SIMULATION STUDY ON SINGLE POINT INCREMENTAL FORMING OF TAILOR WELDED BLANKS

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Abstract: Tailor Welded Blank (TWB) is a technology which offers crucial advantages like weight and cost savings to the manufacturers. However, formability reduction and weld line shift are disadvantages of TWBs. In the present investigation the forming of TWBs has been done using Single Point Incremental Forming (SPIF) process numerically. ABAQUS/Explicit is used to perform the simulation of TWBs using SPIF process. Four different too initial positions are considered during forming and responses like weld line shift, Plastic Equivalent Strain (PEEQ) and thinning [%] are studied. Grey Relational Analysis (GRA) has been performed to determine best possible combination of parameters and tool initial position to result in to minimum value of responses. Geometrical accuracy is investigated for all the different initial positions of tool. The tool initial position which will results in minimum weld line shift, PEEQ and thinning [%] of blanks is determined. The geometrical accuracy along the weld line and across the weld line has been found different for different initial positions tool.
Key words: tailor welded blanks, single point incremental forming, weld line shift, grey relational analysis.

1. INTRODUCTION

Automobile industries are looking at the technology which results in to the fuel-efficient products along with cost reduction. Tailor Welded Blank (TWB) has provided these crucial advantages to the automobile industries. TWB is a product of joining two or more than two materials having different properties or thicknesses before any forming process. As TWB consist of different materials having different properties and thickness, the deformation behaviour of each material during the forming process will be different. During forming, weak/thin material will experience more deformation and thinning in comparison to the strong/thick material. Hence, the weld line shift will shift towards strong side during the forming process (Suresh et al., 2016). The weld line shift towards strong/thick material is observed during conventional forming processes (Suresh et al., 2016, Parente et al., 2016). However, this kind of results is not observed during Single Point Incremental Forming (SPIF) of TWBs (Marathe and Raval, 2019) and that is due to localised tool deformation and effect of tool dragging (Marathe and Raval, 2019). The basic working principle of SPIF process is represented in Figure 1.

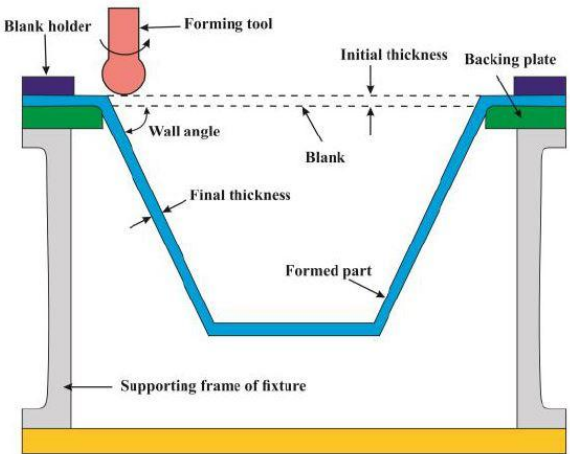


Fig. 1. Basic working principle of SPIF process

In SPIF process, a small tool is used to deform the blank and gradual and small incremental deformations are provided on the blank using the forming tool. SPIF results in to the better formability of the homogeneous blanks in comparison to the conventional forming processes (Martins et al., 2008). However, the combination of SPIF process with TWBs is not much explored by researchers.

Attempts to explore this combination of TWBs and SPIF is made by few researchers (Alinaghian et al., 2017, Tayebi et al. 2019, Silva et al., 2009, Rattanachan et al., 2014). In these investigations, the aim was to check the feasibility of the combination and to check the effect of welding process parameters on the formability of TWBs. The combination of TWB and SPIF process needs more in-depth investigation because this combination has potential to solve the difficulties of TWBs like weld line shift and formability reduction.

In the present investigation, simulation study has been performed on SPIF of TWBs. ABAQUS/Explicit has been used as the simulation tool. During simulation study the effect of different material parameters and tool initial positions has been investigated on the responses like weld line shift, Plastic Equivalent Strain (PEEQ) and thinning [%]. Grey Relational Analysis (GRA) has been adopted to find the best possible combination of materials parameters to get minimum value of all the responses.

2. SIMULATION CONDITIONS

2.1 Material Properties

The aim of the present simulation investigation is to investigate and optimize the material parameters for SPIF of TWBs. Hence, four different material parameter ratios as indicated in Table 1 are selected in the present investigation.

In Table 1, the ratio is defined as property of thick material divided by thin material. In order to achieve the ratios mentioned in the Table 1, three different materials were selected having different properties as represented in Table 2. The properties of materials were hypothetical and these were used as input during definition of parent materials. It was also assumed that material follows the Powe-Law equation.

