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Finite Element Simulation of Exit Hole Filling for Friction Stir Spot Welding – A Modified Technique to Apply Practically

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Abstract

Friction Stir Spot Welding (FSSW) is a solid state joining process which uses a rotating tool consisting of a shoulder and/or a probe. Though it has proven its potential in joining difficult to weld materials, one of the drawbacks of process is prevalence of exit hole at the end of the process. In the recent past new techniques have been developed to eliminate this draw back by filling this unwanted hole. Determining the appropriate tool design and parameters to fill a hole for given situation is a challenge. The article demonstrates the effective method of obtaining these desired parameters a priory. A three dimensional (3D) model is developed in finite element (FE) commercial code DEFORM 3D/Implicit. It was found that internally filleted shoulders help in filling of holes. The obtained optimized process parameter (tool rotation speed of 900rpm, plunge velocity of 30mm/sec and plunge depth of 0.2 mm) for AA2024 plate (5mm thick) have potential to reduce number of experiments.

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*Keywords:*FSSW;FE Modeling; Exit hole filling; Simulation

1. Introduction

Friction Stir Spot Welding (FSSW) is a solid state joining process which was developed in 2001 and is one of the main variant ofFriction Stir Welding (FSW)[1, 2]. FSSW is a solid state joining technology that has the impending to be a replacement for processes like resistance spot welding and rivet technology in certain applications [3].

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In FSSW a rotating cylindrical tool with varying end geometry and pin is plunged into the sheets, while the backing plate below the lower sheet supports the downward force [4, 5].The downward force and the rotational speed are maintained for an appropriate time to generate frictional heat which is called as dwell phase. Then, heated and softened material adjacent to the tool deforms plastically, and a solid-state bond is achieved between the surfaces of the upper and lower sheet. Finally, the tool is drawn out of the sheets and protruded pin leaves a characteristic exit hole in the middle of the joint [6]. The schematic illustration of basic principle of FSSW process is shown in Fig. 1.

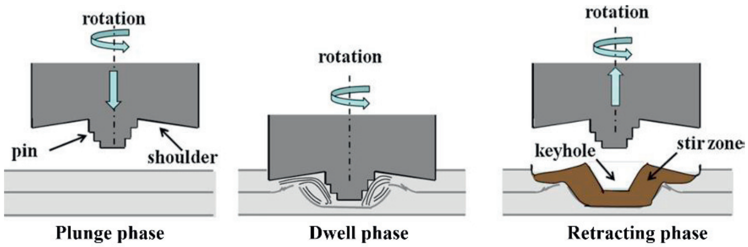


Fig. 1. Basic principle of FSSW process [4, 5].

In the current era it is required to reduce vehicle weight to enhance fuel efficiency. Hence, there is an increasing use of aluminum alloys as it is a lightweight material. This change in materials has forced industries to look for effective method for joining of aluminum alloys for assembly conditions has in case of automotive and aircraft industries since process is offer an alternative to overcome the disadvantages presented by other spot joining technologies[7, 8]. Although Resistance Spot Welding (RSP) is capable of making lap joints in aluminum sheets, the process requires three times more electrical power than it takes for steel. More power leads to higher costs and shorter electrode life[9].As a result, industries have tried several substitutes for RSP, including spot clinching, self-piercing rivets, toggle-locking, spot welding and even ultrasonic welding. But challenges with the mechanical rivets include high cost for fasteners, potentially higher down time due to feeding issues and need for other operations for non-self-piercing rivets. Processes such as toggle-lock are simple and cheap but have less strength than ERSW. FSSW is not saddled with the problems that are cited above due to the unique nature of the process [10]. Higher plastic deformation is obtained in the welding zone of the FSSW process than the resistance spot welding (RSW) process. The hardness increase in the FSSW process is higher than in the RSW process. Also the tensile shear strengths of the FSSW welded joints are higher than those of the resistance spot welded joints [11]. The speed of the process is competitive with ERSW but it is much more consistent because FSSW is not as sensitive to changing material conditions and surface conditions [10]. One of the drawbacks of FSSW is remainder of exit hole at end of the operation.However, recent advancement shows the introduction and development of variety of methods and approaches in filling of keyhole [12-16] like filling friction stir welding (FFSW), refill friction stir spot welding (RFSSW), friction bit joining (FBJ). The filling of key hole can be performed through the any techniques and tools as shown in Fig. 2[12-16]. Few techniques use consumable tools to fill the hole and others use non consumable tools.

