and finally type of forming speed (χ2). It is worth noting that the length of vertical line presented in estimated effect graph is directly related to the statistical significance of a factor, but doesn't give the experimenter a cut-off criterion about the significance. Therefore, next statistical analysis is very important to show whether the calculated effects are "real" or "random variation".

3.3.2 Main Effect Plot Analysis

The main effect plot represents the direction of effect related to each factor when its levels change from low to high level. Fig.8 shows four graphs highlighting the direction of effect of the chosen four control factors. From this figure it is inferred that:

1. The number of forming passes χ1 has a positive effect on the formed thickness. More in detail, the double pass forming greatly enhance the formed thickness (more than 100%). The double pass forming permits splitting of the part height into two small layers. Definitely, detaching the large deformation zone
2. Into two small deformation zones reduces the applied deformation forces which in turn resulting in formability enhancement and forming condition alleviation.
3. The forming speed type (χ2) has a positive effect on the forming thickness, i.e. forming with variable forming speed improves the forming thickness to some extent (up to 3%). Forming with constant forming speed alter the forming time of linear

segments, as their lengths are different. From the other hand, forming using variable forming speed uniform the forming time of these linear segments yields. Accordingly, uniform forming time resulting uniform strain rates distribution in the part surface.

4. Direction of tool travel relative to the rolling direction has a positive effect on the formed thickness. In other words, when the tool motion parallel to the rolling direction RD, the formed thickness will be reduced. If the forming tool direction is orthogonal to the rolling direction (TD), the sheet thickness will improved. These implications can be imputed to the work hardening level of the material which is higher along the rolling direction, where the material pre-stressed, its capacity to resist additional deformation is reduced.
5. Typology of the tool path has a negative effect on the formed thickness i.e. the formed thickness is reduced when using AIPATP. This is reasonable implication; consider a curves segment which is a part of the shape required as shown in Fig.9. Assuming that the curve segment shown in Fig.9.a is decomposed into two small linear segments based on IPATP, and the same curved segment was decomposed into one linear segment based on AIPATP (assuming that δ within the affordable limit) as shown in Fig.9.b. Let P is the applied forming force. In case of (Fig.9.b), the whole linear segment RT is under the action of the tangential force Pt for a long
6. Forming time. While, in case of (Fig.9.a) the tangential forces Pt_1 and Pt_2 acting on the segments RS and ST for a short time this will leads to weaken the segment RT more than RS or ST. Therefore, forming with AIP_ATP increase the thinning ration of the sheet.

3.3.3 Normal Probability Table and Normal Probability Plot

The normal probability is a statistical tool which is used to identify whether the estimated effects in the estimated effect graph are "real" or "chance". The normal probability of each estimated effect can be calculated using the following equation [15].

$$\text{Probability(Pi)} = \frac{100(i - 0.5)}{n} \quad \text{.....(5)}$$

Where i is the rank ascending of ith factor based on effect, n number of control factors and their interactions (n=10). Table 4 shows the normal probability table which is plotted as shown in Fig. 10.

Based on normal probability plot, the effects factors which are close to the central middle line represent a chance effect (non- significant effect). On the contrary, effects of factors which are far away from the central line represent real effect or significant effect. Accordingly, in Fig. 10, factors χ_1, χ_2 and χ_4 are quite a way from the central line and are regarded to be significant.

3.3.4 Thickness Analysis of Variance ANOVA

The normal probability analysis beside its advantages, doesn't give an incisive criterion about how far must a factor be from the central line to be significant. ANOVA has this incisive criterion i.e. the F- Fisher test or probability value P- value. Four way ANOVA was used in this study as the number of control factors studied are four. A 95% level of confidence (5% level of significance) is realized. The ANOVA of two level factors are quite simple, than three level factors. Therefore, the MATLAB function "anovan" is used to create the ANOVA table as shown in Table 5.

