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TECHNICAL PAPER

Numerical investigation on forming behavior of friction stir tailor welded blanks (FSTWBs) during single-point incremental forming (SPIF) process

Shalin Prakashbhai Marathe[1] · **Harit Kishorchandra Raval**[1]

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Abstract

Tailor welded blank (TWB) is a product which is developed by joining two or more than two materials having same/different thickness and/or properties before any forming process. The method to join the materials can be any of the conventional or advanced methods. TWB offers advantages like overall weight and cost reduction in a product. Despite of such advantages, the application of TWBs is partially resisted by the disadvantages associated with it like formability reduction and weld line movement during the forming operations. A lot of effort has been done in order to overcome the mentioned limitations of the TWBs. However, for homogeneous blank, single-point incremental forming (SPIF) results in better formability so in present work, the attempt has been made to study the forming behavior of TWB during the SPIF process. In this work, the effect of TWB material parameters like yield strength ratio, thickness ratio, strength coefficient ratio and strain index ratio of the parent materials has been investigated on the weld line movement and % thinning of the blank through finite element analysis. In order to perform the numerical analysis, ABAQUS/Explicit was used. Using SPIF, round cup geometry is formed from a flat TWB and effect of different initial positions of tool is investigated. It has been found that when the forming process is started from the weld and tool is travelled toward strong material of the blank, it leads to the minimum thinning, weld line shift and plastic equivalent strain (PEEQ).

Keywords Tailor welded blank · Single-point incremental forming · Formability · Weld line shift · Thinning · Finite element analysis

1 Introduction

In tailor welded blanks (TWBs), the world tailor means control. TWBs allow designer to control the location of property while developing the product. TWB is a blank which includes two or more than two materials welded together in butt or lap configuration. The welding methods can be any of the conventional or advance methods. The difference between an ordinary welded blank and a TWB will be the post-processing. TWBs are subjected to the forming operations after the fabrication which is not always the case for all the welded blanks. As the TWB involves joining of material having different densities, the overall weight of the product will be reduced. Before the invention of TWBs, two different blanks were formed by using different dies followed by the welding procedure, while in the case of TWBs, the joining is followed by a forming operation on a single die which leads to the cost reduction as well [1, 2].

A door inner panel as indicated in Fig. 1 is the typical application of TWBs. If the inner door panel would have been made with a homogeneous blank, then the overall weight of the door would have been on higher side. So, the overall weight of the car will be reduced and that will lead to the cost reduction and also the fuel efficiency of the automobiles will improve.

As the inner door panel is made by using TWB technology, the overall weight of the door is less as the side near to

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✉ Shalin Prakashbhai Marathe
shalin.marathe89@gmail.com; d16me008@med.svnit.ac.in

Harit Kishorchandra Raval
hkr@med.svnit.ac.in

1 Department of Mechanical Engineering, Sardar Vallabhbhai National Institute of Technology, AS-11, Raman Bhavan, SVNIT, Ichhanath Circle, Piplod, Surat, Gujarat 395007, India

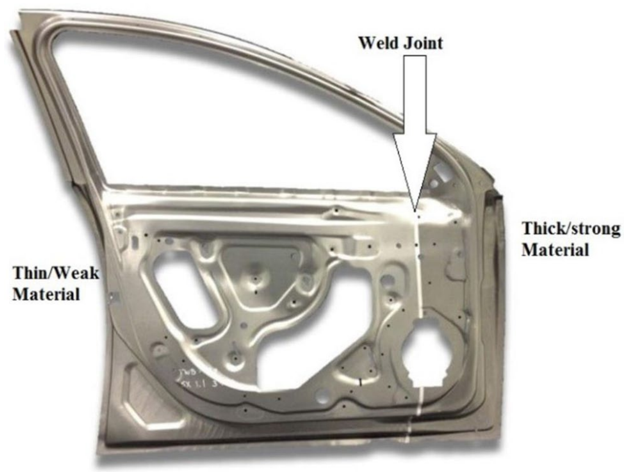


Fig. 1 TWB made from aluminum used in inner door panel of car body (TWB Company, LLC, USA)

the hinged portion of the door is made of stronger/thicker material because at that side, more stress will be generated during the application and the side away from the hinged portion is made of weak/thin material because less amount of stress will be generated at this side. So, in other words, designers are allowed to choose the location of the weld line while developing such products. However, after joining, when the welded blanks are subjected to forming and as it involves joining of two materials having different properties, the deformation characteristics of two materials will be different and due to that there will be movement of weld line [3, 4] The strong/thick material will be able to resist the load more easily in comparison with the weak/thin material and because of that there will be shifting of weld line from weak/thin material to the strong/thick material [1]. This weld line movement indirectly leads to reduce the formability of the TWBs as well [1, 5, 6].

In order to minimize the weld line movement, many efforts have been done by the researchers. A split punch methodology was suggested [4] in which thick/strong side of the TWB was heated and because of which same amount of deformation can be achieved from thick/strong side as that of weak/thin side. During the deep drawing of the TWBs, weld line movement toward thick side has been observed [3] and similar observation has been made by many researchers. One solution to avoid the weld line movement is to use the lower amount of blank holder force for holding the thick/strong material compared to the same used for thin/weak material. Despite of a lot of effort, issue related to the weld line movement has not been resolved completely.

To study the weld line movement and formability of TWBs, many conventional forming methods have been attempted like limiting dome height (LDH) test [7], deep drawing [5], Erichsen cupping test [8], hemispherical dome stretching test [9], standard ball punch test [2] and cylindrical cup drawing (CCD) test, but no significant decrease has been found in the weld line movement.

Now, for the homogeneous blanks, it has been found that the single-point incremental forming (SPIF) process results in the better formability compared to the conventional forming processes as the deformation during the SPIF process is due to the combined effect of bending and stretching [10]. Also, the deformation in the SPIF process is due to the local deformation only, while in the case of conventional forming processes like deep drawing, the deformation is due to the global deformation and this is the reason for improvement in the formability of the blanks. Despite of many efforts to study the weld line movement of TWBs during the forming process, attempts to study the same response during the SPIF process have not been explored much.

It should be noted that the TWBs can be developed using any of the joining processes like laser welding [11], electron-beam welding [12] tungsten inert gas (TIG) [4], metal inert gas (MIG), resistance seam welding [13] and friction stir welding (FSW) [1, 14]. The selection of welding process to develop the TWBs depends upon the parent materials to be joined and also on the application of the joint. For the joining of aluminum and its alloys, FSW is found to be preferable compared to the other conventional welding processes [1].

Formability investigation of the friction stir tailor welded blanks (FSTWBs) during the SPIF process is not attempted by many researchers. One attempt was made by Alinaghian et al. [15] to study the effect of FSW process parameters on the formability during the SPIF process. It was concluded that the combination of SPIF and TWB technology will lead to the exciting results in the domain of metal forming. It was also stated that forming behavior of the TWBs during the forming process depends upon the material properties of parent metals [16, 17]. It is a well-known fact that the FE analysis leads to save the important resources like material and time. So, FE analysis of SPIF process for the TWBs has been attempted to investigate the effect of material properties on the weld line movement during the forming. FE analysis of the TWBs is a challenging task because it involves consideration of the weld metal (WM) properties during the simulation. If the properties of weld zones are not considered, then the simulation results are found to be deviating from the experimental results [3, 6, 18]. On considering the weld metal properties, results of simulation and experimental works are found to be in better agreement with each other [19–21]. The weld metal properties can be extracted from the physical destructive testing or by using the methods like rule of mixture (ROM) [22]. It has been observed that the study of weld line shift and forming behavior of the FSTWBs has been attempted by limited researchers. So, in this research work, efforts have been made to study the weld line shift of FSTWBs during the SPIF process through finite element analysis (FEA). Effect of material properties of participating blanks on the weld line shift, plastic strain and thinning of the blank has been investigated. The suitable conditions leading to minimum weld line shift, strain and thinning are found as concluding remarks.

2 Methodology

2.1 Design of experiment (DOE) for simulation

In order to study the effect of material parameters of participating blank on the forming behavior of FSTWBs, four material parameters strain index (n), strength coefficient (K), sheet thickness and yield strength were selected. Three levels of each parameter for each parent material were selected. In the present simulation work, L9 orthogonal array has been used. Material parameters are varied as per the three levels as indicated in Table 1.

In Table 1, each ratio is defined as ratio of thick to thin material. In order to have the ratio indicated in Table 1, different properties during the simulation were used as indicated in Table 2. According to the parameters represented in Table 1, L9 orthogonal array was adopted and simulations were performed accordingly. Table 3 indicates the table for L9 orthogonal array with levels and values of parameters.

2.2 Simulation strategy

In the present simulation work, ABAQUS/Explicit 6.13 has been used as the simulation tool. In order to simulate the process of SPIF, modeling of two basic instances is required: one is a SPIF tool, and second is a sheet/blank. A rigid tool

Table 1 Material parameters and levels

Sr. no.	Parameter	Levels		
		−1	0	+1
1	n (strain index) ratio	(0.125/0.125) = 1	(0.125/0.112) = 1.116	(0.125/0.100) = 1.25
2	K (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 during simulation

Property	Base metal (BM)-1	BM-2	BM-3
Density (ρ) (kg/mm^3)	2.680×10^{-6}	2.680×10^{-6}	2.680×10^{-6}
Young's modulus G (N/mm^2)	70,300	70,300	70,300
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

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

was modeled having a hemispherical shape as indicated in Fig. 2a, and a deformable blank of 70 * 70 mm^2 was modeled as indicated in Fig. 2b. Radial tool path strategy was adopted to form the round cup, and tool movement was from outer periphery of the blank toward the center of the blank.