Fig. 2(ii) shows the joint and the corresponding tool with different processes. During the FFSW process, the consumable bit of the aluminum alloy along with steel shoulder is plunged into the keyhole left at the end of the FSW joint. The heat generated by friction at the shoulder and the joining bit surface softens the material of keyhole wall and bit. The shoulder provides a forging force which helps in joining of this plasticized section. FSP follows thereafter; where a non-consumable tool consisting of a shoulder without protruding pin provides mechanical mixing and plastic deformation [14]. With non-consumable tool concept no extra material is consumed for each operation unlike its counterpart.

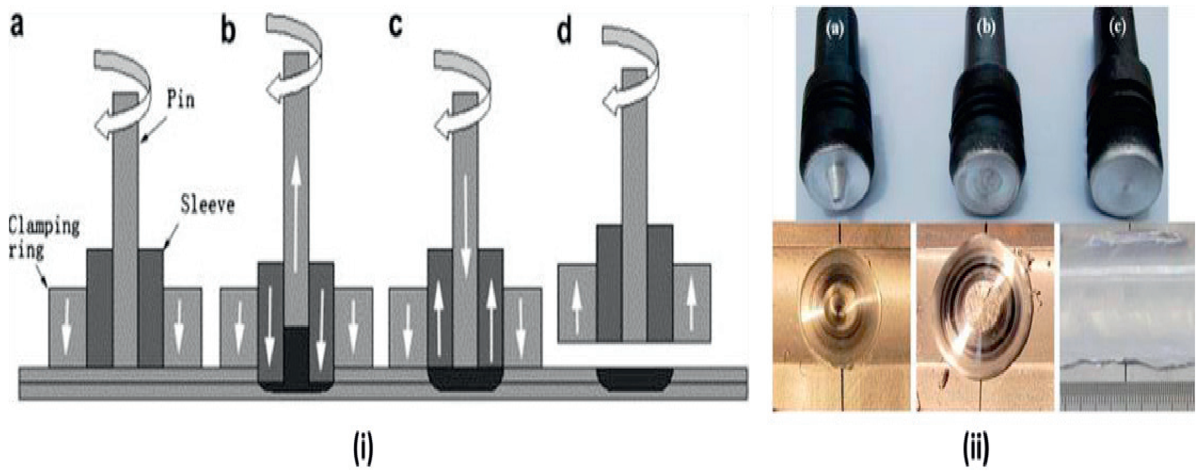


Fig. 2. (i) Schematic illustration of the RFSSW processes, (ii) Joint and corresponding tool with different processes: (a) keyhole left by FSW, b) after FFSW, c) after FSP

In this article, a fully coupled thermo-mechanical finite element model of the plunge phase of a refill FSSW process is presented. DEFORM-3Dimplicit code was used to simulate the refilling operation using non-consumable tools. A similar FSSW process considered is described by Mishra and Ma [17] (Fig. 2(i)). The process uses a three-piece tool system, comprising of a clamping disk, pin and shoulder. The clamp holds the plates firmly against the anvil and confines the material flow around the tool region during the process. The pin and shoulder rotate with the same angular velocity, but can move independently of each other in the axial direction. The process operations can be broadly classified as the plunge and refill phases. As shown in Fig., during the plunge phase, the rotating pin translates into the plates till it reaches a specified plunge depth. The material displaced by the pin moves into the vacant space between the pin and clamp. In the refill phase, the pin retracts back while the shoulder moves down toward the plate, pushing the material in the vacant region back into the plate eliminating the exit hole. The effect of shoulder shape and process parameters on filling was investigated in the current work through FE simulations.