Based on the degree of freedom column, the FT(0,05,1,5)=6.61[16]. Accordingly, each source of variation which has Fc>FT (6.61) and its P-value P>0.05 is considered to be insignificant factor. Therefore the number of forming passes (χ_1), direction of tool travel relative to the rolling direction (χ_3), the type of tool path (χ_4), and the interaction between (χ1 and χ3) are considered to be significant factors. In view these results, only χ_1, χ_3, χ_4 and $\chi_1\chi_3$ will be considered in the next analysis and the other sources will be excluded. An important implication can be gathered from previous ANOVA, is that χ_2 has a positive effect on the measured thickness (Fig.8), but from the ANOVA table it is observed that this factor is non- significant. This implication indicates that the formed thickness is affected by this factor (χ_2) within the maximum forming speed used (1500 mm/min), but this effect is non- significant. Therefore, conducting the experiments within a more than 1500 mm/min may greatly alter the results.

3.3.5 Predictive Model Generation

A multiple regression analysis was used to generate a prediction model that correlates between the significant factors (χ1, χ3, χ4, χ1χ3) and the measured thickness. Taking into account a multiple regression coefficient $R^2 \geq$ 95% and correlation coefficient $r \geq$ 0.9, the following predictive model is generated:

$$t_p = o.6612 + 0.2273\ \chi_1 + 0.0782\ \chi_3 - 0.0285\ \chi_4 + 0.023\ \chi_1\chi_3 \quad ....(6)$$

Table 6 shows the statistical fitting parameters and a comparison between the predicted thickness and experimental thickness. The calculated R2= 98.97 means that only 1.03% of the total variation is not explained by the model, the coefficient of correlation (r=0.99) reveals that the model generated is strong.

5. Conclusions

In this paper the factors influencing the formed thickness incremental sheet metal forming ISMF process have been experimentally investigated by using the advanced engineering statistical methods. The following points can be concluded:

- the analysis of variance (ANOVA) proved to be efficient tool to predict the significance, factors-which affect the forming process-and interaction effects of different influential combinations.
- the analysis results have shown that the most important parameter affecting the formed thickness in the incremental sheet metal forming process is the number of forming passes χ_1 followed by the direction of tool motion relative to the rolling directionχ_3.
- the typology of tool paths χ_4 and the interactions between the number of forming passes and the direction of tool travel (χ_1. χ_3), have significant effects on formed thickness.
- the predictive model is an efficient forecasting tool that correlate between the desired formed thickness and the process parameters.

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Table (1) The Four Control Factors and their Levels

			Levels			
			Original		Coded	
S.no.	Control Factors	Notation	Low	High	Low	High
1	Number of Forming Passes	χ_1	Single Pass (SP)	Double Pass (DP)	-1	+1
2	Typology of Forming Speed	χ_2	Constant Forming Speed (CF)	Variable Forming Speed (VF)	-1	+1
3	Direction of Tool Travel Relative to Rolling Direction	χ_3	Rolling Direction (RD)	Transverse Direction (TD)	-1	+1
4	Typology of Tool Path	χ_4	Iso-parametric Tool Path IP$_A$TP	Adaptive Iso-parametric Tool Path AIP$_A$TP	-1	+1