As indicated in Table 2, total three materials were considered by defining different material properties during all the simulations. During simulations, it was assumed that the developed weld metal will have intermediate mechanical properties compared to the properties of participating base materials [1]. So, the average of two base material properties was assigned to the weld material.

In order to define the weld material during the simulation, an approach called "Weld Zone" [23] was used. In this approach, a separate section is created (see Fig. 3) between the faying surfaces of specific dimensions and this section is assigned the weld metal properties. In the present work, the weld is considered to have the width of 5 mm [24]. 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 [25]. 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)]. So, for all the simulations, the total width of the weld zone is kept 5 mm.

A hemispherical tool of 6 mm radius was considered, and during the simulation, tool radius compensation was considered. Initial blank dimensions were 70 × 70 mm^2, and thickness was varied as per the level of thickness ratio parameter (see Table 1). The coefficient of friction between blank and tool was considered as 0.1 [26]. For all the simulations, the incremental step size was kept as 0.5 mm. Tool translation speed of 15 mm/s was considered with tool rotational speed of 1000 RPM (rotation per minute). A round cup having 45° of wall angle, 20 mm height and 50 mm top diameter was developed using the SPIF process. For a particular blank, the material having high value of strength coefficient, thickness and yield strength is considered as strong material and the other having low value of these mentioned parameters is considered as weak material. Total four different starting positions of SPIF tool were selected as indicated in Fig. 4.

As mentioned earlier, L9 orthogonal array was used to minimize the number of simulations and considering the four different cases as represented in Fig. 4, total 36

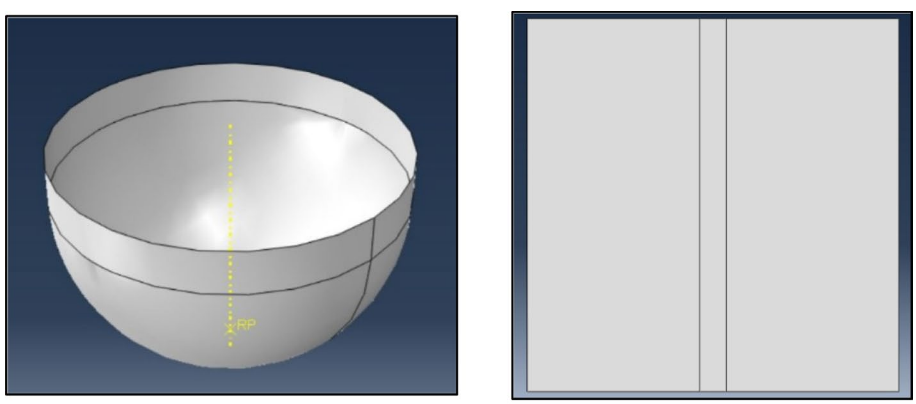


Fig. 2 Modelling of instances in the ABAQUS/Explicit

(a) Hemispherical rigid tool **(b) Deformable blank**

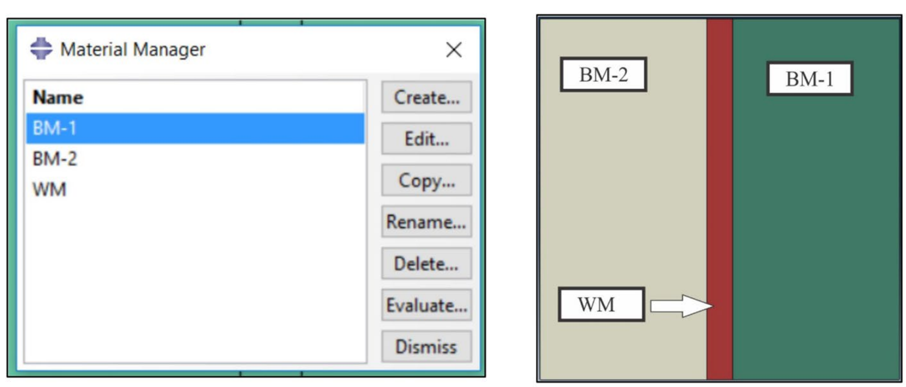
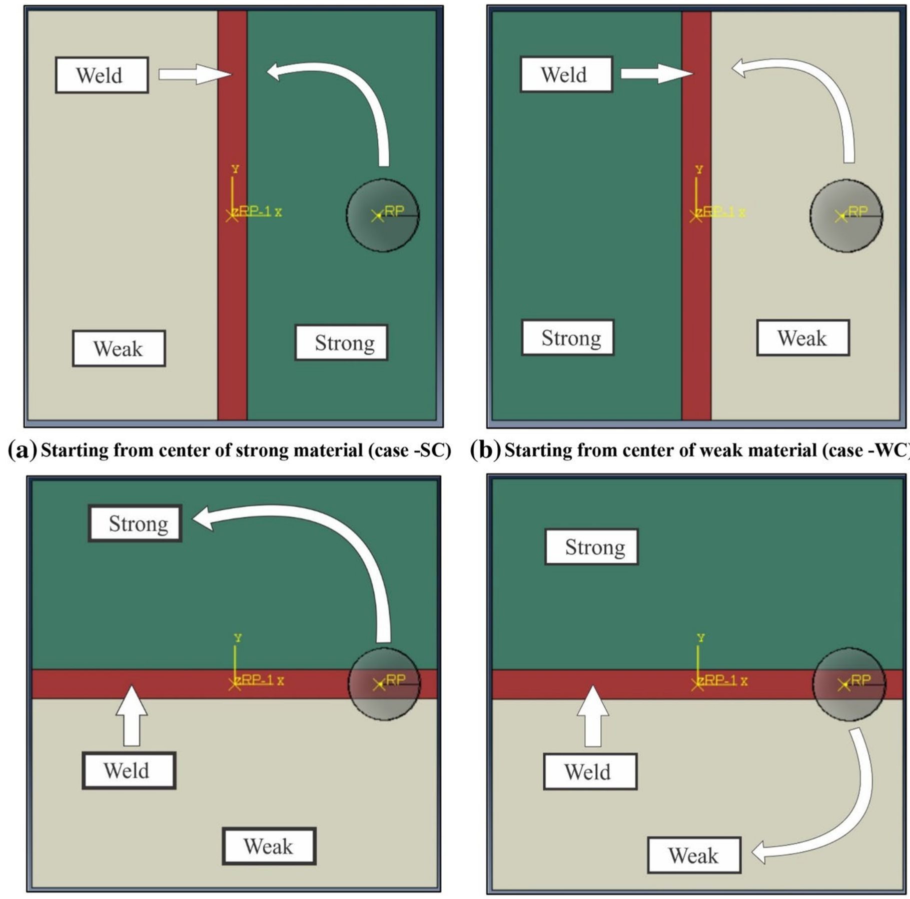


Fig. 3 Weld zone approach

(a) **Separate material properties defined for base material and weld material** **(b)** **Assignment of material properties to the respective material**

Fig. 4 Different starting positions of SPIF tool during the forming operation



(a) Starting from center of strong material (case -SC) (b) Starting from center of weak material (case -WC)

(c) Starting from weld material and moving towards strong material (case -WTS) (d) Starting from weld material and moving towards weak material (case -WTW)

simulations were performed. It was noted that one simulation was taking average time to complete of about 2 days. Also, it should be noted that during all the simulations, type and size of the element were kept constant while meshing the instances. The linear quadrilateral elements S4R which are used to mesh the shell objects were used with mesh size of 0.5 to mesh the deformable blank.

3 Results and discussion

From the simulation of each case, results of weld line movement, % thinning and equivalent plastic strain (PEEQ) were extracted and compared. In order to extract the weld line movement, a node path was created along the weld line and its displacement was recorded. Figure 5a, b represents the top view and side view of the formed component, respectively, for one of the simulations. From the top view, it can be observed that the weld line shift has occurred from weak material to strong material of the blank. From the side view of the formed geometry, similar observation can be made. The reason for such observation is discussed in detail in the next section.

3.1 Mechanism of weld line shift

As mentioned earlier, TWB consists of two materials having different strengths, welded together prior to the forming process. During forming, the thin/weak material deforms more compared to the strong/thick material as thin material is having low yield strength and it offers less resistance to the deformation. Due to this, the weld line which is at center before forming experiences shift from the weak material as it expands and because of that the weld shifts toward the strong side. However, for SPIF process, the direction of weld line shift depends upon the initial position of tool.