Table 1. Material parameters and levels

Sr. No.	Parameter	Levels		
		-1	0	+1
1	Strain Index Ratio	(0.125/0.125) = 1	(0.125/0.112) = 1.116	(0.125/0.100) = 1.25
2	Strength Coefficient Ratio	(300/300) = 1	(300/275) = 1.090	(300/250) = 1.2
3	Thickness Ratio	(2/2) = 1	(2/1.5) = 1.33	(2/1.25) = 1.6
4	Yield Strength Ratio	(200/200) = 1	(200/175) = 1.142	(200/150) = 1.333

Table 2. Properties used for parent metals during simulation

Property	BM-1	BM-2	BM-3
Density (ρ) (kg/mm^3)	2.680 x 10^{-6}	2.680 x 10^{-6}	2.680 x 10^{-6}
Young's Modulus G (N/mm^2)	70300	70300	70300
Yield Stress (σ_y) (N/mm^2)	200	175	150
Poisson's ratio (μ)	0.33	0.33	0.33
Strength Coefficient (K) (N/mm^2)	300	275	250
Strain Hardening index (n)	0.125	0.112	0.100
BM = Base Metal			

To reduce the simulation efforts and time consumption, L9 orthogonal array was selected as indicated in Table 3 and accordingly the simulations were run. The property of weld material was considered as average of properties of both the parent blanks for respective simulation run (Parente et al., 2016).

Table 3. L9 orthogonal array

Simulation No.	Levels				Values			
	Strain Index Ratio	Strength Coefficient Ratio	Thickness Ratio	Yield Strength Ratio	Strain Index Ratio	Strength Coefficient Ratio	Thickness Ratio	Yield Strength Ratio
1	-1	-1	-1	-1	1	1	1	1
2	-1	0	0	0	1	1.09	1.33	1.142
3	-1	1	1	1	1	1.2	1.6	1.333
4	0	-1	0	1	1.116	1	1.33	1.333
5	0	0	1	-1	1.116	1.09	1.6	1
6	0	1	-1	0	1.116	1.2	1	1.142
7	1	-1	1	0	1.25	1	1.6	1.142
8	1	0	-1	1	1.25	1.09	1	1.333
9	1	1	0	-1	1.25	1.2	1.33	1

After the successful simulations, responses like weld line shift, Plastic Equivalent strain (PEEQ) and thinning [%] of blanks are investigated.

2.2 Grey Relation Analyses (GRA)

Grey Relational Analysis (GRA) is one of the effective methods used for multi-objective optimization (Bhatt and Raval, 2018). In the present investigation, GRA is used to optimize the material parameters ratios for the desired responses. The steps followed during GRA are mentioned below (Julong, 1989).

- Identification of input and response parameters
- Execution of experiments as per the fractional design
- Responses should be normalized
- Perform grey relation generation and determine Grey Relation Coefficient (GRC)
- Take average of GRC and determine Grey Relational Grade (GRG)
- Use GRG to study the result and determine the

optimum levels of process parameters
- Execution of confirmation test for validating the results.

In the present investigation, all the responses have smaller-the-better characteristics. The normalization of responses having smaller-the-better characteristics can be done using following equation (Lin, 2004, Julong, 1989).

$$x_i^*(k) = [\{\max x_i^0 (k) - x_i^0 (k)\} \div \{\max x_i^0 (k) - \min x_i^0 (k)\}] \quad (1)$$

In equation (1), $x_i^0 (k)$ is the original value of the results, $x_i^*(k)$ is normalized value of the results, max $x_i^0 (k)$ is the largest value of $x_i^0 (k)$ and min $x_i^0 (k)$ is the smallest value of $x_i^0 (k)$. The Grey Relational Coefficient (GRC) and Grey Relational Grade (GRG) are calculated as per equation (2) and (3) respectively (Lin, 2004, Julong 1989). The GRC $\xi_i (k)$ is calculated for the k^{th} performance characteristics in the i^{th} trial from equation (2),

$$\xi_i (k) = [\{\Delta_{min} + \xi \Delta_{max}\} \div \{\Delta_{0i} (k) + \xi \Delta_{max}\}]$$
$$0 < \xi (x_i^0 (k), x_i^*(k)) \leq 1 \quad (2)$$

Where,
$\Delta_{0i} (k) = | x_i^0 (k) - x_i^*(k) |$
$\Delta_{max} = \max | x_i^0 (k) - x_i^*(k) |$
$\Delta_{min} = \min | x_i^0 (k) - x_i^*(k) |$
After calculating GRC, GRG (γ_i) can be calculated using equation (3),

$$\gamma_i = (1/n) (\Sigma \xi_i (k)) \quad (3)$$

Where k=1 to n; n= number of response functions.
The simulation run which has highest GRG can be considered as the optimum and best option for the set of combination of parameters (Lin, 2004, Julong, 1989). The results of GRA are reported in the upcoming sections.