2. Brief FE modeling details and description of simulations

Commercial FEA software DEFORM-3D[18] was chosen for FE modeling. Lagrangian implicit code specially designed for metal forming processes is adopted by the software. In the proposed FEM model, single block continuum approach was used to avoid contact instabilities. The work-piece was modeled as a rigid visco-plastic material, and the welding tool was assumed to be rigid. A rigid-visco-plastic material model with Von Mises yield criterion and associated flow rule was used. Accuracy of simulation results depends on flow stress values considered over a range of temperature as flow stress is a function of strain, strain rate and temperature. Flow stress is mathematically represented as shown in equation (1).

$$\bar{\sigma} = \bar{\sigma}(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T) \quad (1)$$

Where $\bar{\sigma}$ is the flow stress, $\bar{\varepsilon}$ the effective plastic strain, $\dot{\bar{\varepsilon}}$ the effective strain rate and T the temperature.

To obtain this accuracy, flow stress data between Room Temperature (T_{room}) – Melting Temperature (T_{melt}) of material being processed were used in FEM package before running the simulations. Hot working guide was referred for flow stress data that was unavailable in software material library[19]. This guide contains flow stress data recorded from experiments at various strains, strain rates and temperatures for different engineering materials. To know actual flow stress values at temperatures of interest, for data that is unavailable hot compression tests can be performed. The values k=180 [N/(s°C) and c=2.4 [N/ (mm^2°C)] are taken for thermal conductivity and thermal capacity respectively based on previous work. A constant interface heat exchange coefficient of 1 and 11[N/(mm-s-°C)] was used for contact between work piece-backing plate and work piece-tool surfaces respectively [20]. To resemble actual clamping during experiments the plate was constrained accordingly.

Refilling type FSSW has been modelled in the present work. The following table explains different components used in the Modeling and the corresponding material. The material assigned for non-consumable tools (pin, curved and modified flat shoulders) was AISI H13 and for work piece was Al 2024. Fig. 3 shows the components used in modelling of filling FSSW and Fig. 4 shows the assembly of components at initial stage.