Figure 6 represents the results of weld line shift for the case of WC for a TWB. Figure 6a indicates the top view of the formed component. In this case, the forming was started from weak material and the tool was positioned at the center of the weak material, i.e., at 25 mm from the weld center, as indicated in Fig. 6b. For better understanding, Fig. 6a, b can be compared to understand the results. Figure 6b is divided

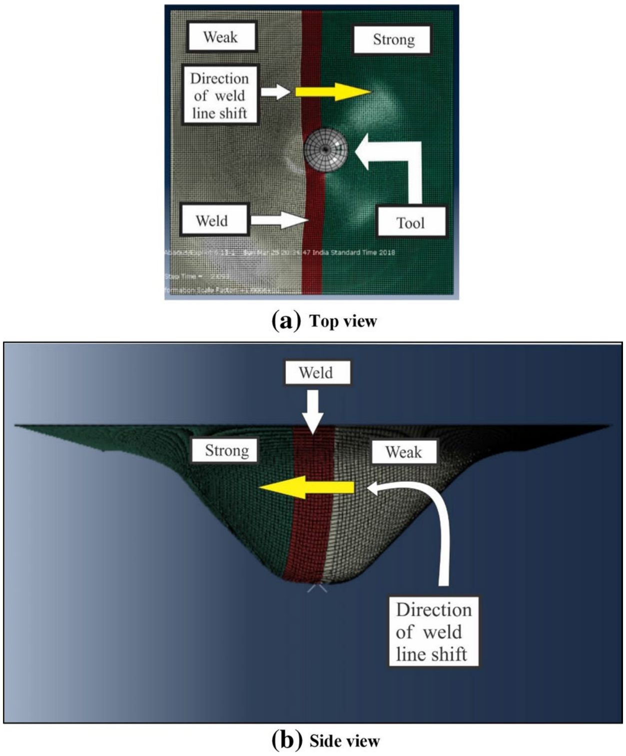


Fig. 5 Round cup geometry formed using SPIF on TWBs in ABAQUS/Explicit

into section A and section B. The magnified view of Fig. 6b is represented in Fig. 7.

Figure 7 reveals that the weld line shift observed in section A is more in comparison with section B. During SPIF, there are two factors which are responsible for the weld line shift: one is tool dragging effect, and second is deformation of weak material. When the tool moves across the weld line, due to friction between tool and blank, tool tries to drag the weld line from its original position. Now, due to the downward movement of tool, blank is deformed. This deformation is more in weak material compared to the strong material. Due to this, the weld line moves toward the strong material. In section A, tool dragging effect is supported by the deformation of weak material, while in section B, tool dragging effect is opposed by the deformation of weak material; this is the reason in section A, high magnitude of weld line shift is observed compared to section B.

3.2 Comparison of results

From all the simulation, results of weld line movement, % thinning and PEEQ were recorded. For each case, the simulation number which leads to maximum and minimum weld line shift is represented in Tables 4 and 5, respectively.

For all the cases, simulation numbers 3 and 6 resulted in the maximum and minimum weld line shift, respectively. From Table 4, it can be observed that WTS case gives minimum weld line movement compared to SC, WC and WTW cases. It should be noted that more thinning of material leads to the more weld line movement and same can be observed in Tables 4 and 5. Now, as explained earlier, the weld line shift is observed toward the strong side because of more deformation of weak material, but particularly for SPIF, it depends upon the starting position of forming tool. Result of WTS case represents that the weld line shift is toward the weak side. The tool dragging effect is playing major role in shifting the weld line from strong to weak side. The weld line shift due to deformation of weak material is overcome by the weld line shift due to tool dragging effect. This is the reason due to which for WTS case, the weld line shift is observed toward the weak material. Simulation number 6 of WTS case leads to the minimum weld line movement, PEEQ and % thinning in comparison with all other cases for the given simulation conditions.

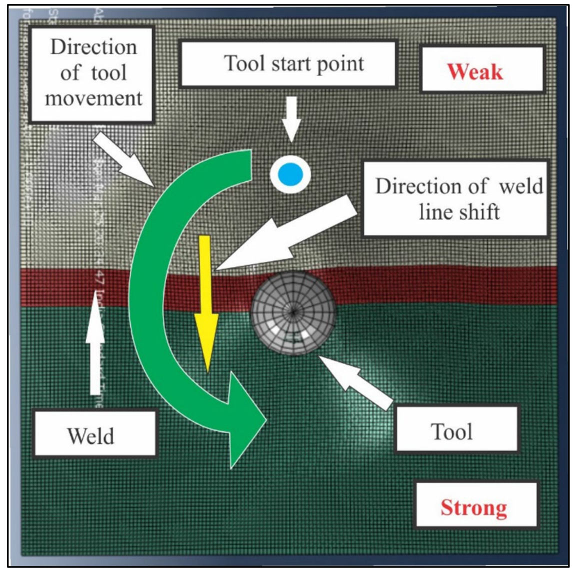
3.3 Thinning zones

As mentioned earlier, in SPIF process, the blank is clamped from all the sides and the blank material is not allowed to draw during forming operation. As material is not allowed to draw inside, stretching takes place during SPIF process. This stretching phenomenon may lead to the thinning of the blank being formed. Thinning of the TWBs has been studied in the present study and has been reported as thinning zones. Figures 8, 9, 10 and 11 represent the thickness distribution in the formed part for cases SC, WC, WTS and WTW, respectively. In simulation number 6, both parent materials are having same thickness, while in simulation number 3, both parent blanks are having different thicknesses.

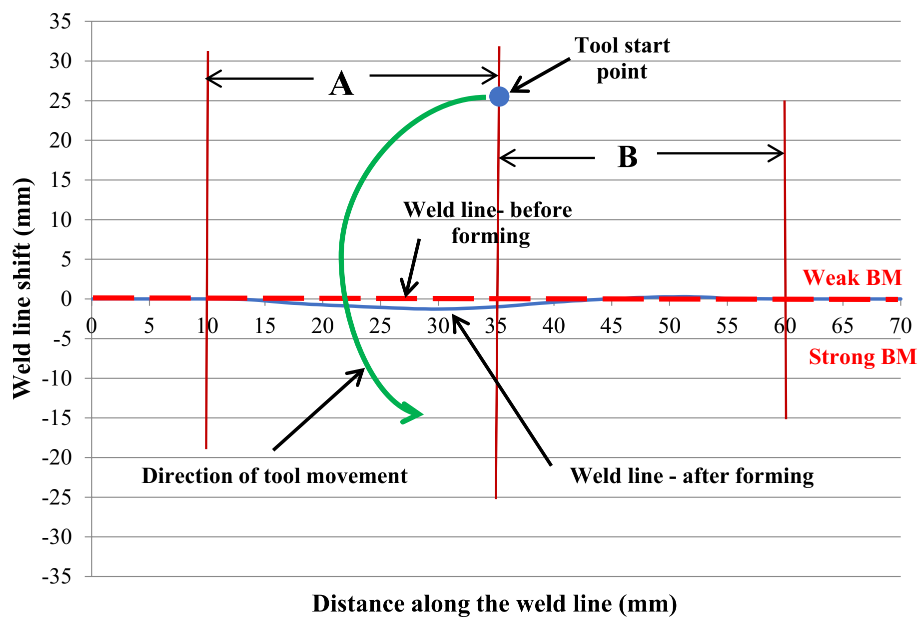
It can be observed that thinning in the formed part has taken place at majority of two places: one at the starting point where the blank is deformed due to tool and second near the boundary between weld and base material.

The thinning due to tool is observed because when the tool comes to its starting point after completing one cycle, it moves down by incremental step size (0.5 mm for present study) in the direction of thickness of blank, deforming the blank. This deformation of blank occurs after each cycle of tool and due to which excessive thinning of blank may happen. This thinning can be observed in the form of tool marks on the experimentally formed cup as well. When the tool initial position is as strong center, thinning will be observed on strong material due to tool movement (see Fig. 8). Similarly, for weak center case, weak material will be subjected to more thinning due to tool movement (see Fig. 9). For cases WTS and WTW, tool initial position is on weld; therefore, weld region will be subjected to more thinning (see Figs. 10, 11).

Fig. 6 Weld line shift in the SPIF formed component from a TWB–WC case



(a) Top view



(b) Weld line shift in the formed cup for a TWB

The second thinning zone is observed at the boundary of weld metal and parent metal (see Figs. 8, 9, 10, 11). At the boundary of the parent metal and weld metal, there is a discontinuity in the blank in terms of material properties and thickness of the blank (for simulation number 3). It is a well-known fact that any kind of discontinuity in the material may give rise to the stress concentration and which may lead to the excessive thinning of the blank. So, this is the reason which gives rise to the thinning of blank at the boundary of parent metal and the weld metal. As this discontinuity is less for the conditions of simulation number 6, less amount of thinning (see Tables 4, 5) is observed in simulation number 6 for all the cases in comparison with simulation number 3 conditions (see Figs. 8, 9, 10, 11).

3.4 Results for DOE

From the performed DOE on simulations, signal-to-noise ratio (S–N) plots for all the cases were extracted and studied. The S–N ratio plot for SC case is represented in Fig. 12. Figure 12a–c represents the S–N ratio graph for weld line shift, PEEQ and %thinning, respectively.