2.3 Modelling of Parts

To perform the simulations, ABAQUS/Explicit has been used. In order to perform the simulation of SPIF process, a rigid tool and a deformable blank is required as represented in Figure 2. The radius of tool considered was 6 mm (Ambrogio et al., 2007, Silva et al., 2011) and the blank dimension was 70 mm × 70 mm. The weld zone approach (Zadpoor et al., 2007) was used in the present investigation. Hence, a separate section on the blank was created on the deformable blank and separate properties were allocated to it as shown in Figure 2 (c).
The TWBs involved aluminium as parent materials are developed using FSW process. The FSW of parent materials having thickness in the range of 0.5–2 mm thickness is done with the help of a tool having pin diameter same as thickness of plate being welded. For such cases, the shoulder diameter is generally kept three times the pin diameter (Mishra et al., 2014). This results in the total weld zone of nearly 5–6 mm (including Weld Nugget (WN), Thermo-Mechanically Affected Zone (TMAZ), Heat-Affected Zone (HAZ)). Therefore, for all the simulations, the total width of the weld zone is kept 5 mm (Garware et al., 2010).

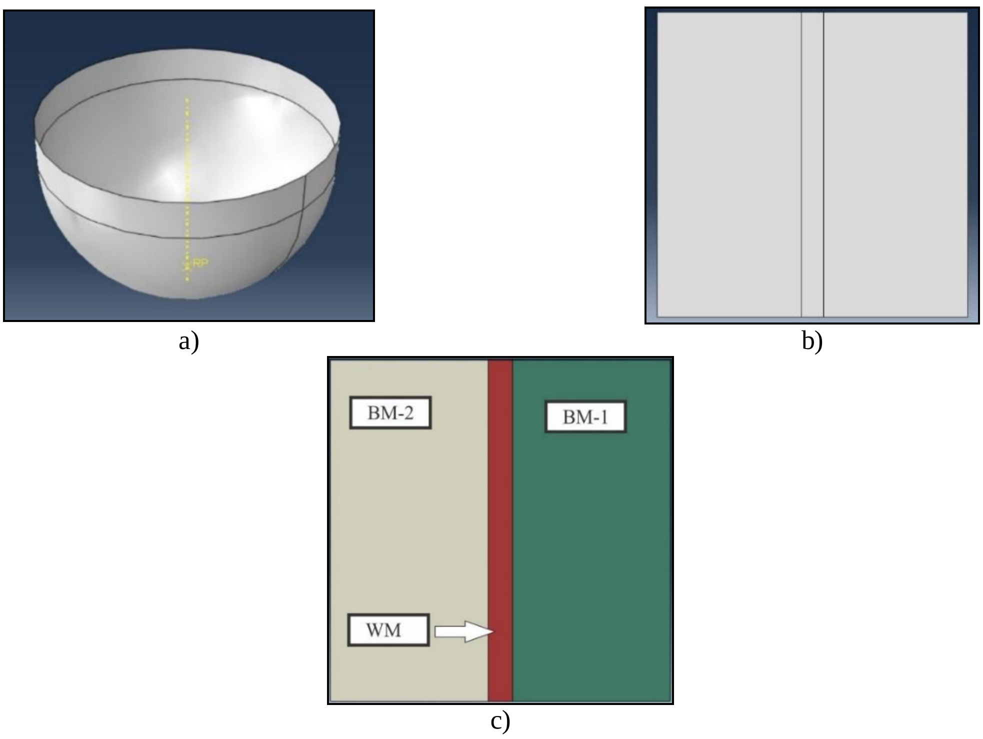


Fig. 2. Tool and blank used in the simulation study: (a) Hemispherical rigid tool; (b) Deformable blank; (c) Assignment of material properties to the respective material in Weld zone approach

During SPIF process, contour tool path strategy was used in which deformation on blank is provided by tool after completing one planner movement as shown in Figure 3. The amount of step down and step over depends upon the target geometry.

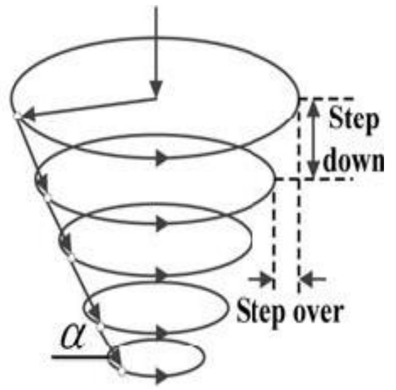


Fig. 3. Contour tool path strategy (α=wall angle) (Desai et al., 2014)

The target geometry in the present investigation is a truncated cone having 45° of wall angle and 20 mm of forming height as represented in Figure 4.

