EXPERIMENTAL INSPECTION OF RESIDUAL STRESSES INDUCED IN PARTS PRODUCED BY TWO-POINT INCREMENTAL FORMING (TPIF) PROCESS

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Abstract

Residual stresses play a vital role in evaluating the performance of the parts produced by two point incremental forming (TPIF) process. As such. The residual stress in cylindrical cup shapes was analysed by studying three factors namely, tool diameter, step down and tool path. The suggested analysis is based on the main effects plot (MEP), Box-Behnken design (BBD) of experiment and contour plots for the purpose of studying the effects of those component (forming) parameters on the measured residual stresses. The X-ray diffraction (XRD) technique has been utilized for the residual stress measurement. The results showed that the largest effect on the residual stress was caused by the step down parameter, while the lowest influence was due to the tool path factor. In addition, the dual interaction of forming factors giving high residual stresses was obtained by adopting 14 mm tool diameter with each iso-planar tool path and step down values of 0.2 and 0.6 mm separately.

Keywords: Box-Behnken design (BBD), Main effects plot (MEP), Residual stresses, Two-point incremental forming (TPIF), X-ray diffraction (XRD).

1.Introduction

Incremental sheet metal forming (ISMF) is a recent manufacturing technique in which a geometry is formed progressively by inducing a local strain on a flat sheet. This process is useful for rapid prototyping or for establishing custom parts in small batches and can be used as a successful alternative to die-forming due to cost reduction, increased forming constraints and increased efficiency [1]. ISMF is a flexible sheet forming process that adopts manufacturing with layer-bases. The geometric information of part is converted to a series of 2D parameters by ISMF method. Then through the movements of the forming tool, the local plastic deformation is realized layer by layer which in turns can make parts with complicated geometries through a CNC milling machine [2].

Depending upon the existence or absence of a support post or die, the two major types of the process are recognized as Single Point Incremental Forming (SPIF) and Two Point Incremental Forming (TPIF). TPIF is based on the presence of a full or partial die (as shown in Fig. 1), which supports the sheet during deformation. When using TPIF, two points on the sheet will be distorted contemporary: the contact points between sheet and tool and between sheet and die. The sheet deformation method described here allows for increased the geometric accuracy that can be accessed in a single pass compared to SPIF [3, 4].
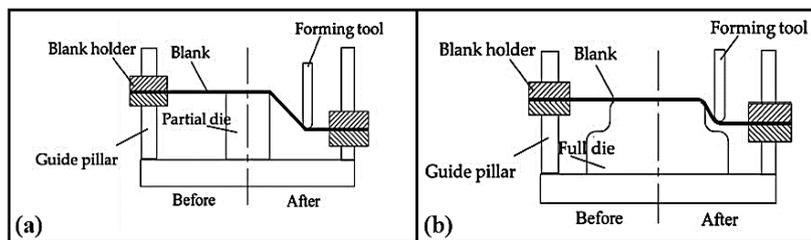

Fig. 1. TPIF process with (a) Partial die (b) Full die [4].

The remaining residual stress in the part plays an essential role in the analysis of ISMF operation as it is considered as a necessary indicator to evaluate the performance of the parts produced by TPIF. Therefore, several studies by many researchers have been devoted for this purpose in recent years.

Abed et al. [5] concluded that the magnitude of residual stresses will be reduced for bottom plates when increasing the thickness of the top plate as well as when using graphite with grease between two plates, a lower residual stress of (60.173 MPa) was obtained. In contrast when using MoS_2, larger residual stresses (146.617 MPa) in the bottom plate will be induced. Jiménez et al. [6] found that there is a relationship between the bending and residual stress distribution with respect to thickness variation of the sheet that influences the microstructure development of the aluminium parts. Alinaghian et al. [7] proved that the step down of 0.25 mm and tool size of 16 mm produced lesser residual stress as well as the variation in the rotational speed does not influence it much. Maaß et al. [8] suggested that the effect of the tool path plan on the induced residual stress is a non-categorical effect. The results showed that the characteristic residual stresses were observed in the bending-dominated regions. Besides, the resulting state of residual stress is less prominent in the case of shear loading domination. Maqbool et al. [9] explained that the proposed forming method can be utilized to control the residual stresses

and shape in the disc springs. Afzal et al. [10] indicated that the comparison between the experimental and FE results demonstrates a good match. Therefore, the developed numerical strategy provides an accurate prediction of the residual stresses and can be used to design the properties of the disc spring by modifying the residual stresses, which is possible by changing the relevant parameters of the ISMF process. Maaß et al. [11] have showed a correlation between the forming mechanisms, process parameters, mechanical properties and the residual stresses of an incrementally formed component. Shearing-induced hardening is recognized as a relevant effect on the state of residual stress induced in cones.