From Fig. 12, it can be observed that thickness ratio contributes more on all the responses followed by yield strength

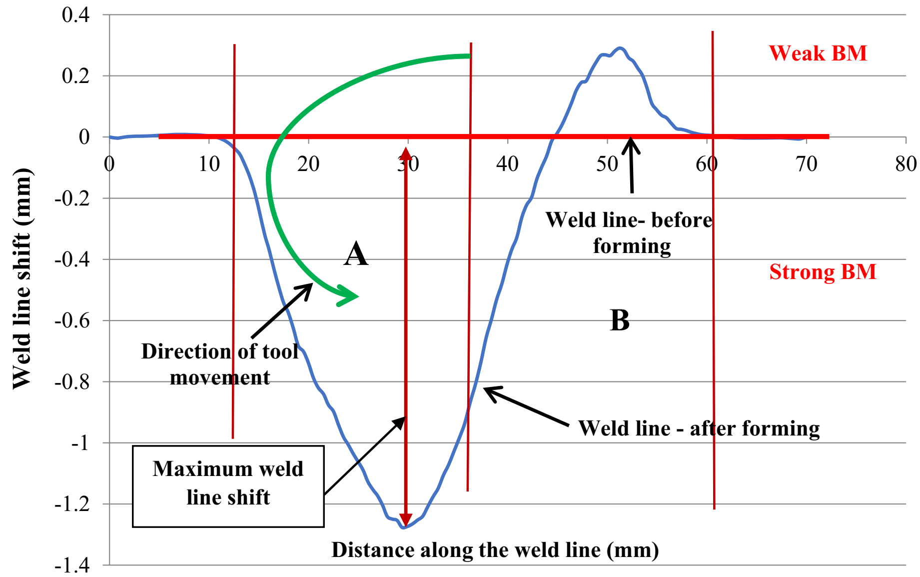


Fig. 7 Magnified view of weld line movement for WC for SPIF of TWB

Table 4 Comparison of cases for maximum weld line movement

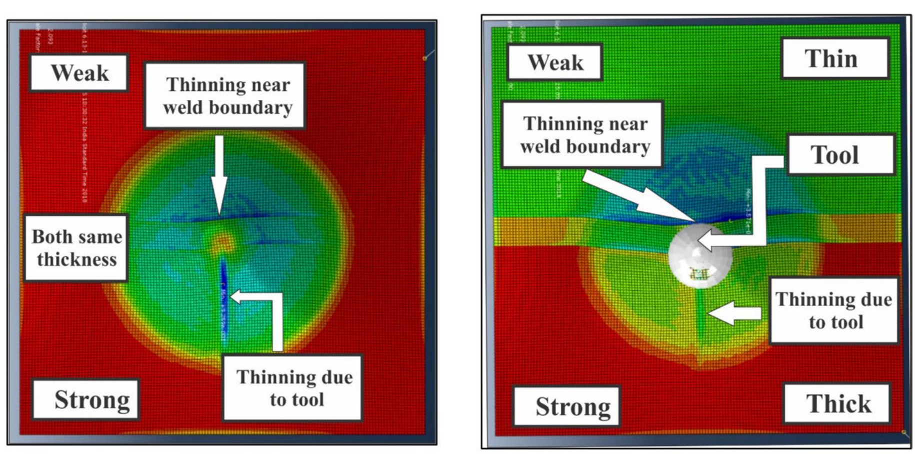
Sr. no.	Case	Simulation number	Weld line movement (mm)		PEEQ	% thinning
			Value	Toward which side		
1	SC	3	1.860	Strong	3.920	71.432
2	WC	3	1.867	Strong	4.170	65.312
3	**WTS**	**3**	**1.617**	**Weak**	**4.638**	**66.224**
4	WTW	3	2.034	Strong	3.832	72.512

The bold text indicates the minimum weld line movement in comparison to other cases

Table 5 Comparison of cases for minimum weld line movement

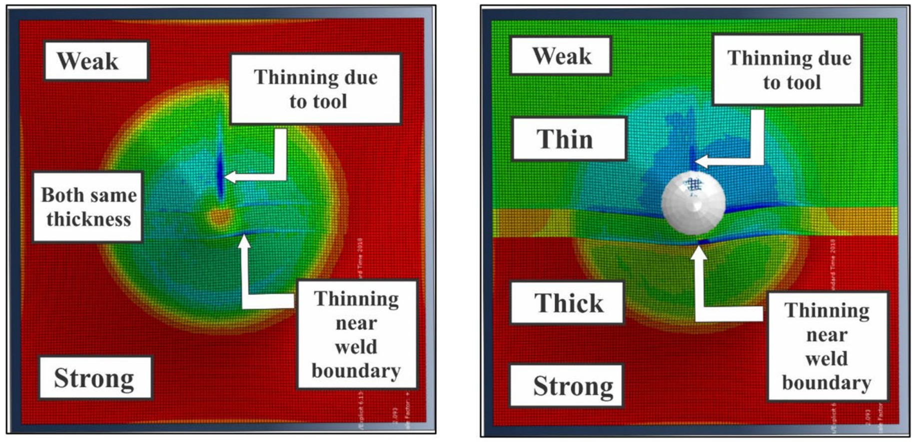
Sr. no.	Case	Simulation number	Weld line movement (mm)		PEEQ	% thinning
			Value	Toward which side		
1	SC	6	0.785	Strong	2.719	53.705
2	WC	6	– 0.940	Strong	3.043	56.580
3	**WTS**	**6**	**– 0.556**	**Weak**	**2.705**	**51.475**
4	WTW	6	– 1.057	Strong	2.943	55.355

The bold text indicates the minimum weld line movement in comparison to other cases



(a) Simulation 6 - TWBs made of same thickness (b) Simulation - 3 TWBs made of different thickness

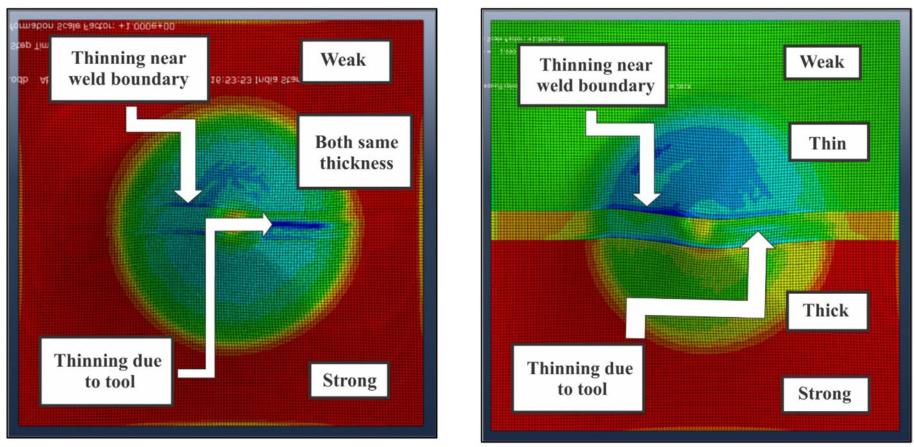
Fig. 8 Blank thickness for SC case after forming



(a) Simulation 6 - TWBs made of same thickness

(b) Simulation 3 - TWBs made of different thickness

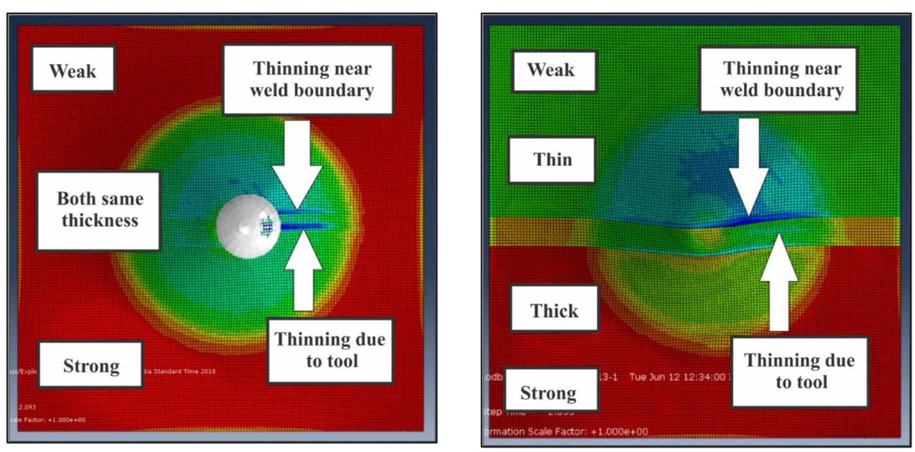
Fig. 9 Blank thickness for WC case after forming



