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ORIGINAL ARTICLE

An investigation to find an appropriate starting position and elimination of pin hole defect in FSW for maximizing the joint length

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Abstract Friction stir welding (FSW) is relatively an advanced solid-state joining process in which no consumable materials are used. It is an energy-efficient and environment-friendly process. However, one of the limitations of the FSW process is that a pin hole remains at the end of the joint and some offset distance needs to be provided at the start of the joint. The present work focuses on different approaches in finding an appropriate starting position and to eliminate the end hole type of defect in FSW process. It is based on several distinct experimental trials. These trial runs consist of numbers of different cases of start and end locations. The main aim of these case studies is to achieve maximum joint length and minimum material wastage while joining two 6-mm-thick aluminum plates by FSW process. All the process parameters like rotational speed, welding speed, plunging depth, tool geometry, and dwell time were kept constant during the trial runs. From the experimental results, it was found that by restricting edge deformation by means of an abutting plate at an appropriate position, full starting length can be utilized as a proper joint. Also by providing a runoff material of an appropriate size, the end hole can be transferred to the runoff plate and joint length will get maximized.

Keywords Friction stir welding · Start and stop points · End hole · Ultimate tensile strength · Joint length

1 Introduction

Friction stir welding (FSW) is a solid-state joining technique in which the materials are joined below the melting point. The motivation behind the invention of FSW process in TWI [1] is to join lightweight materials like aluminum and its alloys which has always been a great challenge for designers. All that is needed is a rotating friction stir tool with a shoulder and pin which is inserted into the joining edges of materials. Then, the traverse movement of the tool along the joint line causes sufficient mixing to produce the joint. The necessary heat for joining the materials is generated by the friction between the tool and the workpiece and plastic deformation of the workpiece. Being a solid-state process, defects like solidification cracking and porosity could be avoided which leads to significant improvement in joint properties.

In the usual practice, the FSW process is being carried out [2–11], as shown in Fig. 1a, b. It can be seen that some offset distance, the distance between the edge of the plates and actual weld, is needed both at the start and end of the joint. As a result of which, some volume of material is needed to be removed both from the start as well as end part of the joint in many cases. This reduces the effective joint length which is approximately equal to the sum of two offset distances and two times the tool shoulder diameter. Therefore, to ensure a certain weld length, longer workpiece dimension has to be considered and post-welding operation also increases, and both of these increase production cost.

The abovementioned offsets are required to avoid outward material flow at both the positions. It occurs when the welding starts and finishes exactly by aligning the tool shoulder with the starting and ending edges of the workpiece material as shown in Fig. 2a. The material deformation occurs due to the movement of some volume of plasticized material from the weld zone. Figure 2b shows the as-welded image of

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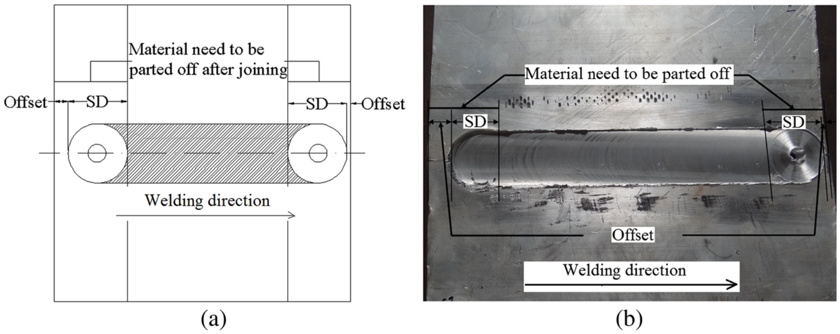


Fig. 1 Schematic diagram. **a** Welding by usual practice. **b** Welded plate

material flow. Another measure limitation of the process is the keyhole or pin hole which remains at the end of the joint. The keyhole at the end of the weld is due to the removal of the FSW tool from the workpiece as the final step of welding, leaving a hole of diameter equal to the tool pin. The load-carrying capacity of the welded joint is decreased if the start and end hole defects are left in the welded assembly. Moreover, these defects often provide points of initiation of fatigue cracks, and are therefore generally undesirable. Altogether, the above-discussed issues reduce the joint length leading to wastage of material.

There are very few published literatures about refilling or repairing the keyhole in FSW welds. Huang et al. [12] developed filling friction stir welding (FFSW) to repair the keyhole. The keyhole was repaired by the combined use of plastic deformation and flow of the consumable joining tool. But in the process, three different subprocesses need to be carried out, namely FSW, FFSW, and friction stir processing (FSP). And also, each time, the tool and shoulder geometry and tool material need to be different which makes the technique time taking and complex. FFSW uses a consumable joining bit same as the workpiece material and non-consumable shoulder. The steps involved in the process are localized heating (friction between the joining bit and the wall of the exit hole), flow of material (softening and stirring of the plunged bit material and exit hole), and material filling (joining) [12]. Zhou et al. [13] also used FFSW technique to repair the keyhole in friction stir welding of austenitic stainless steel (316L). FSP is an emerging surface modifying technique based on the principle of FSW. It uses a tool having a pin and shoulder or only a shoulder which is inserted into the workpiece material and traversed on the required direction of interest. The localized heating by the friction of the tool and workpiece material results in intense and controlled material deformation and grain refinement. It enhances the tensile strength, fatigue strength, hardness, and formability of the material.