Table (2) The Results of the 24 design matrix Based FFD

$S_{n.}$	Coded Value				Original Value				t [mm]
	X_1	χ_2	χ_3	χ_4	χ_1	χ_2	χ_3	χ_4	
1	-1	-1	-1	-1	SP	CF	RD	IP$_A$TP	0.40
2	+1	-1	-1	-1	DP	CF	RD	IP$_A$TP	0.82
3	-1	+1	-1	-1	SP	VF	RD	IP$_A$TP	0.40
4	+1	+1	-1	-1	DP	VF	RD	IP$_A$TP	0.87
5	-1	-1	+1	-1	SP	CF	TD	IP$_A$TP	0.50
6	+1	-1	+1	-1	DP	CF	TD	IP$_A$TP	1.00
7	-1	+1	+1	-1	SP	VF	TD	IP$_A$TP	0.50
8	+1	+1	+1	-1	DP	VF	TD	IP$_A$TP	1.00
9	-1	-1	-1	+1	SP	CF	RD	MIP$_A$TP	0.33
10	+1	-1	-1	+1	DP	CF	RD	MIP$_A$TP	0.70
11	-1	+1	-1	+1	SP	VF	RD	MIP$_A$TP	0.37
12	+1	+1	-1	+1	DP	VF	RD	MIP$_A$TP	0.74
13	-1	-1	+1	+1	SP	CF	RD	MIP$_A$TP	0.46
14	+1	-1	+1	+1	DP	CF	TD	MIP$_A$TP	0.96
15	-1	+1	+1	+1	SP	VF	TD	MIP$_A$TP	0.47
16	+1	+1	+1	+1	DP	VF	TD	MIP$_A$TP	0.99

Table (3) General response Table of the formed thickness

S.no	Thickness [mm]	X1		X2		X3		X4		X1 X2		X1 X3		X1 X4		X2x3		X2x4		X3x4	
		-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	-1	1	-1	1	-1	1
1	0.4	0.4		0.4		0.4		0.4	0.4		0.4		0.4		0.4		0.4		0.4		0.4
2	0.87		0.82	0.82		0.82		0.82		0.82	0.82		0.82		0.82		0.82		0.82		0.82
3	0.4	0.4			0.4	0.4		0.4	0.4			0.4	0.4		0.4	0.4		0.4			0.4
4	0.82		0.87		0.87	0.87		0.87		0.87		0.87	0.87		0.87	0.87		0.87			0.87
5	0.5	0.5		0.5			0.5	0.5	0.5		0.5			0.5	0.5	0.5			0.5	0.5	
6	1		1	1			1	1		1	1			1	1	1			1	1	
7	0.5	0.5			0.5		0.5	0.5	0.5			0.5		0.5	0.5		0.5	0.5		0.5	
8	1		1		1		1	1		1		1		1	1		1	1		1	
9	0.37	0.33		0.33		0.33			0.33		0.33		0.33				0.33	0.33		0.33	
10	0.74		0.7	0.7		0.7				0.7	0.7		0.7				0.7	0.7		0.7	
11	0.33	0.37			0.37	0.37			0.37			0.37	0.37			0.37			0.37	0.37	
12	0.7		0.74		0.74	0.74				0.74		0.74	0.74			0.74			0.74	0.74	
13	0.47	0.46		0.46			0.46		0.46		0.46			0.46		0.46		0.46			0.46
14	0.99		0.96	0.96			0.96			0.96	0.96			0.96		0.96		0.96			0.96
15	0.46	0.47			0.47		0.47		0.47			0.47		0.47			0.47		0.47		0.47
16	0.96		0.99		0.99		0.99			0.99		0.99		0.99			0.99		0.99		0.99
Total	10.51	3.43	7.08	5.34	5.17	4.63	5.88	5.49	3.43	7.08	5.34	5.17	4.63	5.88	5.49	5.21	5.3	5.29	5.22	5.14	5.37
Value	16	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Average	0.64	0.42	0.88	0.64	0.66	0.57	0.73	0.68	0.42	0.88	0.64	0.66	0.57	0.73	0.68	0.65	0.66	0.66	0.65	0.64	0.67
Effect		0.46		0.02		0.16		-0.06		-0.01		0.05		-0.02		0.01		-0.01		0.03	

Table (4) Calculations for Normal Probability Plot of Formed Thickness.