Trzepieciński et al. [12] investigated the state-of-the-art methods features of single point incremental sheet forming (ISF) of lightweight metals. The study focused on the metals exhibit a poor formability in the sheet metal-forming processes. Besides, the paper studied the possibility of forming process of sheet metals in the conventional ISF and thermally- assisted ISF variants as well as the effect of different parameters, i.e., forming tool, forming path, forming parameters on the geometric accuracy and surface finish of products. Daoud et al. [13] used the shot peening approach to reduce the residual stresses induced on the surface of the products. FE simulation was utilized to predict residual stresses at different parameters namely, shot size (D), shot velocity (V), coverage (C), and impact angle (α). The results showed that FE gives a relatively good prediction of the residual stress profiles. Aliemeke et al. [14] employed the Box-Behnken design of experiments to simulate the forming parameters of sandcasting process. A mathematical model was developed using multiple linear regression technique to predict the hardness of the aluminium alloy. The results showed a similar response to the predicted hardness value through developed model.

From the previous studies presented, there is a clear requirement to predict the relevant parameters affecting the residual stresses induced through TPIF process. Consequently, three parameters have been selected and investigated in this work namely, tool diameter, step size and tool path for the purpose of studying their effects on the residual stresses in TPIF process. As such, an experimental investigation on Aluminium sheet (AA-1050) with a specified thickness to disclose the influence of main forming parameters on the residual stresses in two-point incremental forming process has been conducted.

2. Experimental Setup Coefficients

2.1. Equipment

ISMF process is different from other sheet forming operations which have used dies and punches specific to one size and shape of the final product. Besides, ISMF process is distinguished by using CNC milling machine as well as utilizing very simple equipment. These equipment are forming frames and dies, CNC milling machine, forming tool and sheet metal as shown in Figs. 2(a)-(c).

The sheet metals of an Al-alloy (AA1050) have been utilized in all experiments conducted in this work. The preliminary size of the sheet is 220×220×1 mm. Hemispherical head tool of 10, 12 and 14 mm diameter have been used as illustrated in Fig. 2(c). The forming tool length is 100 mm. The material of the tools is manufactured from tool steel with hardness of 60 HRC. For the purpose of achieving the best likely surface finishing at the tool tip, all 3 tools have been polished via suitable finishing paper and grinding paste.
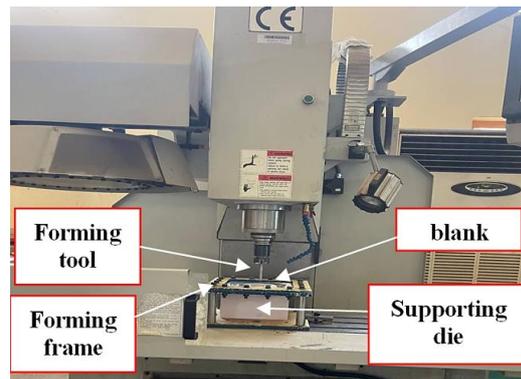
(a)

(b)   **(c)**

Fig. 2. The forming structure adopted for experiments,
(a) TPIF setup, (b) Forming frame, (c) Forming tools.

2.2. Geometry of the parts

Figure 3 shows the geometry of the used formed parts with their dimensions in different views. A cylindrical cup with total depth of 40 mm for all products were used. This geometry strategy is intended for all the nine runs in order to study and comparison the influence of the three used factors in this work with a constant geometry.
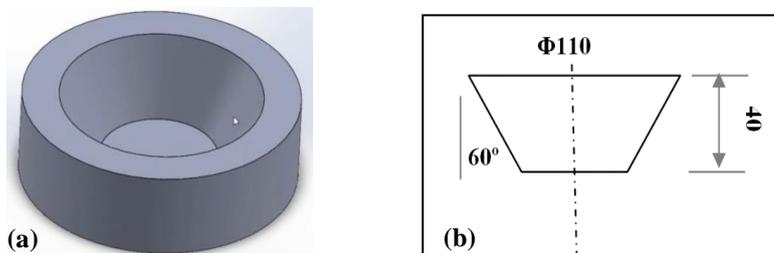
(a)   **(b)**

Fig. 3. The used CAD model for TPIF
(a) Cylindrical cup, (b) Dimensional details.