2.4 SPIF process parameters

The target geometry of truncated cone was developed using SPIF process. The process parameters for SPIF process are indicated in Table 4.

The SPIF process parameters were kept constant for all the simulations. The forming of TWBs during SPIF process can have different initial positions of forming tool as indicated in Figure 5.

Table 4. Process parameters of SPIF

Sr. No.	Parameter	Unit	Value
1	Forming tool radius (Ambrogio et al., 2007, Silva et al., 2011)	mm	6
2	Coefficient of friction between tool and blank (Zhang et al., 2010, Kumar and Reddy, 2016)	-	0.1
3	Incremental depth (Desai et al., 2017, Desai et al., 2014, Bansal et al., 2017)	mm	0.5
4	Tool travel speed (Dakhli et al., 2019, Kilani et al., 2020)	mm/sec	15
5	Tool rotational speed (Centeno et al., 2014)	rpm	1000

The tool starting from centre of strong material will be considered as Strong Centre (SC) condition as shown in Figure 5 (a). Similarly, Weak Centre (WC) condition can be considered as shown in Figure 5 (b). The tool starting from weld material and deforming strong material immediately will be considered as Weld-To-Strong (WTS) condition (see Figure 5 (c)). Similarly, Weld-To-Weak (WTW) tool initial position can be considered as depicted in Figure 5 (d).