Control Factors And their Interactions	Estimated effects (E)	Rank Order (i)	Probability $(p_i)=100(i-0.5)/10$
χ 1	0.4562	1	5
χ 3	0.1563	2	15
X1 χ3	0.0488	3	25
X 3χ4	0.0256	4	35
χ 2	0.0213	5	45
X 2χ3	0.01	6	55
X1 χ4	-0.0078	7	65
X1 χ2	-0.0078	8	75
X2 χ4	-0.0144	9	85
χ4	-0.0588	10	95

Table (5) Analysis of Variance Results of Formed Thickness for Oyster shape.

Source	Sum Sq.	d.f.	Mean Sq.	F_c	Prob>F
χ1	0.82701	1	0.82701	1744.679	0.0000*
χ2	0.0022231	1	0.0022231	4.69	0.082597
χ 3	0.097844	1	0.097844	206.414	0.0000*
χ 4	0.013007	1	0.013007	27.4408	0.0033583*

$\chi 1^* \chi 2$	0.00020164	1	0.00020164	0.42539	0.54305
$\chi 1^* \chi 3$	0.0084364	1	0.0084364	17.7977	0.008338*
$\chi 1^* \chi 4$	0.0011834	1	0.0011834	2.4964	0.17494
$\chi 2^* \chi 3$	0.00053361	1	0.00053361	1.1257	0.33723
$\chi 2^* \chi 4$	0.00020022	1	0.00020022	0.42239	0.54442
$\chi 3^* \chi 4$	0.0031248	1	0.0031248	6.5922	0.050186
Error	0.0023701	5	0.00047402		
Total	0.95613	15			

F_T (0.05, 1, 5) = 6.613 for single and interacted factors

Table (6) Fit Statistics for Formed Thickness (t) of Oyster shape

S. no.	Statistical Parameter	Value
1	SST	0.9561
2	SSE	0.0098
3	df	11
4	K_r	4
5	R^2	98.97
6	Adj.R^2	98.60
7	r	0.9948

Statistical Comparison

S.no	t[mm]	t_p[mm]	|E%|
1	0.40	0.40	0
2	0.87	0.81	6.89
3	0.40	0.40	0
4	0.82	0.81	1.21
5	0.50	0.51	2.00
6	1.00	1.01	1.00
7	0.50	0.51	2.00
8	1.00	1.01	1.00
9	0.37	0.35	5.40
10	0.74	0.75	1.35
11	0.33	0.35	6.06
12	0.70	0.75	7.14
13	0.47	0.46	2.12
14	0.99	0.96	3.03
15	0.46	0.46	0
16	0.96	0.96	0

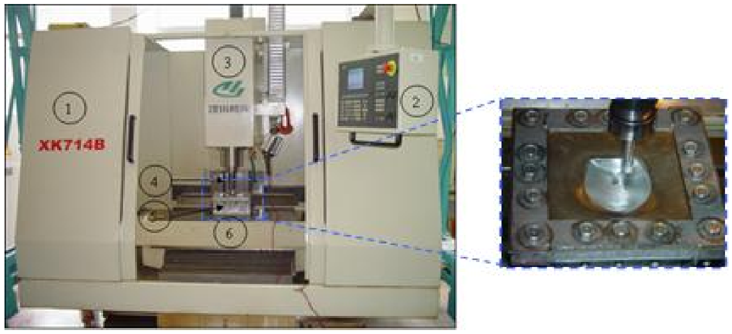

Figure (1) The CNC milling machine used in the experimental campaign (1) CNC machine, (2) Machine controller (3) Movable head, (4) Tool holder (5) Forming frame (6) Machine table

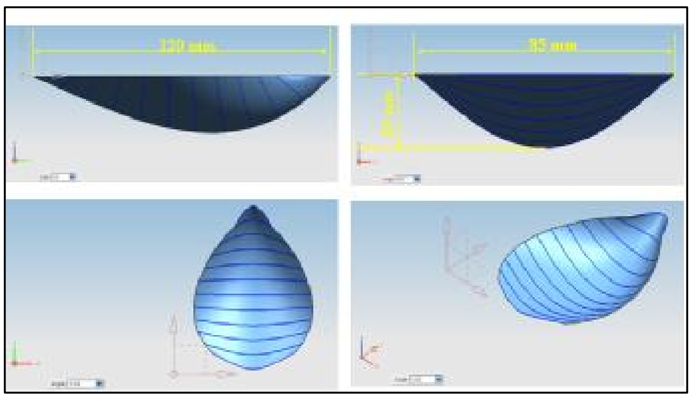

Figure (2) Different sites of the oyster-like shape which show the instantaneous change in the part curvature