2.3. Forming parameters

The forming parameters used in this study are tool diameter (D), step down (ΔZ) and tool path (P). Three different values have been utilized for each of these parameters namely, 10, 12 and 14 mm for tool size and 0.2, 0.4 and 0.6 mm for step down. Figure 4 illustrates the cylindrical like cups that have been shaped using TPIF operation. Besides, three categories of tool path were utilized which are helical (P_1), iso-planar (P_2) and bi-directional iso-planar (P_3) tool path as depicted

in Fig. 5. All types of tool paths for the cylindrical shapes have been created and modelled via Siemens PLM (UGS-NX) CAD/CAM package software.

It is worth mention here that the lubrication type, feed rate and rotational speed have been kept constant in all carried out experiments. Machine oil (SAE 30) have been selected as the type of lubricant used while the feed rate and the rotational speed magnitudes were selected of 500 mm/min and 500 r.p.m respectively. The selected forming parameters with their different levels have been described in Table 1.

**Table 1. The proposed parameters with their
levels test model specifications and test conditions.**

No.	Parameter	Units	Levels		
1	Tool Diameter, D	mm	10	12	14
2	Step down, ΔZ	mm	0.2	0.4	0.6
3	Tool Path, P	-	1	2	3

**Fig. 4. Various views of the cups produced
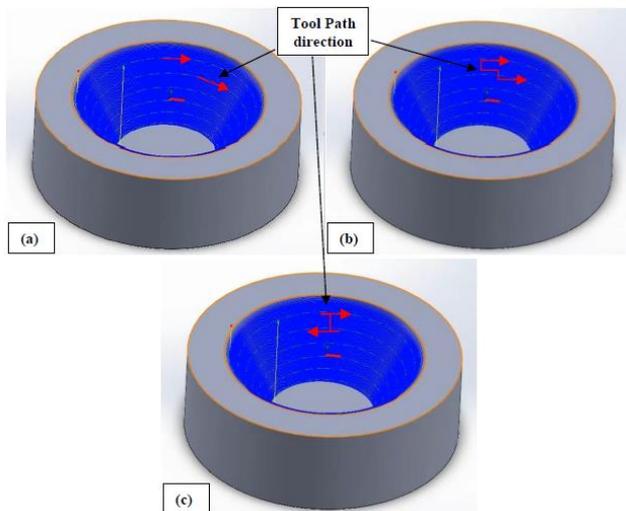(a) TPIF process (b) Produced cylindrical cups.**

**Fig. 5. Types of adopted tool paths (a) Helical path (P_1),
(b) Iso-planar path (P_2), (c) Bi-directional iso-planar path (P_3)**

2.4. Measurement of residual stresses

For both static and dynamic loading applications, the residual stresses play an important role because they influence the operating conditions of the contacting objects either in negative or positive manner depending upon the used application type.

In this paper, a specimen of round shape of 27 mm diameter has been cut from each face of the cylindrical fabricated as shown in Fig. 5(b) in order to determine the residual stress. The determination of residual stress levels in formed specimen has been conducted through the x-ray technique. As a result, an x-ray diffractometer of brand "Shimadzu XRD-6000" has been utilized to measure the residual stress developed in the cups produced by TPIF operation. A series of tests to measure the residual stresses have been performed at the national center for construction labs/Baghdad central Laboratory. Figure 6 shows the x-ray diffractometer "Shimadzu XRD-6000 model" used in this work.