(a) Simulation 6 - TWBs made of same thickness

(b) Simulation 3 - TWBs made of different thickness

Fig. 10 Blank thickness for WTS case after forming

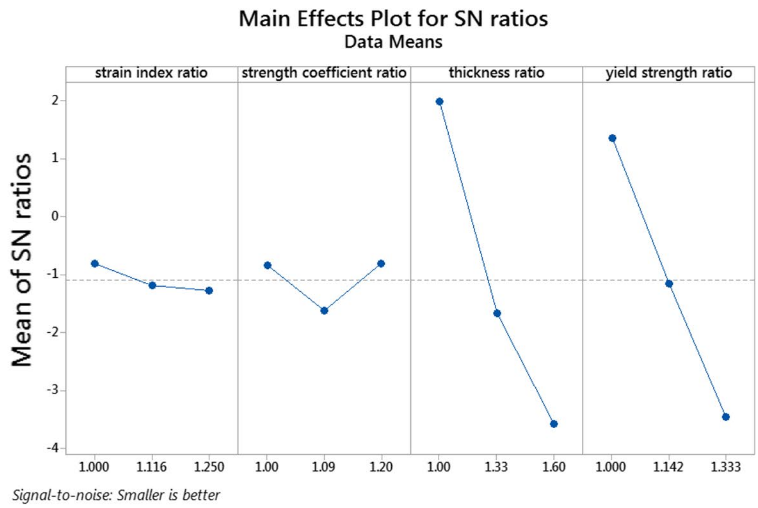


(a) Simulation 6 - TWBs made of same thickness

(b) Simulation 3 - TWBs made of different thickness

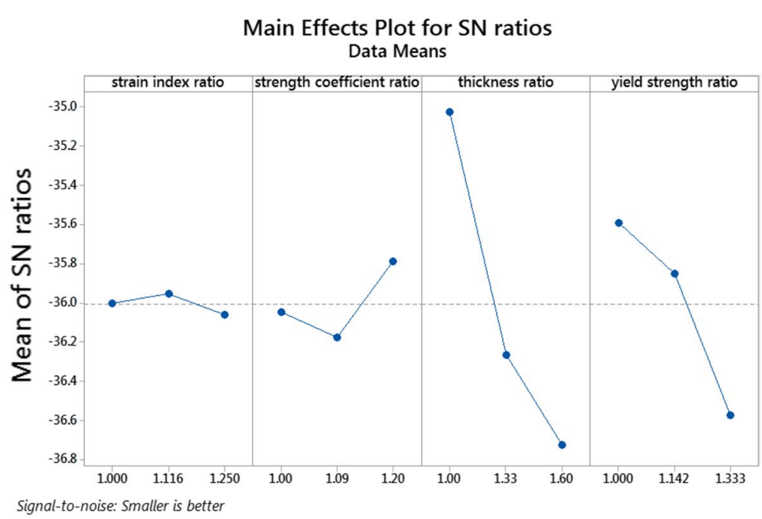
Fig. 11 Blank thickness for WTW case after forming

Fig. 12 S–N ratio plots for SC case



(a) For weld line shift

(b) For PEEQ



(c) For thinning

Table 6 Rank for contribution of each factor for different cases

Cases	Responses	Strain index ratio	Strength coefficient ratio	Thick-ness ratio	Yield strength ratio
SC	Weld line movement	4	3	1	2
	PEEQ	4	3	1	2
	% thinning	4	3	1	2
WC	Weld line movement	4	3	1	2
	PEEQ	4	3	1	2
	% thinning	**4**	**3**	**2**	**1**
WTS	Weld line movement	4	3	1	2
	PEEQ	4	3	1	2
	% thinning	4	3	1	2
WTW	Weld line movement	4	3	1	2
	PEEQ	4	3	1	2
	% thinning	4	3	1	2

The bold text indicates that rank of factors for contribution for all the cases and responses is same except for the response "% thinning" of "WC" case

Table 7 Values of different parameters for extended simulation study-1

Simulation no.	Strain index ratio	Strength coefficient ratio	Yield strength ratio	Thickness ratio
A	1	1	1	1.33
B	1	1	1	1.6
C	1	1	1.142	1
D	1	1	1.333	1
E	1	1.090	1	1
F	1	1.2	1	1
G	1.116	1	1	1
H	1.25	1	1	1

ratio, strength coefficient ratio and strain index ratio. Similar observations are noted for WTS and WTW cases except % thinning of WC case. The details of contribution of each factor for all the responses for each case are represented in Table 6.

It can be stated from this observation that the thickness ratio and yield strength ratio of the thick to thin participating blanks should be chosen to vary carefully in order to minimize the weld line shift and improve the formability of the TWBs.

3.5 Order of significance, cause and effect of parameters

In order to study the effect of individual parameter on the responses, the present simulation study was extended. During this extended study, value of each ratio was varied keeping all the other ratios constant (see Table 7). The responses observed for the change in the values of different ratios are represented in Table 8.

After the successful extended simulation study-1, the possible cause and effect for each parameter was studied and it is reported below.

(a) Thickness ratio

In this article, the thickness ratio is defined as the ratio of thickness of thick material to thickness of thin material participating in the TWB. From Table 8, it can be observed that the thickness ratio has major effect on all the responses compared to other parameters. As the thickness ratio increases, it increases the geometrical heterogeneity present in the blank. Even if the participating materials in the TWB have same properties and only there is a difference in thickness between them, that increases the geometrical heterogeneity. More amount of geometrical heterogeneity will result in more thinning of thin blank and that indirectly will result in generation of more plastic strain in thin blank. More amount of plastic strain indicates that thin participating blank is experiencing more deformation than the thick participating blank and that leads to high amount of weld line shift during the forming operations.

Table 8 Results for extended simulation study-1

Simulation no.	Max. weld line shift (mm)	Max. PEEQ	% thinning	Remarks
A	0.86	3.257	70.75	Represents effect of change in thickness ratio
B	1.24	3.402	78.95	
C	0.78	2.719	53.75	Represents effect of change in yield strength ratio
D	1.13	3.104	61.85	
E	0.57	2.806	52.95	Represents effect of change in strength coefficient ratio
F	0.57	2.806	52.95	
G	0.57	2.806	52.95	Represents effect of change in strain index ratio
H	0.57	2.806	52.95	

(b) Yield strength ratio

In this study, yield strength ratio is defined as the ratio of yield strength of strong material to the yield strength of weak material participating in the TWB. For yield strength ratio, it can be observed that it has the second major effect on all the mentioned responses as indicated in Table 8. Consider that there are two materials having same thickness and material parameters except yield strength. If a material is having high yield strength, it indicates that it can withstand high amount of stress without deforming plastically. The high value of this ratio indicates that the TWB has two materials out of which one material is having low yield strength. So, that material will reach plastic stage early than the material having high yield strength. This will result in excessive thinning of blank having low yield strength and ultimately that will lead to increase in the weld line shift during forming operations.

(c) Strength coefficient ratio

In the present simulation study, strength coefficient ratio is defined as ratio of high value of strength coefficient to the low value of strength coefficient of participating blanks. A high value of strength coefficient indicates low formability of a blank as high amount of force is required during forming of such blanks, while a blank having low value of strength coefficient will deform easily and it will