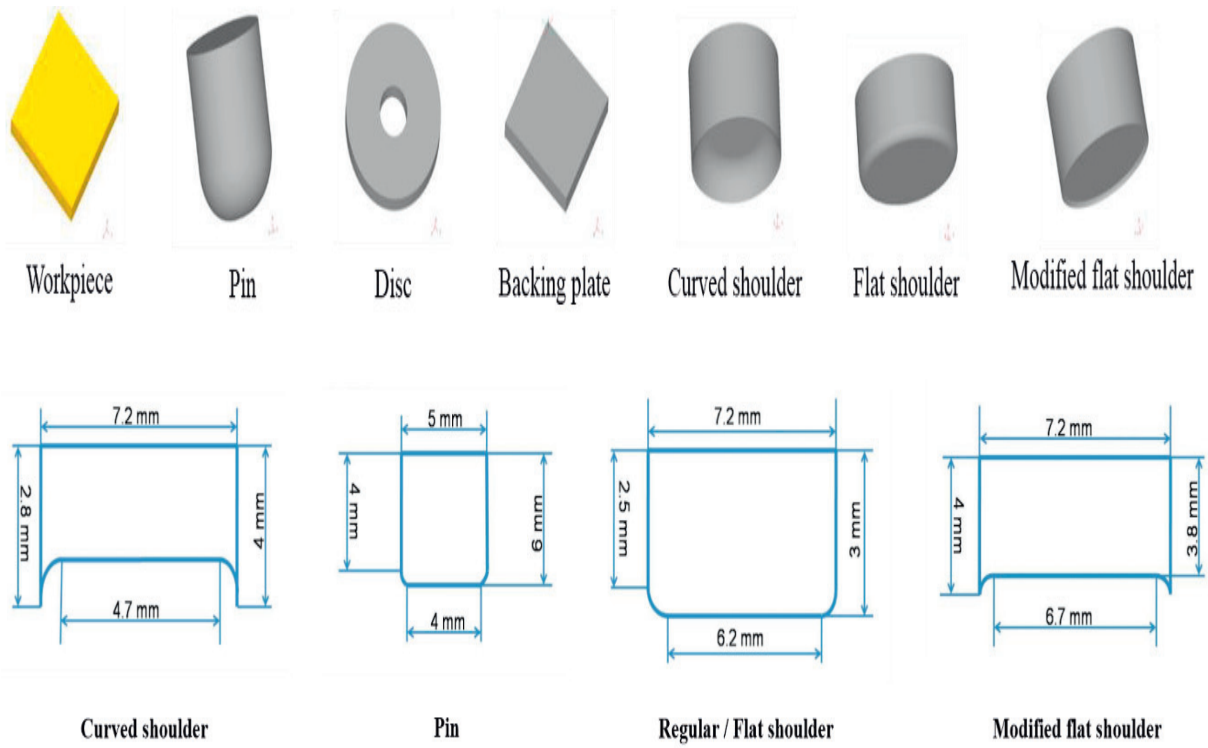


Fig. 3. Components used in modeling of filling FSSW and main components with dimensions