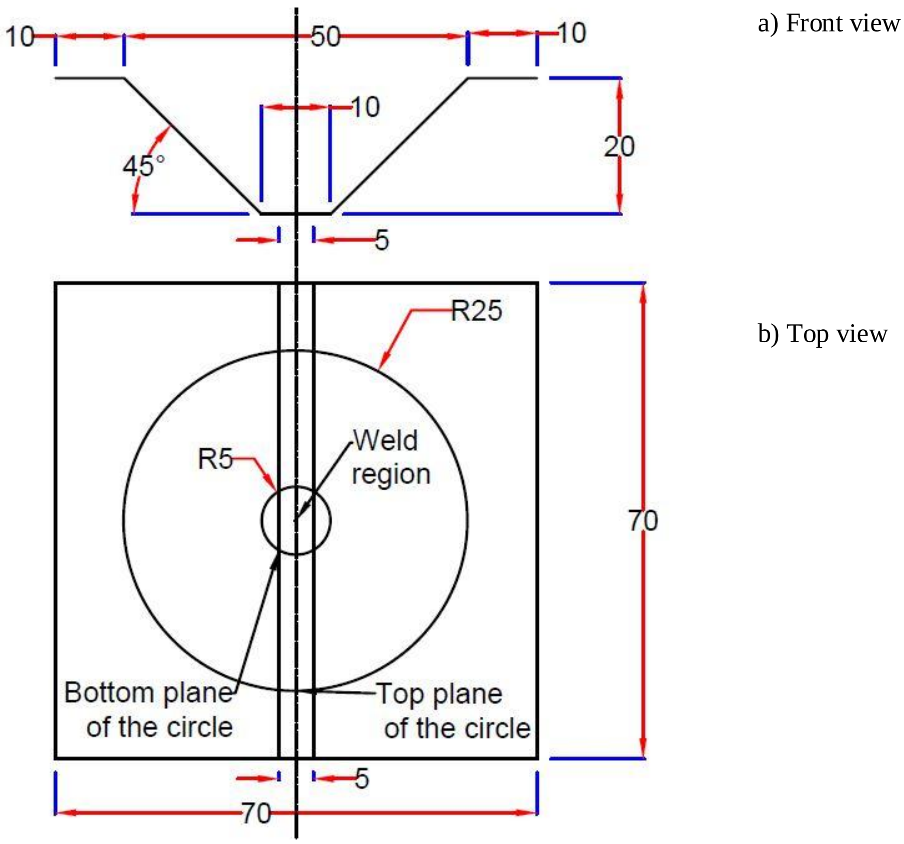


Fig. 4. Target geometry (truncated cone) – All the dimensions are in mm

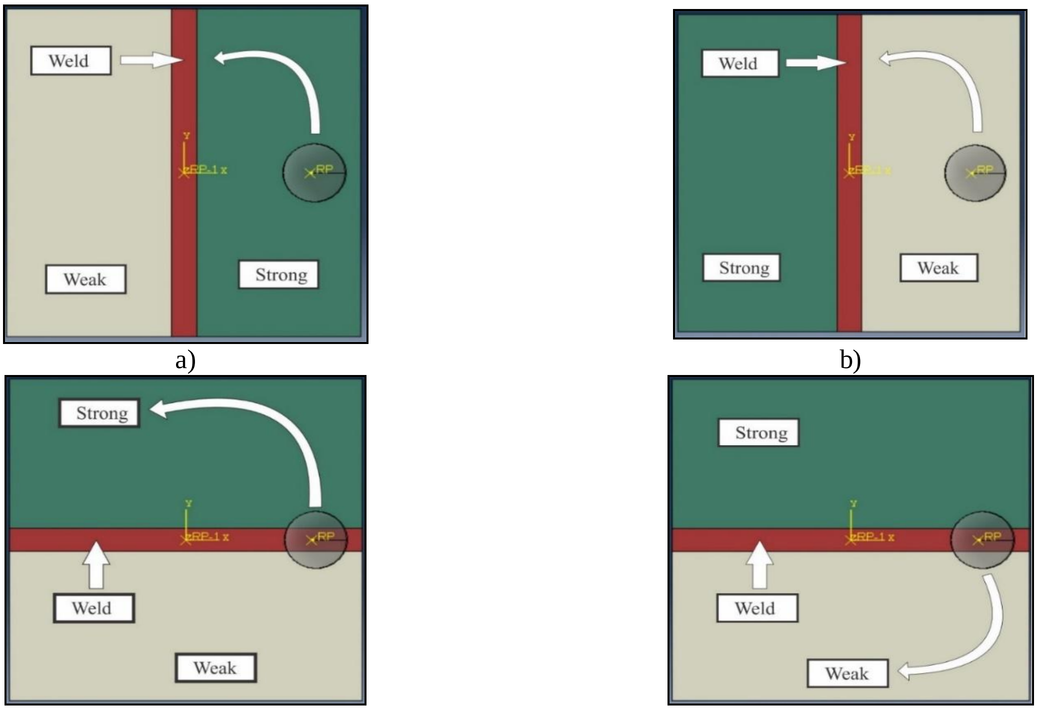


Fig. 5. Different starting position of SPIF tool during the forming operation: (a) Starting from centre of strong material (SC); (b) Starting from centre of weak material (WC); (c) Starting from weld material and moving towards strong material (WTS); (d) Starting from weld material and moving towards weak material (WTW)

For each initial position of tool, L9 orthogonal array was followed and responses like weld line shift, PEEQ and thinning [%] were studied.

3. RESULTS AND DISCUSSION

TWB involved different parent blanks having different material properties and different thicknesses. Hence, during any forming process, the deformation experienced by each material will be different resulting in to the weld line shift. More weld line shift indicates that one material has undergone more thinning and has experienced more plastic strain during forming process (Marathe and Raval, 2019). The responses like weld line shift, PEEQ and thinning [%]is determined for all tool initial position and reported in the next section.

3.1 Results of GRA

The GRG value and rank for SC condition and for all the simulation run are tabulated in Table 5. The highest GRG value was found for simulation number 1 followed by simulation number 6.

Table 5. GRG for SC case

Sim. No.	WLS	PEEQ	Thinning [%]	GRG	Rank
1	0.566	2.775	54.035	0.960	1
2	1.258	3.371	65.200	0.466	5
3	1.861	3.920	71.432	0.333	9
4	1.565	3.600	69.387	0.387	8
5	1.226	3.363	66.312	0.463	6
6	0.785	2.719	53.705	0.916	2
7	1.510	3.586	68.144	0.399	7
8	1.136	3.104	61.805	0.555	4
9	0.906	2.998	60.907	0.630	3

In simulation number 1, the strain index ratio, strength coefficient ratio, thickness ratio and yield strength ratio are 1. This indicates that the blank in simulation number 1 can not be considered as a TWB. Hence, simulation number 1 can be ignored. Simulation number 6 has the second highest GRG value and second rank. Hence, it can be said that simulation number 6 will result in to the minimum weld line shift, PEEQ and thinning [%] of the blank. Similar observations are made for WC and WTW conditions as represented in Table 6 and 8 respectively.

It has been found that during forming of TWBs, thickness ratio and yield strength ratio are the influencing factors in comparison to the other parameters like strain index ratio and strength coefficient ratio (Narayanan and Narasimhan, 2007). It has been also reported that the difference in thicknesses (Khan et al., 2014, Korouyeh et al., 2013) and yield strength of the parent blanks should be as low as possible (Marathe and Raval, 2019) resulting in to more homogeneous nature of blank. Similar observation can be made in Tables 5 to 8 where simulation number 1 resulted in maximum GRG value because it involves both materials of same thickness and yield strength.