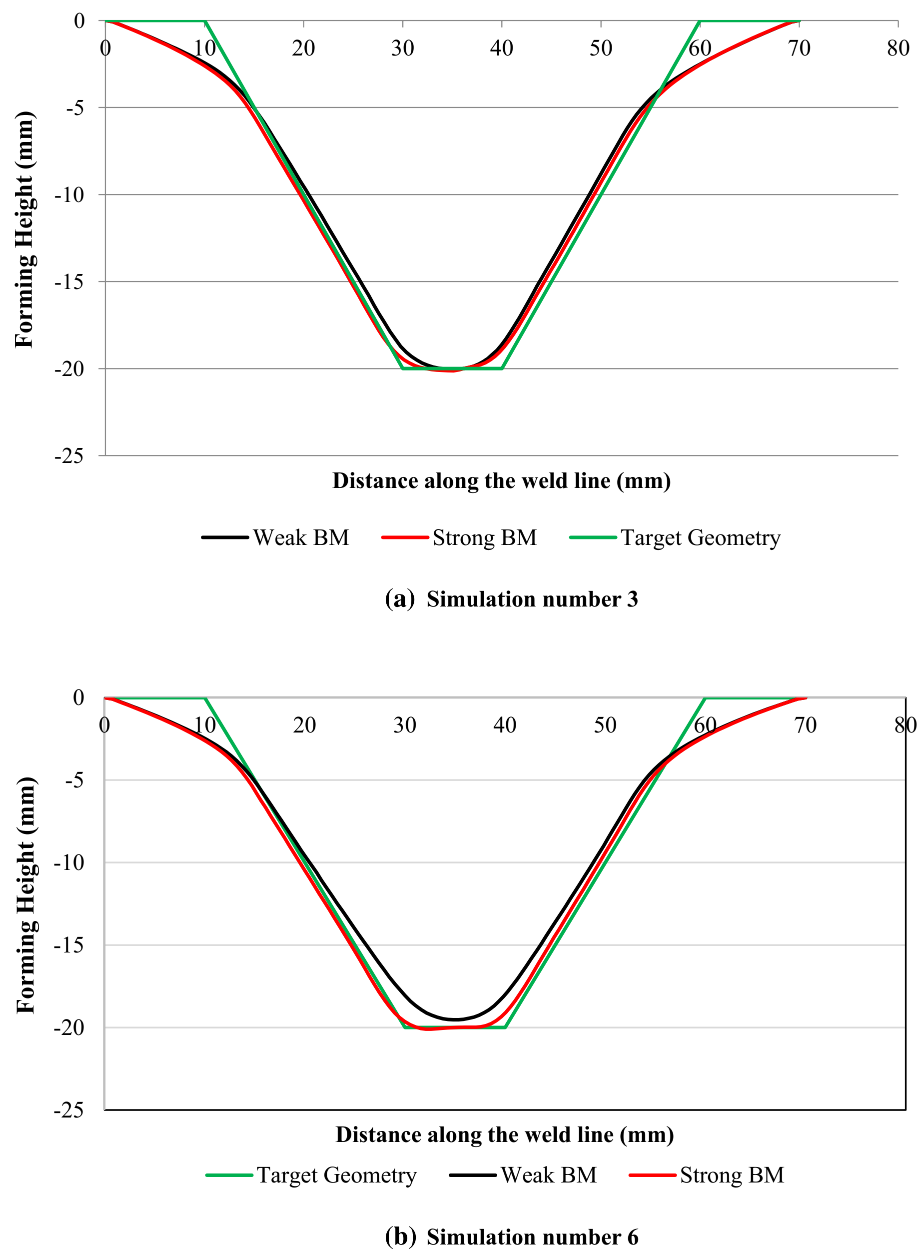


Fig. 13 Forming height comparison for SC case

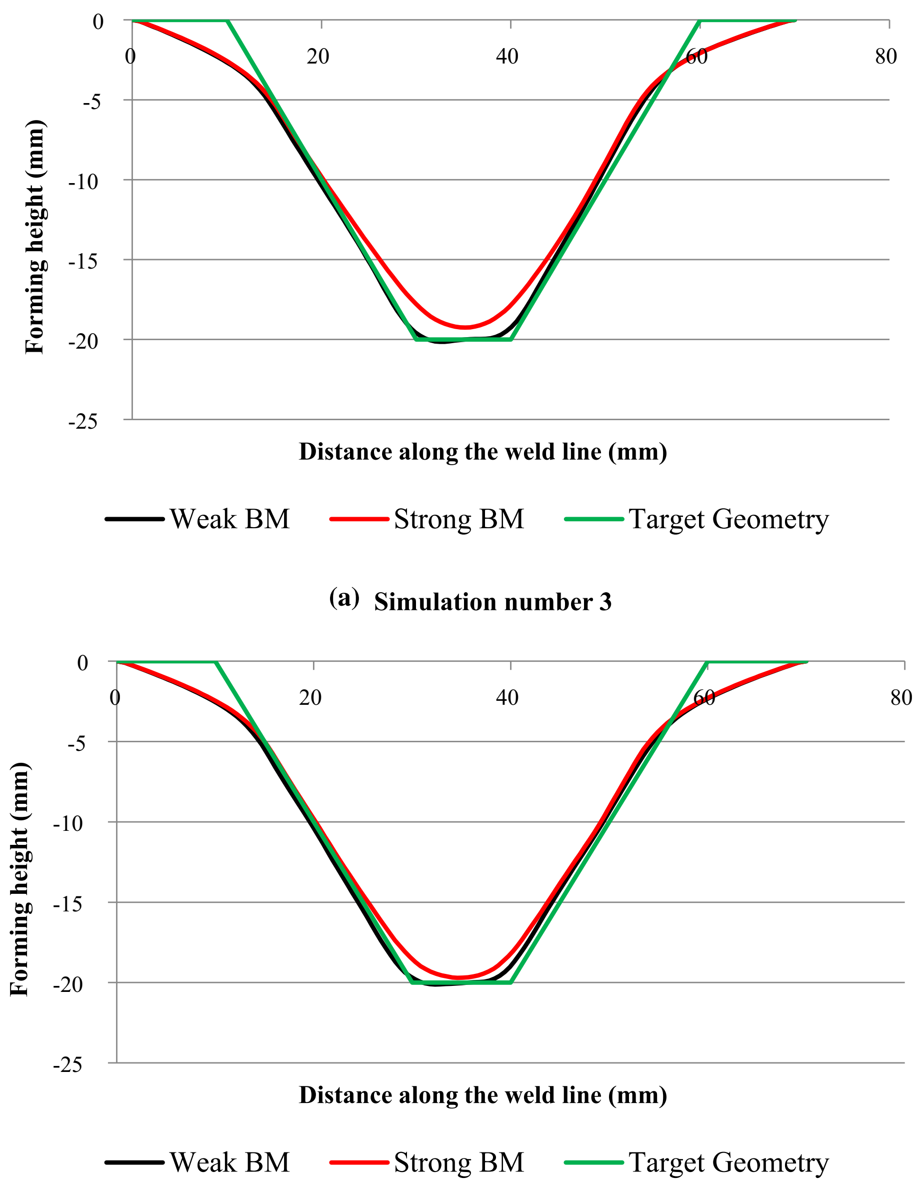
require less amount of force during forming. So, a high value of strength coefficient ratio indicates there is one blank which is having good formability compared to the other participating blanks. These different forming behaviors of participating material will lead to the heterogeneous behavior of TWB during forming. This phenomenon ultimately leads to decrease the overall formability of the TWBs.

From Table 8, the contribution of strength coefficient ratio and strain index ratio is found to be same on the mentioned responses. In order to evaluate the more significant parameter out of strain index ratio and strength coefficient ratio, forming force calculation for unit area and constant strain was carried out based on the power law equation. From the calculation, it was found that the change in the value of strength coefficient has more effect on the forming force required compared to the change in the values of strain index. This is the probable reason that strength coefficient ratio was the third major contributing factor.

(d) Strain index ratio

For this study, strain index ratio has been defined as ratio of high values of strain index to low value of strain index of the participating blanks. A high value of strain index indicates good formability of blank as the forming force required will be less during forming of such blanks, while a low value of strain index represents low formability of blank as the

Fig. 14 Forming height comparison for WC case



(b) Simulation number 6

forming force required will be high during forming of such blank. If a TWB involves two blanks having a different strain index, then both blanks will have a different deformation behavior during forming. Due to this, the overall formability of the TWB is reduced. As explained for strength coefficient, the effect of change in strain index value on forming force is less compared to the strength coefficient. Due to this, the strain index was the least contributing factor among all.

3.6 Comparison with target geometry

Despite of many advantages of SPIF process, one major limitation associated with SPIF process is the phenomenon of spring back in the formed components. As the TWBs involve two different materials, the spring back observed for different materials will be different. In order to study that, the formed geometry of simulation is compared with the target geometry. The TWB consists of two different parent materials along with the weld material. Now, when a TWB is formed in a cup, indirectly these three materials will be formed in a cup as well. As both base metal and weld metal are having different properties, the shape gained by them will be different. The shape gained by two parent metals and weld metal is compared with the target geometry. Figures 13, 14, 15 and 16 compare the mentioned response for simulation numbers 3 and 6 which resulted in the maximum and minimum weld line shift, respectively.

Figure 13a, b compares the shape gained by strong and weak material with target geometry for simulation 3 and 6 respectively for SC case. It can be observed that the deviation between shape gained by strong material and target

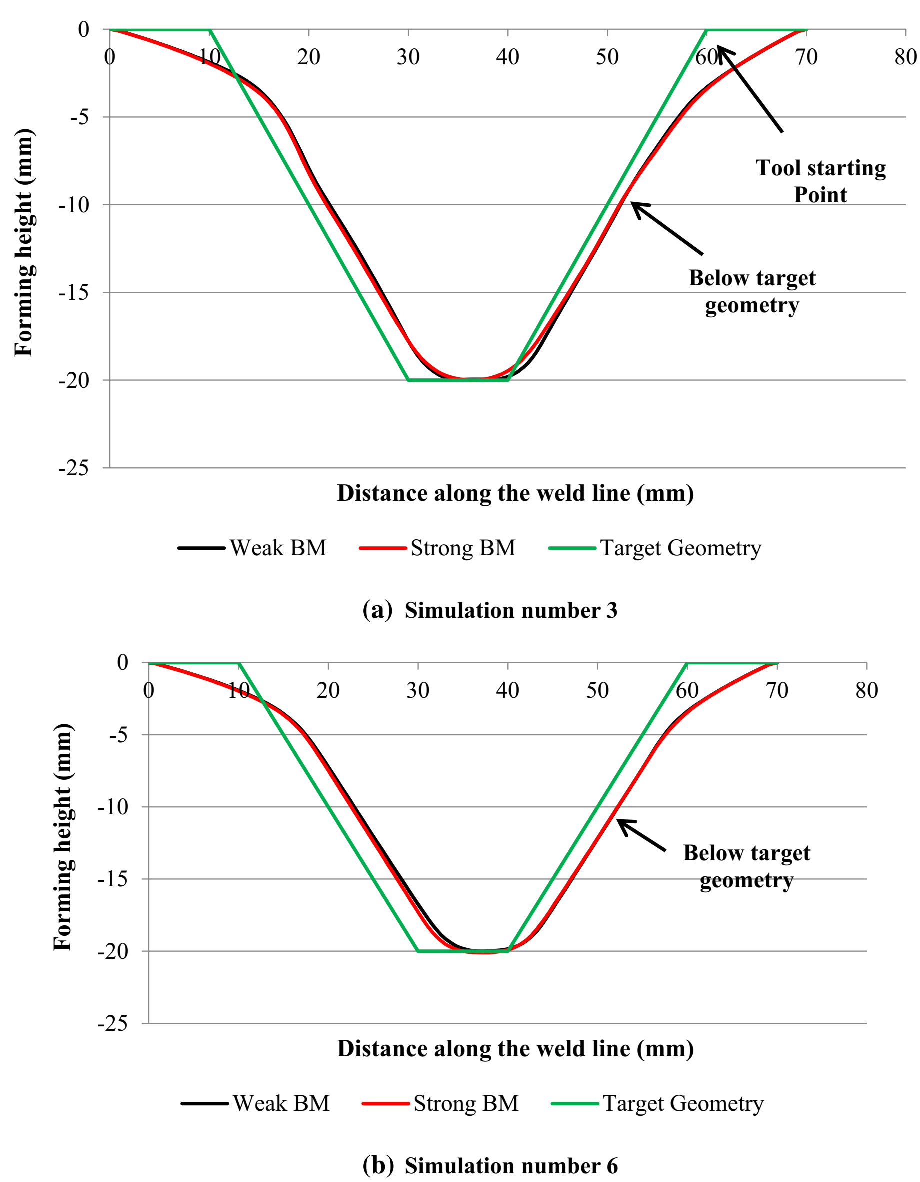


Fig. 15 Forming height comparison for WTS case

geometry is high in comparison to the deviation between shape gained by weak material and target geometry.