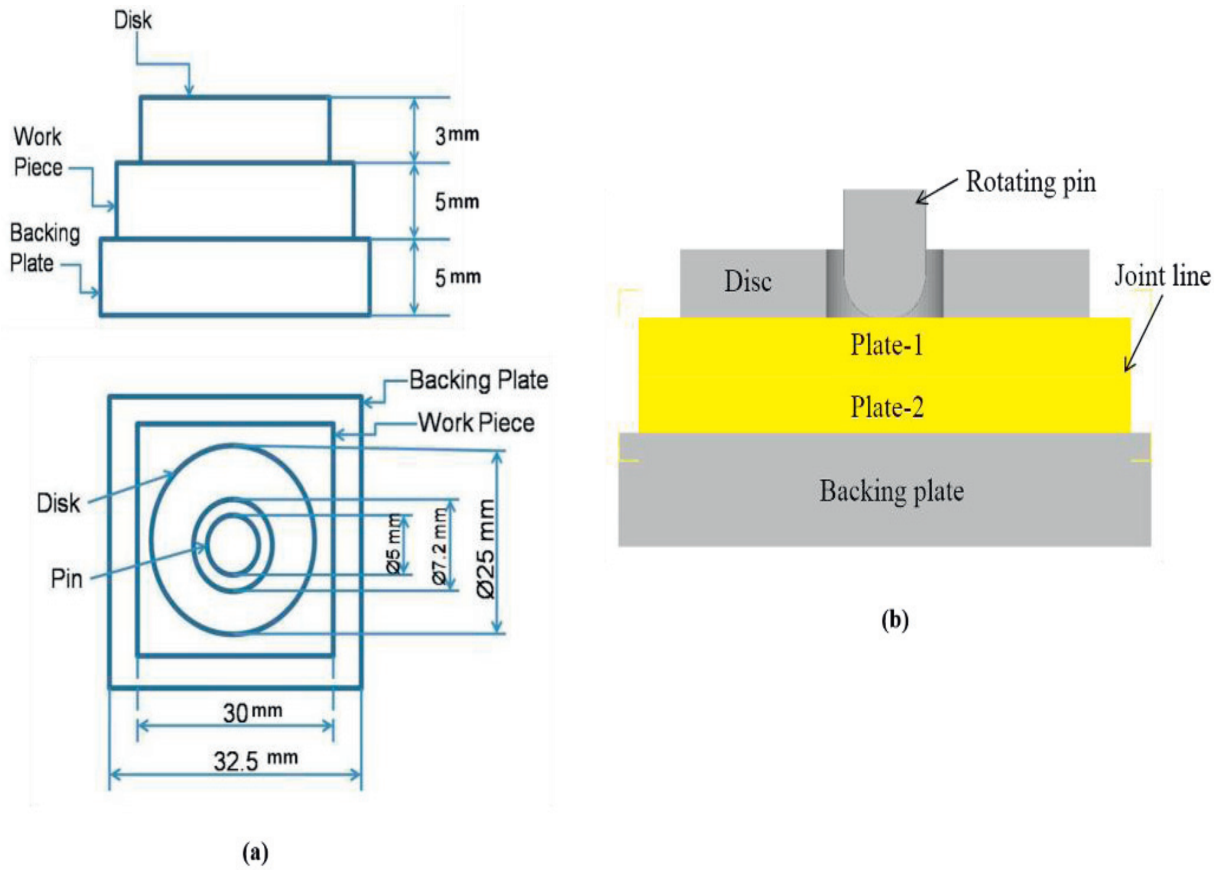


Fig. 4. (a) Initial assembled stage of components with dimensions, (b) Section view (DEFORM-3D Image)

A single workpiece of thickness 5 mm was used for modeling in order to avoid contact instabilities associated with numerical analysis of two work pieces. This is equivalent to welding two work pieces of 2.5 mm thickness. A brief explanation is given on different phases exercised in simulations:

(i) Plunge phase: The rotating pin was assigned a downward movement of 0.5 mm/sec with rotation of 900 rpm for a depth of 3mm descent. During this stage workpiece material is pushed in the empty space between the pin and disc.

(ii) Dwell phase: The traverse movement of rotating pin is reduced to zero and the pin is rotated for 2 seconds, in order to plasticize the material.

(iii) Filling phase: This phase was performed in two stages to fill the hole.

a) With curved shoulder: The first stage with internally curved shoulder draws the material inside the hole for filling. A downward movement of 0.5 mm/sec with rotation of 900 rpm was provided to the shoulder.

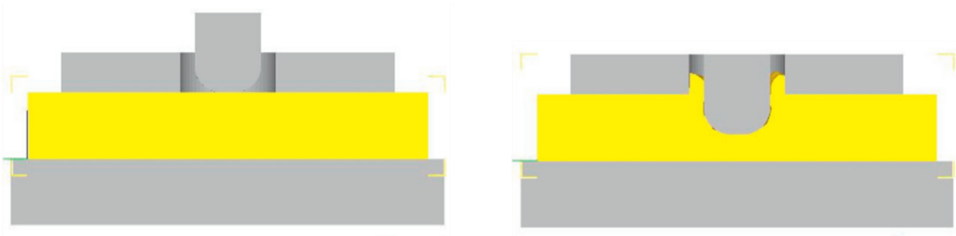
b) With flat shoulder: The second stage was to fill the hole with modified flat shoulder. In this phase entire hole is filled with 0.2 mm plunge depth of shoulder into workpiece. The shoulder is assigned downward movement of 0.5 mm/sec with rotation of 900 rpm.

3. Results and discussion

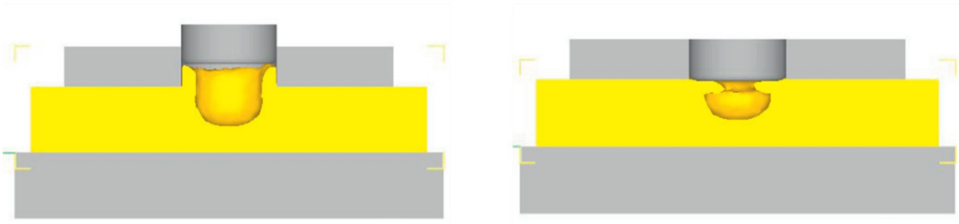
The initial simulations were done in two stages with two components (a) Pin and (b) Flat shoulder. This yielded incomplete filling of hole. The failure or success of filling can be attributed to shoulder design and process parameters (e.g. pin and shoulder rotation speed, their plunge velocity and depth of penetration in plates). To overcome the problem of incomplete filling extra component (curved shoulder) was included in operation at second stage. The third stage flat shoulder was also slightly modified providing it with internal fillets at the edges. The second stage curved shoulder was provided with relatively larger internal fillets which aided in drawing the material into the hole for filling. After few simulation trials the optimized process parameters obtained were as follows, initial pin penetration of 3 mm into the workpiece, pin and shoulder rotation speed of 900 rpm, plunge velocity of 30mm/min and plunge depth of 0.4 mm for final shoulder.