In the present investigation, the value of thickness ratio is 1 in simulation number 1, 6 and 8 while value of yield strength ratio is 1 in simulation number 1, 5 and 9. Due to this, the difference in the results of these simulations is not significant. The significance of thickness ratio is more than yield strength ratio (Narayanan and Narasimhan, 2007). Hence, in simulation number 6, minimum amount of weld line shift is observed.

Unlike SC, WC and WTW condition of forming tool, simulation number 6 of WTS has resulted in to maximum value of GRG. Hence, simulation number 6 will result in to the lower responses in comparison to the simulation number 1 as reported in Table 7 for WTS condition of forming tool.

Table 6. GRG for WC case

Sim. No.	WLS	PEEQ	Thinning [%]	GRG	Rank
1	0.566	2.775	54.035	1.000	1
2	1.277	3.194	64.287	0.493	5
3	1.868	4.170	65.312	0.340	9
4	1.576	3.585	66.400	0.396	8
5	1.266	3.693	60.000	0.474	6
6	0.941	3.043	56.580	0.688	2
7	1.551	3.923	62.384	0.400	7
8	1.223	3.193	62.390	0.516	4
9	1.001	2.956	57.267	0.683	3

Table 7. GRG for WTS case

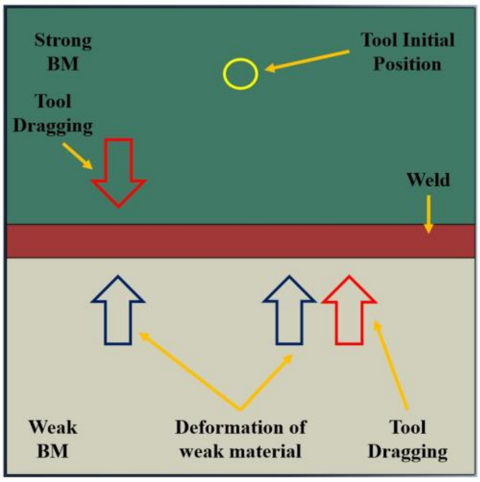
Sim. No.	WLS	PEEQ	Thinning [%]	GRG	Rank
1	0.566	2.775	54.035	0.886	2
2	0.861	3.580	62.600	0.520	5
3	1.617	4.638	66.224	0.333	9
4	1.176	4.405	65.167	0.391	8
5	0.863	4.027	62.648	0.485	6
6	0.556	2.705	51.475	1.000	1
7	1.274	3.776	64.112	0.423	7
8	0.797	3.557	57.810	0.586	4
9	0.652	3.114	57.313	0.702	3

Table 8. GRG for WTW case

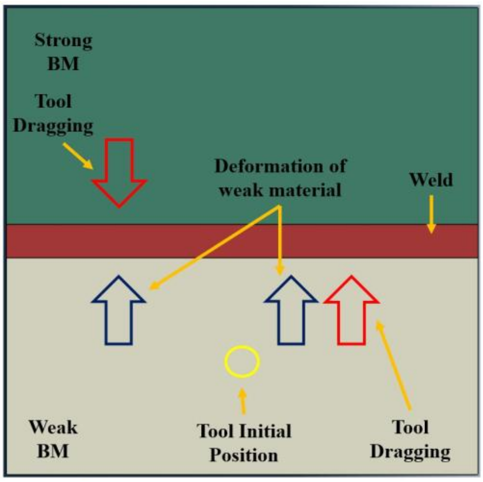
Sim. No.	WLS	PEEQ	Thinning [%]	GRG	Rank
1	0.566	2.775	54.035	1.000	1
2	1.476	3.222	65.633	0.477	5
3	2.034	3.832	72.512	0.333	9
4	1.755	3.628	71.387	0.371	8
5	1.463	3.285	64.984	0.472	6
6	1.058	2.943	55.355	0.744	2
7	1.728	3.494	69.488	0.395	7
8	1.452	3.068	61.640	0.548	4
9	1.168	3.063	58.293	0.627	3

The comparison of simulation number 6 for SC, WC, WTS and WTW condition of tool reveals that the maximum GRG value is found for WTS initial position of tool. Hence, it can be stated that WTS condition of tool will result in minimum weld line shift, PEEQ and thinning [%] of blanks. For such results, tool dragging is responsible. The tool dragging is different for different tool initial position as represented in Figure 6.