Figure 14a, b represents the comparison of target geometry with shape gained by strong and weak material for WC case for simulation numbers 3 and 6, respectively. In this case, the deviation of shape gained by weak material from target geometry is less compared to deviation of strong material from the target geometry.

Figure 15a, b compares the target geometry with the formed geometry for strong and weak material for WTS case for simulation numbers 3 and 6, respectively. Similarly, Fig. 16a, b compares the target geometry with the formed geometry for strong and weak material for WTW case for simulation numbers 3 and 6, respectively. It can be observed in Figs. 15 and 16 that the formed geometry has been shifted toward the right side from the target geometry. For WTS and WTW cases, the tool position is not at the center of the blank, but it is at the center of the weld as indicated in Fig. 4c, d. Due to the repetitive deformation produced by tool on the edge of the blank, the whole formed geometry shifts toward the right side from the target geometry.

For WTW case, it is observed that the difference in the shape gained by the strong and weak material is large, while this difference is very less for the WTS case. This observation indicates that in WTS case, the strain distribution is more uniform compared to the other three cases.

From Figs. 13, 14, 15 and 16, it can be observed that the geometrical accuracy achieved in the SPIF process not only depends upon the material properties but also depends upon the starting point from where the deformation is initiated. The detailed investigation on effect of initial position of tool is reported in next section.

3.7 Effect of initial position of tool

In order to investigate the effect of initial position of tool, different starting positions of tool were selected in extended

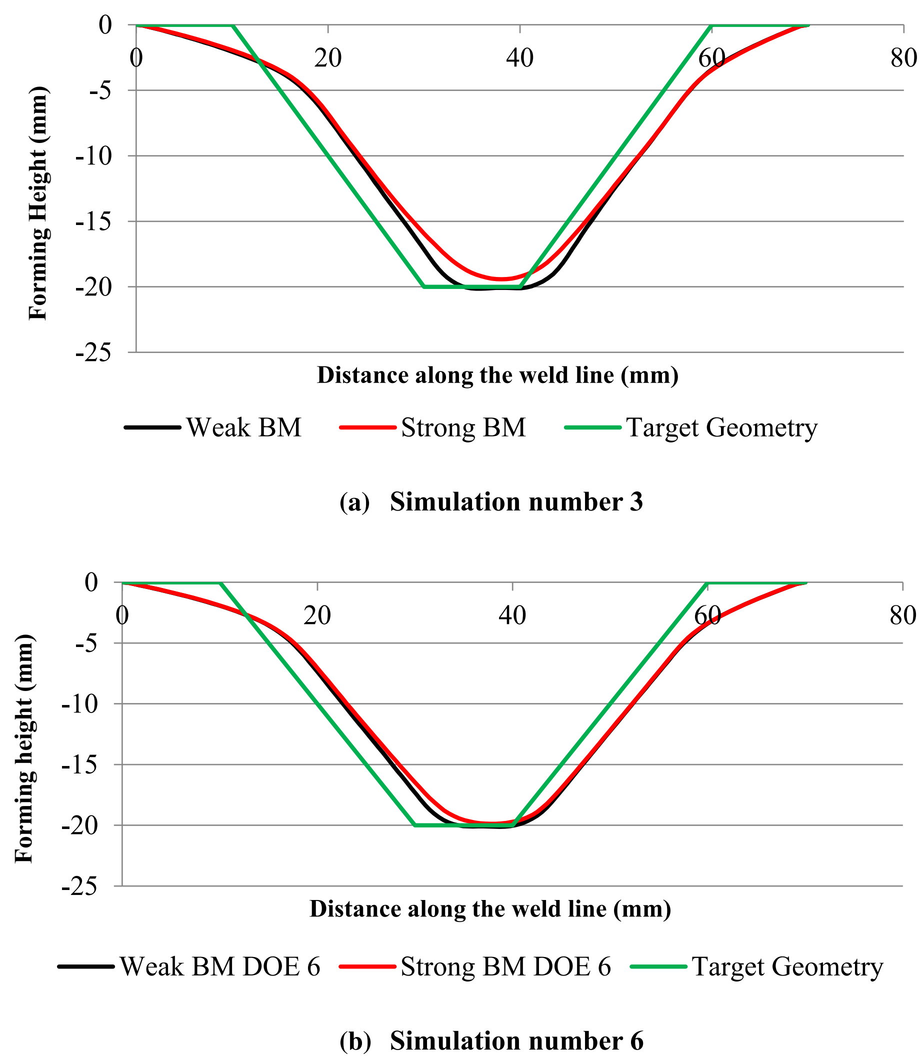


Fig. 16 Forming height comparison for WTW case

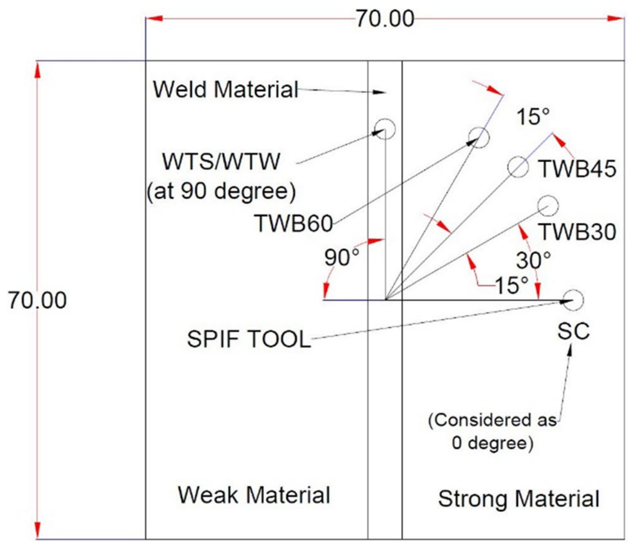


Fig. 17 Different starting positions of SPIF tool (all the dimensions are in mm)

simulation study-2 as indicated in Fig. 17. As depicted in the figure, the position of tool for the SC case was considered at 0° and with respect to that tool positions were varied at angle of 30°, 45° and 60° which are represented as TWB30, TWB45 and TWB60, respectively. The starting position of tool for WTS and WTW can be considered at 90^0.

The forming was done for all the positions mentioned in Fig. 17, and formed geometries were extracted normal to the direction of weld line. During this forming, the material and process parameters were kept same as SC, WC, WTS and WTW cases. The comparison of formed geometries for all different positions of SPIF tool is represented in Fig. 18.

From Fig. 18, it can be observed that the deviation of formed geometry is different for different cases of tool starting position. As the tool position is shifted from SC (0°) to TWB30 (30°), the formed geometry gets closer to the target geometry. Similarly, as the tool's initial position is shifted from TWB30 to TWB45 (45°), TWB60 (60°) and to WTS/WTW (90°), the deviation decreases. In addition to that, the spring back and shape gained by strong material are different for all the cases and similar observation can be made for weak material as well. So, if the tool initial position is considered on a particular parent material of TWB and if only the angular position of tool on that particular material is changed (Fig. 17), then the spring back and geometrical accuracy will be affected and this is due to the mechanism of localized deformation produced by the SPIF tool during forming. In a nutshell, it can be said that, the spring back and geometrical accuracy of formed part in SPIF depends upon tool initial position along with the material properties of parent materials.

4 Conclusions

In the present finite element study, simulation of SPIF process is performed for the TWBs. Effect of different material properties of parent materials on the forming behavior of TWBs has been investigated. From the reported study, following points can be concluded:

- Apart from the SPIF process parameters, initial position of the SPIF tool affects the weld line shift, PEEQ, % thinning and forming height of the blank.
- Tool dragging plays major role on the weld line shift. Better the lubrication less will be the friction and that will reduce the tool dragging effect. More weld line shift means more thinning and that leads to reduce the formability of the TWBs.
- Out of the four considered parameters, thickness ratio is having major contribution on the responses followed by yield strength ratio, strength coefficient ratio and strain index ratio.