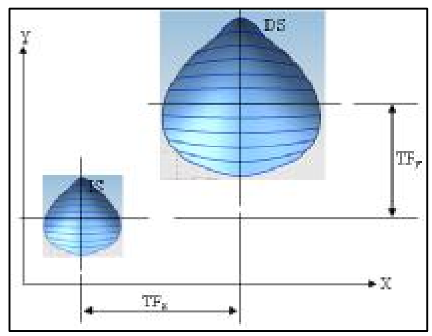

Figure (3) The method of determining the size and location of the intermediate shape (IS) and desired shape (DS).

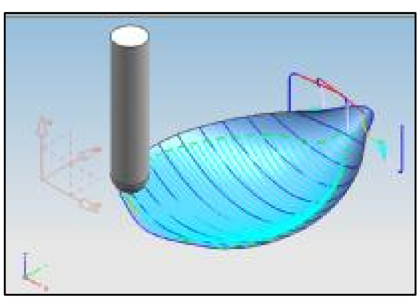

Figure (4) Shows the proposed IPATP to form oyster shape and its intermediate shape.

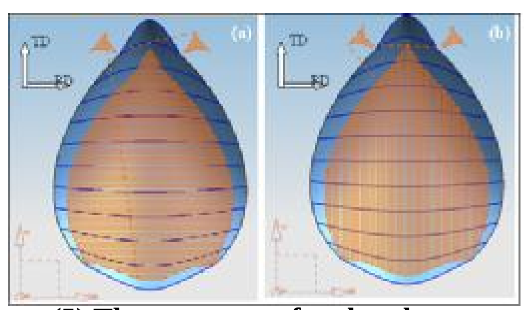

Figure (5) The two types of tool paths generated related to the sheet rolling direction, (a) RD tool path, and (b) TD tool path.