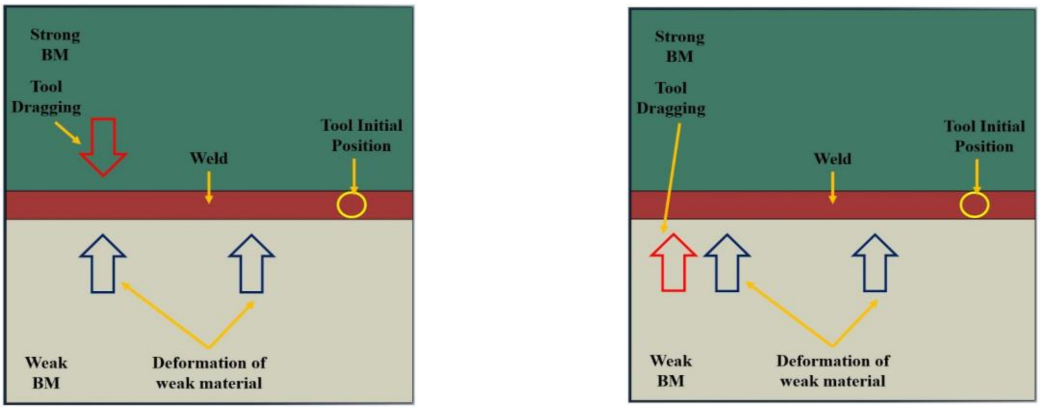
For SC condition of forming tool, the repetitive deformation will be on strong material. Tool dragging will be at the weld area when the tool will move from strong to weak material and from weak to strong material as represented in Figure 6 (a). During forming of blank, weak material will undergo more amount of deformation. Due to the deformation of weak material, weld line is shifted towards the strong material. If the deformation of weak material and tool dragging are in same direction and supporting each other that will result in to more amount of weld line shift. For SC, WC and WTW condition of forming tool, tool dragging and deformation of weak material supports each other as represented in Figure 6 (a), (b) and (d). For WTS condition of forming tool, deformation of weak material and tool dragging do not support each other leading low weld line shift during SPIF process.



a)



b)



c) d)

Fig. 6. Tool dragging for different initial positions of forming tool: (a) SC condition of forming tool; (b) WC condition of forming tool; (c) WTS condition of forming tool; (d) WTW condition of forming tool

The low value of weld line shift also indicates that the strain experienced by both the parent materials is nearly same during forming process. Hence, during WTS condition of forming tool, parent blanks undergo nearly same amount of deformation leading less weld line shift in comparison to the other tool initial positions. Due to this, WTS results in less PEEQ and thinning [%] of blanks as well in comparison to other tool initial positions.

3.2 Geometrical accuracy

SPIF process has limitation of spring back like any other forming process. In the present investigation, forming of TWBs is done using SPIF process which involves deformation of blank using a very small tool. This leads to the localized deformation and small contact area between forming tool and blank being formed. The TWB involves strong and weak material having different material properties leading to different spring back. In SPIF process, the formed geometry also depends upon the tool initial position. In the present investigation, the formed geometry is extracted along the weld line and across the weld line and compared with the target geometry as represented in Figures 7 to 10.

The formed geometry along the weld line and across the weld line is compared with the target geometry for SC condition as depicted in Figure 7.

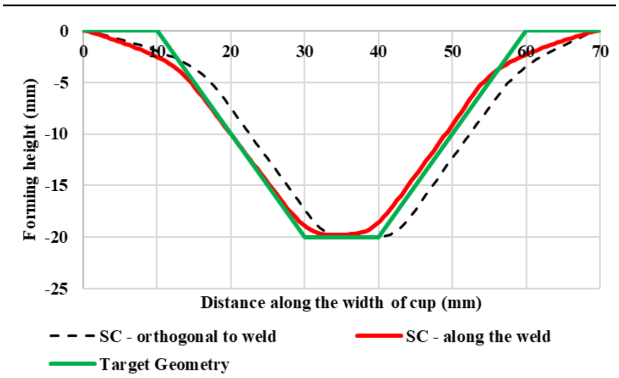


Fig. 7. Comparison between target and formed geometry for SC case

In Figure 7, it can be observed that the geometry formed orthogonal to the weld has shifted towards the right side of the target geometry. The geometry formed along the weld line is in agreement with the target geometry. In SC initial position of tool, repetitive deformations are provided on the strong material. The location of deformation is orthogonal to the weld line and at the centre of the strong base material. Hence, the material at the starting position of tool will be deformed more and due to the repetitive deformation, it will have less chances of spring back. Due to this phenomenon, the formed geometry is shifted towards the right side of target geometry and the geometry formed along the weld line is having good agreement with the target geometry. Similar observations are made for WC condition of forming tool (see Figure 8).

For WTS initial position (see Figure 9) of tool, the tool is deforming the weld material repetitively. Hence, the deformation experienced by weld material at tool initial position will be more in comparison to the deformation experienced by parent materials.