The residual stress was measured at around the center of the specimen via the X-ray diffractometer with the following angles: $2\theta = 157°$ and $\psi = 0°$, $15°$, $30°$ and $45°$. Subsequently, the final amount of the residual stress has been computed through the measurement setup illustrated in Fig. 6.
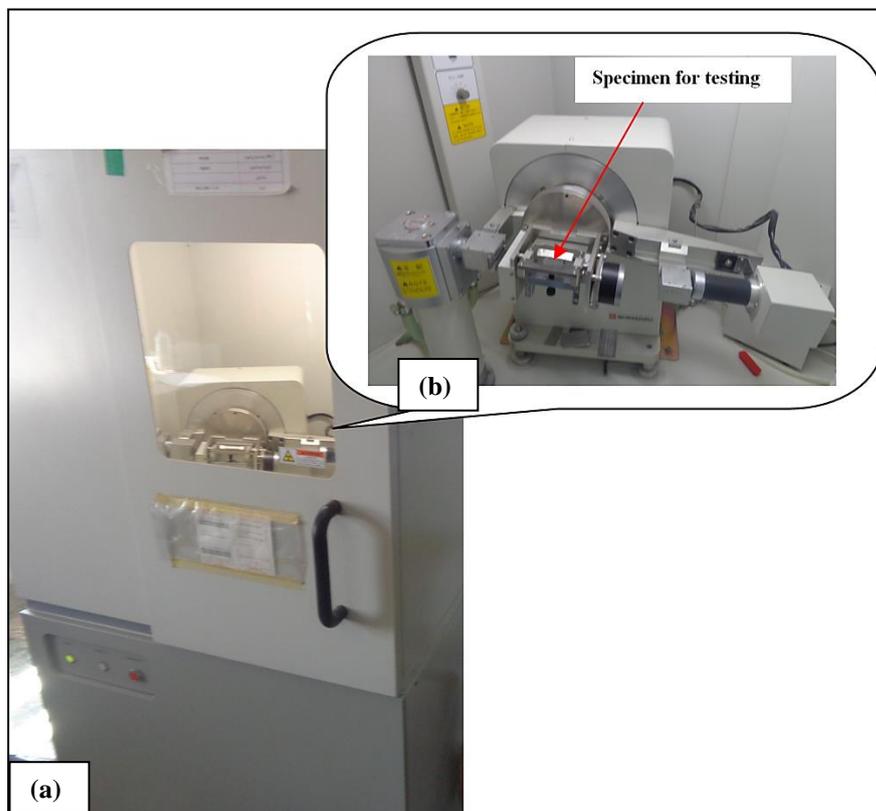

**Fig. 6. X-ray diffractometer (a) Measurement setup,
(b) Major components of the diffractometer with specimen.**

3. Results and Discussion

Box-Behnken design (BBD) of experiment accompanied with D-optimality criterion has been used in this experimental work to construct the layout design of the experimental matrix that includes nine runs by using statistical package software (Minitab 16). Table 2 describes the eventual design layout of the experimental matrix with corresponding results of residual stresses at different proposed control parameters. Because of the tool path is of categorical parameter, the results analysis has been performed in coded units for all parameters at each level. The main effects plot (MEP) and contour plot techniques have been utilized in order to analyse the data extracted from the experimental results for identifying the effects of the dominant parameters on the residual stress in parts produced by TPIF process.

Table 2. The experimental residual stresses according to BBD method.

| No. | Forming Parameters | | | | | | Residual Stress (MPa) |
| | Uncoded Units | | | Coded Units | | | |
	D (mm)	ΔZ (mm)	P	D	ΔZ	P	
1	10	0.6	P3	1	3	3	31.628
2	14	0.2	P2	3	1	2	44.192
3	12	0.6	P3	2	3	3	36.584
4	10	0.6	P1	1	3	1	27.553
5	10	0.4	P3	1	2	3	23.196
6	14	0.6	P2	3	3	2	47.059
7	12	0.4	P3	2	2	3	13.912
8	10	0.4	P2	1	2	2	30.991
9	12	0.2	P1	2	1	1	37.774

I. Main Effects Plot (MEP)

For the purpose of specifying the correlation between the forming factors and the residual stress, main effects plot (MEP) method has been utilized. Figure 7 shows the MEP for all parameters. From this MEF, the tool diameter is directly proportional to the residual stress while step down and tool path factors incorporate both relations within different levels as illustrated in Fig. 7. The MEP also indicates that the parameter that has the largest effect on the residual stress is the step down (ΔZ) while the smallest influence is caused by the tool path (P).
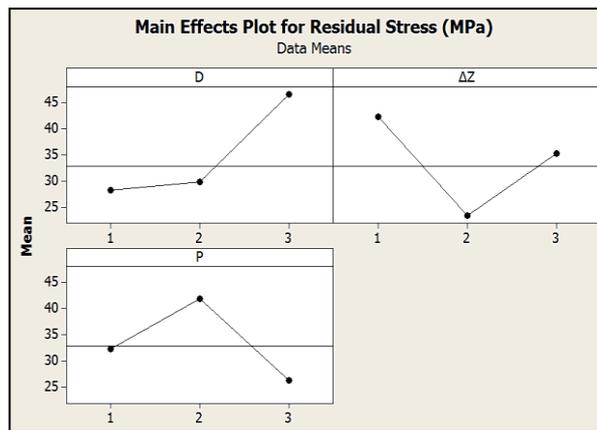

Fig. 7. MEP for residual stress in coded units.