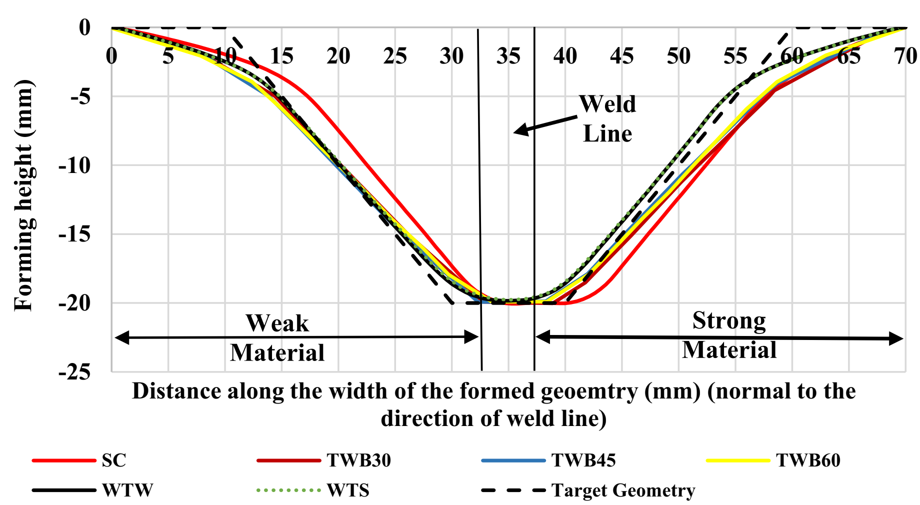


Fig. 18 Comparison of formed geometry with target geometry for different starting positions of tool

- During the SPIF, thinning of blank is observed at two different locations of the TWBs. The thinning of blank is found to be at the tool starting position and at the boundary between weld and both the parent metals.
- The conditions of simulation numbers 3 and 6 for each case resulted in the maximum and minimum weld line movement, respectively. Conditions of simulation number 6 for the WTS resulted in the minimum weld line shift, PEEQ and % thinning.
- From the comparison of formed and target geometry for all the cases, simulation number 6 of case WTS leads to even distribution of strain which will lead to the better forming behavior of the TWBs, but shift of formed geometry from target geometry has been observed.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Parente M, Safdarian R, Santos AD, Loureiro A, Vilaca P, Jorge RN (2016) A study on the formability of aluminum tailor welded blanks produced by friction stir welding. Int J Adv Manuf Technol 83(9–12):2129–2141. https://doi.org/10.1007/s00170-015-7950-0
2. Riahi M, Amini A (2013) Effect of different combinations of tailor-welded blank coupled with change in weld location on mechanical properties by laser welding. Int J Adv Manuf Technol 67(5–8):1937–1945. https://doi.org/10.1007/s00170-012-4620-3
3. Panda SK, Hernandez VB, Kuntz ML, Zhou Y (2009) Formability analysis of diode-laser-welded tailored blanks of advanced high-strength steel sheets. Metall Mater Trans A 40(8):1955–1967. https://doi.org/10.1007/s11661-009-9875-4
4. Suresh VS, Regalla SP, Gupta AK (2017) Combined effect of thickness ratio and selective heating on weld line movement in stamped tailor-welded blanks. Mater Manuf Process 32(12):1363–1367. https://doi.org/10.1080/10426914.2016.1257128
5. Kesharwani RK, Panda SK, Pal SK (2015) Experimental investigations on formability of aluminum tailor friction stir welded blanks in deep drawing process. J Mater Eng Perform 24(2):1038–1049. https://doi.org/10.1007/s11665-014-1361-5
6. Panda SK, Kumar DR (2008) Improvement in formability of tailor welded blanks by application of counter pressure in biaxial stretch forming. J Mater Process Technol 204(1–3):70–79. https://doi.org/10.1016/j.jmatprotec.2007.10.076
7. Chatterjee S, Saha R, Shome M, Ray RK (2009) Evaluation of formability and mechanical behavior of laser-welded tailored blanks made of interstitial-free and dual-phase steels. Metall Mater Trans A 40(5):1142–1152. https://doi.org/10.1007/s11661-009-9808-2
8. Ma X, Guan Y, Yang L (2015) Determination of elastoplastic mechanical properties of the weld and heat affected zone metals in tailor-welded blanks by nanoindentation test. Chin J Mech Eng 28(5):911–918. https://doi.org/10.3901/CJME.2015.0320.035
9. Chung K, Lee C, Kim H (2014) Forming limit criterion for ductile anisotropic sheets as a material property and its deformation path insensitivity, part II: boundary value problems. Int J Plast 58:35–65. https://doi.org/10.1016/j.ijplas.2014.03.014
10. Micari FA, Ambrogio G, Filice L (2007) Shape and dimensional accuracy in single point incremental forming: state of the art and future trends. J Mater Process Technol 191(1–3):390–395. https://doi.org/10.1016/j.jmatprotec.2007.03.066
11. Shibata K, Iwase T, Sakamoto H, Kasukawa M, Chiba K, Saeki H (2003) Welding of aluminium tailored blanks by Nd:YAG lasers. Weld Int 17(4):282–286. https://doi.org/10.1533/wint.2003.3088
12. Buste A, Lalbin X, Worswick MJ, Clarke JA, Altshuller B, Finn M, Jain M (2000) Prediction of strain distribution in aluminum tailor welded blanks for different welding techniques. Can Metall Q 39(4):493–502. https://doi.org/10.1179/cmq.2000.39.4.493
13. Hariharan K, Kalaivani K, Balachandran G (2012) Foil optimization in tailor welded blank of an automotive floor component. Mater Manuf Process 27(9):936–942. https://doi.org/10.1080/10426914.2011.610077
14. Tronci A, McKenzie R, Leal RM, Rodrigues DM (2011) Microstructural and mechanical characterisation of 5XXX-H111 friction stir welded tailored blanks. Sci Technol Weld Join 16(5):433–439. https://doi.org/10.1179/1362171811Y.0000000012
15. Alinaghian I, Ranjbar H, Beheshtizad MA (2017) Forming limit investigation of aa6061 friction stir welded blank in a single point incremental forming process: RSM approach. Trans Indian Inst Met 70(9):2303–2318. https://doi.org/10.1007/s12666-017-1093-y
16. Tang B, Wang Q, Wei Z, Meng X, Yuan Z (2016) FE simulation models for hot stamping an automobile component with tailor-welded high-strength steels. J Mater Eng Perform 25(5):1709–1721. https://doi.org/10.1007/s11665-016-2011-x
17. Rattanachan K, Sirivedin K, Chungchoo C (2014) Formability of tailored welded blanks in single point incremental forming process. In: Mekhum W, Sangwaranatee N, Limsuwan P, Kim HJ, Djamal M, Kaewkhao J (eds) Advanced materials research, vol 979. Trans Tech Publications, Stafa-Zurich, pp 339–342. https://doi.org/10.4028/www.scientific.net/AMR.979.339
18. Reis A, Teixeira P, Duarte JF, Santos A, Da Rocha AB, Fernandes AA (2004) Tailored welded blanks—an experimental and numerical study in sheet metal forming on the effect of welding. Comput Struct 82(17–19):1435–1442. https://doi.org/10.1016/j.compstruc.2004.03.039
19. Song Y, Hua L, Chu D, Lan J (2012) Characterization of the inhomogeneous constitutive properties of laser welding beams by the micro-Vickers hardness test and the rule of mixture. Mater Des 37:19–27. https://doi.org/10.1016/j.matdes.2011.12.029
20. Jia Q, Guo W, Li W, Zhu Y, Peng P, Zou G (2016) Microstructure and tensile behavior of fiber laser-welded blanks of DP600 and DP980 steels. J Mater Process Technol 236:73–83. https://doi.org/10.1016/j.jmatprotec.2016.05.011
21. Chu GN, Liu G, Liu WJ, Yuan SJ (2012) An approach to improve thickness uniformity within tailor-welded tube hydroforming. Int J Adv Manuf Technol 60(9–12):1247–1253. https://doi.org/10.1007/s00170-011-3792-6
22. Abdullah K, Wild PM, Jeswiet JJ, Ghasempoor A (2001) Tensile testing for weld deformation properties in similar gage tailor welded blanks using the rule of mixtures. J Mater Process Technol 112(1):91–97. https://doi.org/10.1016/S0924-0136(01)00555-6

23. Zadpoor AA, Sinke J, Benedictus R (2007) Finite element modeling of transition zone in friction stir welded tailor-made blanks. In: AIP conference proceedings, May 17, vol 908, no 1. AIP, College Park, pp. 1457–1462. https://doi.org/10.1063/1.2741014
24. Garware M, Kridli GT, Mallick PK (2010) Tensile and fatigue behavior of friction-stir welded tailor-welded blank of aluminum alloy 5754. J Mater Eng Perform 19(8):1161–1171. https://doi.org/10.1007/s11665-009-9589-1
25. Mishra RS, De PS, Kumar N (2014) Friction stir welding and processing: science and engineering. Springer, London
26. Saidi B, Boulila A, Ayadi M, Nasri R (2015) Prediction of the friction coefficient of the incremental sheet forming SPIF. In: The 6th international congress design and modelling of mechanical systems CMSM