So, in WTS case, weld material has less chances of spring back in comparison to the base materials. Hence, the geometry formed along the weld material will be shifted towards the right side of the target geometry due to the repetitive deformations of forming tool. The geometry formed across the weld line will have better agreement with target geometry. Similar kind of results are observed for WTW initial position of tool as shown in Figure 10.

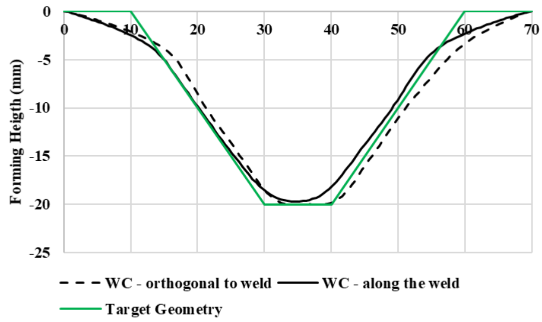


Fig. 8. Comparison between target and formed geometry for WC case

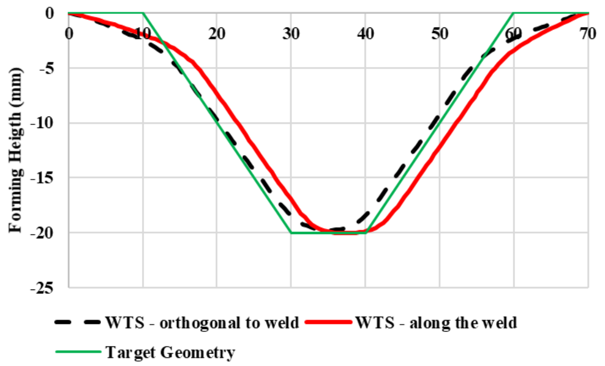


Fig. 9. Comparison between target and formed geometry for WTS case

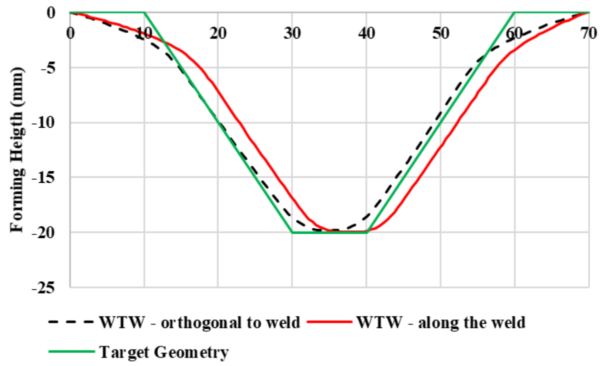


Fig. 10. Forming height comparison for WTW case

In conventional forming processes the spring back depends only upon the properties of the material being formed. SPIF process involves localized deformation using different tool initial positions of forming tool and hence the spring back in SPIF process depends upon the tool initial position as well. Due to this the geometrical accuracy achieved for different initial positions of forming tool will be different. If the geometrical accuracy is measured along the path of tool repetitive deformation then the agreement between formed geometry and target geometry will be less. The agreement between target geometry and the formed geometry will be more if the formed geometry is extracted orthogonal to the path of repetitive deformation of forming tool.

4. CONCLUSIONS

In the present simulation investigation, SPIF of TWBs is performed. Different material parameter ratios like strain index ratio, strength coefficient ratio, thickness ratio and yield strength ratio are considered. GRA analysis has been performed and best simulation run has been determined which will result in minimum value of all the responses. Geometrical accuracy was also studied by comparing the target geometry along with the formed geometry.
This study indicates not only the process parameters but also the material parameters are also important while forming of TWBs during SPIF process. The study on effect of different ratio of material property revealed that, the combination of material parameters of simulation number 6 will give minimum weld line shift, PEEQ and thinning [%] of the blanks. The comparison of all the initial position of tool showed that WTS position of forming tool results in to the minimum value of all the responses.
The geometrical accuracy for the formed geometry extracted along and across the weld line is different and for such result the localized deformation of forming tool is responsible. For SC and WC initial position of forming tool, the formed geometry along the weld line will have better agreement with target geometry in comparison to the formed geometry across the weld line. For WTS and WTW initial position of tool, the formed geometry orthogonal to weld will have better agreement with target geometry in comparison to the geometry formed along the weld line. The agreement between target geometry and formed geometry will be good if the formed geometry is extracted from path orthogonal to the repetitive deformation of forming tool. In addition to the material properties, in SPIF process, the spring back and the geometrical accuracy depends upon the initial position of the forming tool.

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