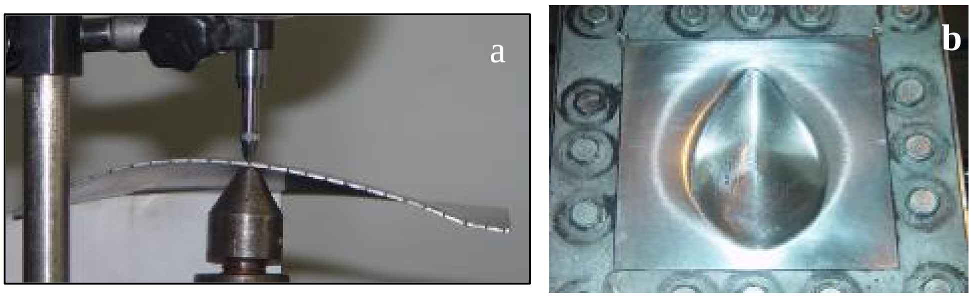

Figure 6 (a) method of measuring thickness,(b) symbol of produced parts

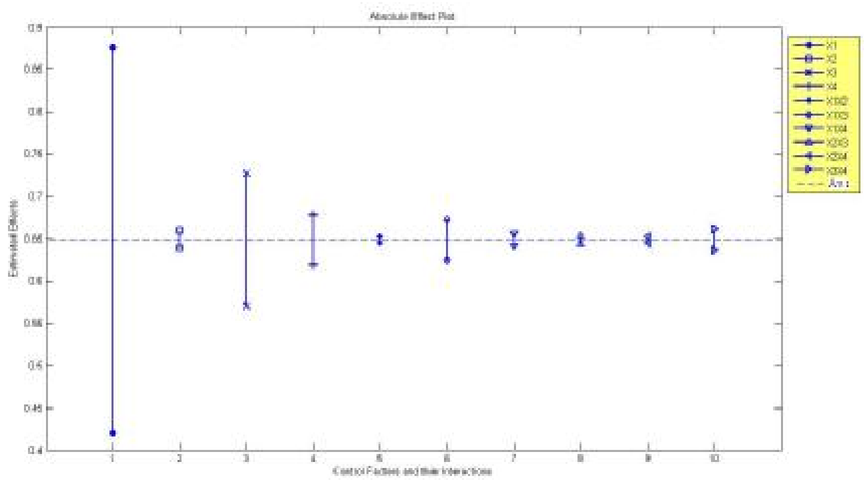

Figure (7) The estimated effect- of the four control factors and their interaction- on formed thickness.

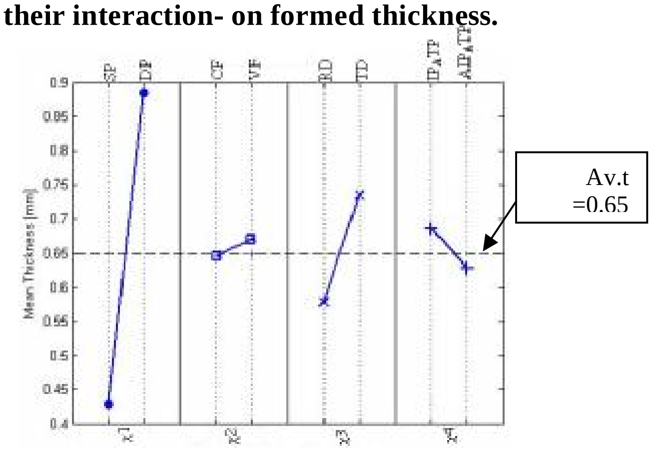

Figure (8) The main effect plot of the control factor.

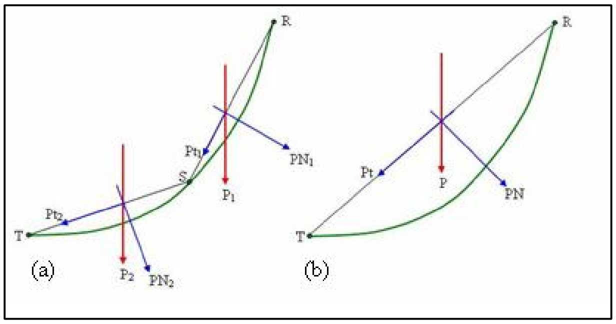

Figure (9) The effect of tool path and forming forces on formed thickness.(a) Decomposition based on IPATP,(b) Decomposition based on AIPATP.

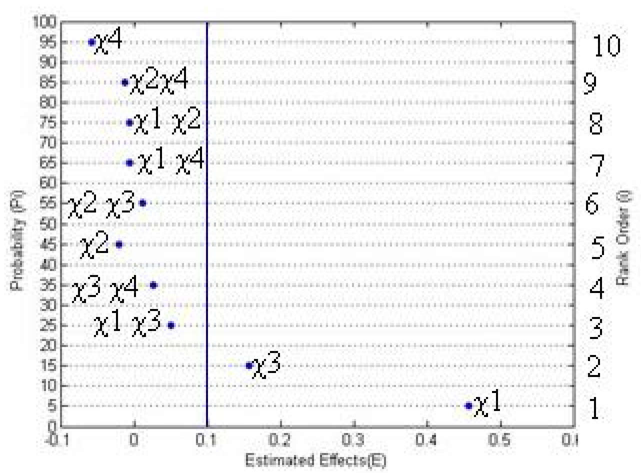

Figure (10) Normal probability plot for formed thickness