The two stage filling with pin (start and end of pin plunge) and flat shoulder (start and end of shoulder plunge) is shown inFig. 5. One of the reasons for incomplete filling from shoulder design perspective was external fillets at shoulder edges. Pictorial three stage filling with pin, curved shoulder and modified flat shoulder (start and end of plunge for each component) is shown in Fig. 6. Internal fillets for shoulders along with appropriate process parameters aided in proper filling of holes.

Metal flow was studied in filling FSSW process using the proposed model. “Point tracking” feature in DEFORM-3D was used to perform this. Three points were placed on the workpiece and their coordinates are shown in Table 1. Flow was examined for both the cases of successful and incomplete filling. The change in coordinate of the three points placed during the course of welding and final coordinate respectively are illustrated in Fig. 7. Incomplete filling case showing unconsolidated flow using points and consolidate flow of points resulting in proper mixing at the weld zone contrary with flat shoulder case are shown in Fig. 8 and Fig. 9 respectively.



(a)



(b)

Fig. 5. Two stage operation (a) with pin and (b) with flat shoulder resulting in incomplete filling

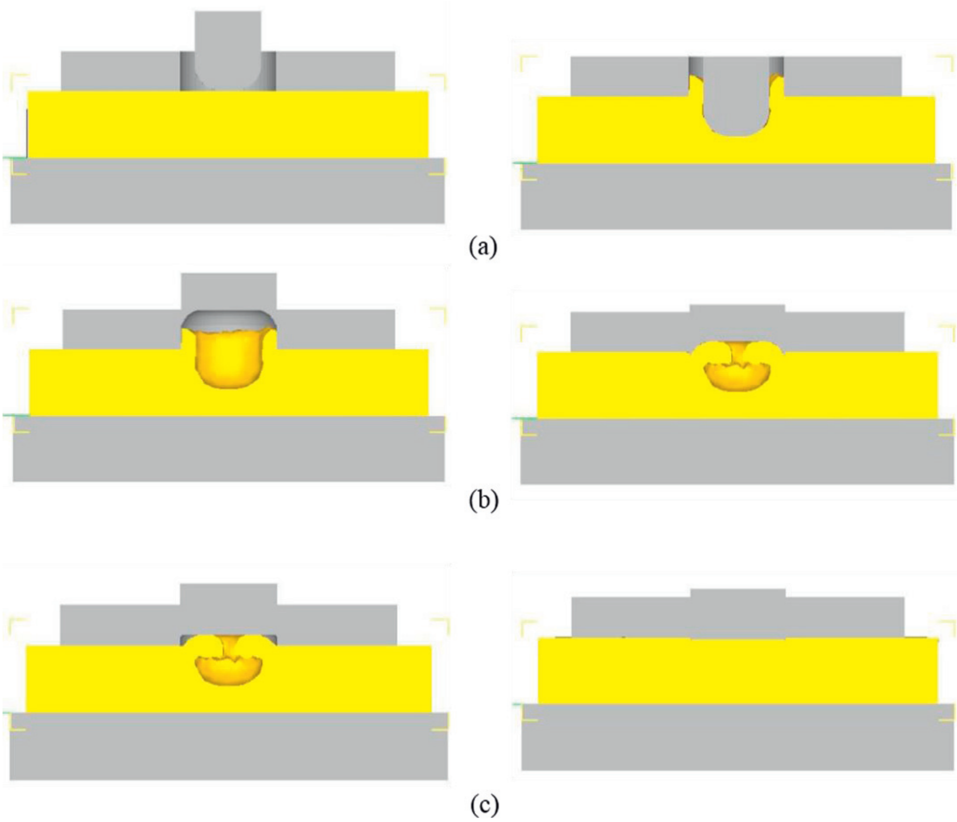


Fig. 6. Three stage operation (a) with pin, (b) with curved shoulder and (c) with modified flat shoulder resulting in successful filling