II. Contour Plot

In order to identify the relationship between the interaction of any two forming parameters and the residual stress measured, contour plot technique has been utilized. Such method relies on the colour gradient to determine the influence of the factor pair. Figure 8 shows the contour plots for all parameters.

Contour plot, Fig. 8(a), indicates that the tool diameter (D) at the higher level (14 mm) accompanied with approximately the intermediate level of the tool path (iso-planar "P_2") generate the largest residual stresses. Additionally, the contour plot of step down-tool diameter "ΔZ-D" interaction, Fig. 8(b), shows that the highest stress is caused by using both the lowest and highest levels of ΔZ (0.2 and 0.6 mm) with the largest level of D (14 mm) while the minimum stress values have been reached at the intermediate levels of both factors ($\Delta Z = 0.4$ mm and $D = 12$ mm). Figure 8(c) demonstrates that the interaction of the intermediate level of tool path (iso-planar path "P2") with each lower and higher level of ΔZ gives the largest residual stresses while the minimum values are reached by the interaction of only the highest level of tool path "P3" (bidirectional iso-planar) with the intermediate level of ΔZ (0.4 mm).
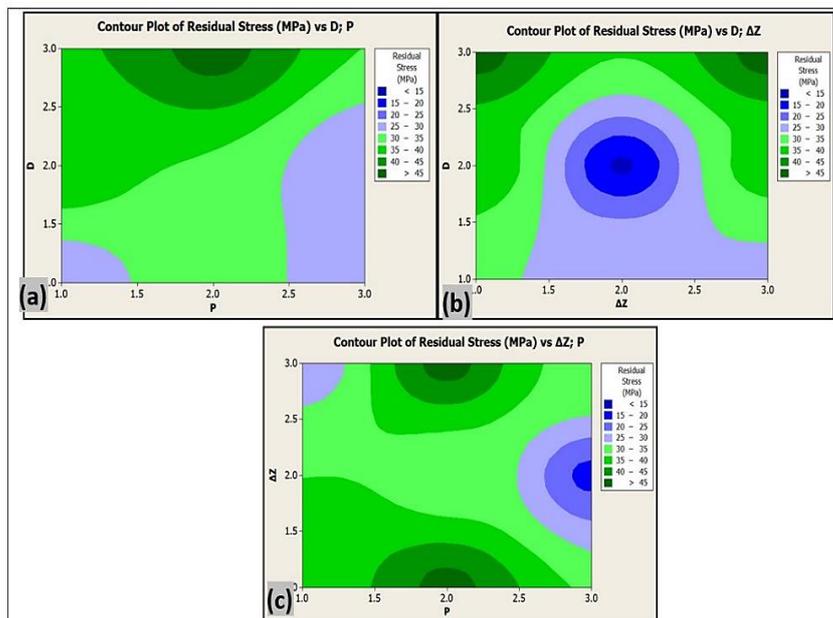

Fig. 8. Contour plots for residual stress in coded units.

4. Conclusion

In this work, an experimental analysis was performed to reduce the residual stresses caused by the two point incremental forming (TPIF) process. Three main parameters of the forming process are investigated namely, tool diameter (D), step down (ΔZ) and tool path (P) for a constant geometry model through the main effects plot (MEP), Box-Behnken design (BBD) of experiment and contour plots

techniques. Depending on the experimental data obtained throughout this study, the following points can be remarked:

- The tool diameter is directly proportional to the residual stress while step down and tool path factors incorporate both relations within different levels.

- The highest effect on the residual stress was caused by the step down (ΔZ) parameter, while the lowest influence was observed by the tool path (P) parameter.

- In general, the dual interaction of forming factors that gives high residual stresses was obtained by adopting 14 mm tool diameter for both iso-planar tool path and step down values of 0.2 and 0.6 mm, separately.

- The Box-Behnken design (BBD) of experiments accompanied with the D-optimality criterion used in this study represents a powerful technique for designing the experiments that cover the whole TPIF factors at a minimum cost and less time.

- Finally, the residual stresses can be reduced by calibrating between the step down (ΔZ) parameter and tool path (P) parameter.

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