Table 1. Coordinates of points placed initially

Points	Coordinates		
	X	Y	Z
Point 1	14	14	4.7
Point 2	14	16	4.7
Point 3	15	15	3

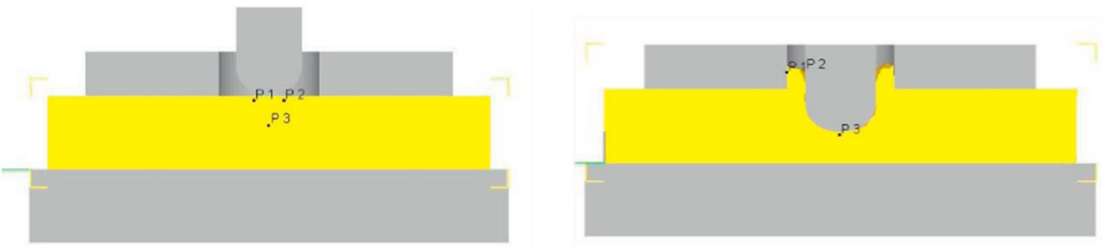


Fig. 7. Arrangement displaying points placed (Section view):
(a) Before the pin penetrating and (b) Resulting displacement of point due to pin penetration

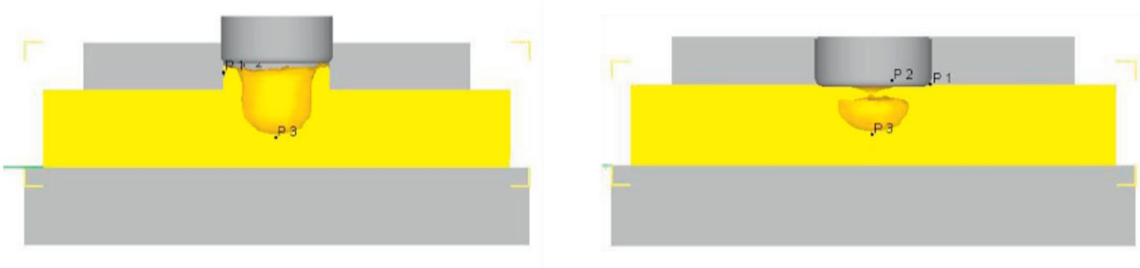


Fig. 8. Incomplete filling case showing unconsolidated flow using points

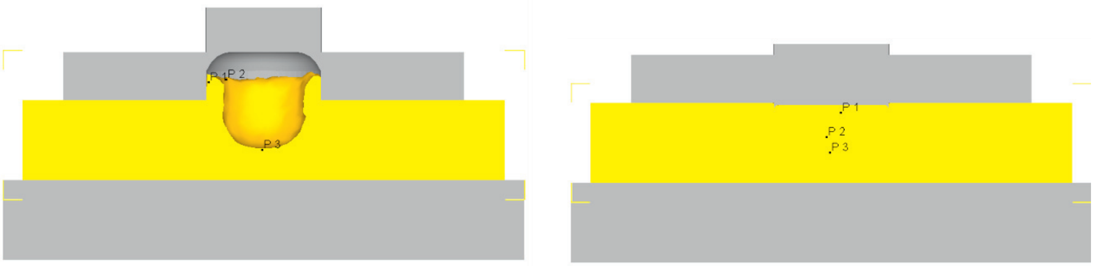


Fig. 9. Successful filling case showing consolidated flow of points

4. Conclusions

Based on the investigations performed through simulations following conclusions are drawn.

(i) Refilling of exit hole using non consumable tool concept was successfully simulated for FSSW. This helps in understanding the requirements like shoulder, pin design and process parameters for successful filling.
(ii) These simulation trials have ample potential to reduce the number of actual experiments required for fine tuning of the process.
(iii) Point tracking in simulations sheds some light on mixing of material between two plates.
(iv) Further studies can be performed to predict process temperature, strain, strain rates etc., occurring during spot filling. This would give some insight on metallurgical aspects.
(v) Spot filling with consumable tools can also be attempted.

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