However, the double-acting, retractable, or auto-adjusting FSW tools [14–17] consisting of an outer shoulder and inner pin were developed in order to eliminate or refill the end hole. Uematsu et al. [16] used a double-acting tool which consists of an outer flat shoulder and inner retractable probe. It was used in friction stir spot welding process in which initially, the tool was plunged into workpieces in a conventional way. After joining, the inner pin was retracted into the outer shoulder and then the flat face of the tool is again plunged in order to refill the pin hole. Ding and Oelgoetz [17] patented a hydraulically actuated auto-adjusting pin tool. In this process, the pin can be incrementally withdrawn from the workpieces which eliminates the end hole in the weld. The system consists of a welding head housing with a motor connected to the controller instrument. The arbor forms an interior cylinder and supported by bearings. As the welding head progresses, the controller senses any pressure variation on the lower face of the shoulder housing. It adjusts the arbor to keep the vertical pressure constant in order to keep the pin at a proper depth in the workpieces. The piston moves towards the workpieces thus

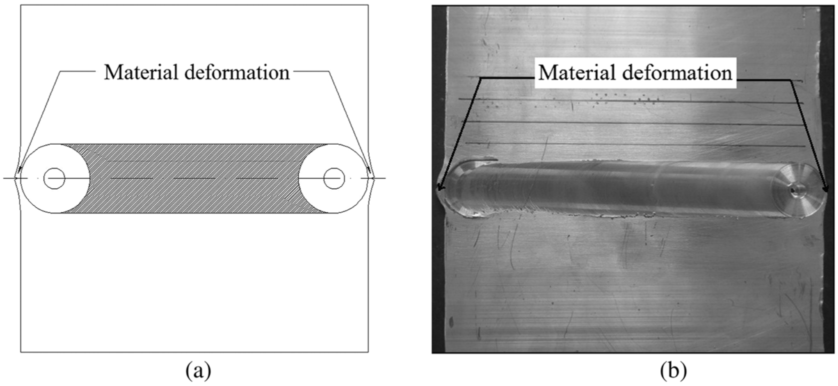


Fig. 2 **a** Schematic diagram of material deformation at start and end. **b** Image of welded specimen with edge deformations

Table 1 Chemical composition and mechanical properties of workpiece material

Chemical composition (wt. %)	Cu	Si	Fe	Al
	0.05	0.2	0.1	Balance
Mechanical properties	Ultimate tensile strength (MPa)	Yield strength (MPa)	% Elongation	Vickers Micro-hardness (*HV*)
	153.05	84.93	33.04	44

extending the pin further from the shoulder. This operation was used to incrementally withdraw the pin during the final stage of the process to eliminate the keyhole.

The objective of the proposed research work is to investigate the possibilities for obtaining an appropriate starting point and elimination of the exit hole defect in FSW which will maximize joint length and reduce material wastage as well as some post-weld machining operations. Though some scarce efforts are reported to eliminate exit hole defect by refilling or repairing the keyhole, these are very complex and uneconomical. Moreover, no work is reported to address the starting issue. Therefore, in the present work, an attempt has been made to provide a better solution to resolve these limitations, i.e., starting issue and end hole defect. In this regard, various ideas have been formulated and evaluated experimentally by measuring weld qualities. The detailed experimental methodologies followed in this work are given in the following section.

2 Experimental details

Commercial grade aluminum alloy (1100 AA) plates 100 mm long, 100 mm wide, and 6 mm thick were used in the present work as the workpiece material. The rolled plates, without heat treatment, were cut and machined into rectangular pieces then surfaces were prepared using coarser and finer grade emery papers for joining purpose. Welding was carried out in butt joint configuration using FSW process. The chemical composition and mechanical properties of the aluminum plates are given in Table 1. Stainless steel (SS-310) is used as tool material. The tool material should be such that it can withstand the vertical pressure and applied torque. The tool should not wear out easily. The considered tool material has excellent high temperature properties with good ductility. A vertical milling machine was used to carry out the FSW experiment with the following specifications: spindle speed 12 steps (50–1500 rpm), table feed 8 steps (22–555 mm/min), main spindle motor power 5.5 kW, and table motor power 0.75 kW. The process parameters considered for studying all the cases are presented in Table 2.

Table 2 Parameters settings used in the experiments

Parameters	Value
Plunging depth (mm)	0.09
Tool rotational speed (rev./min)	1100
Welding speed (mm/min)	98
Tool geometry	Threaded straight cylindrical pin with flat shoulder as shown in Fig. 3
Shoulder diameter (mm)	25
Pin diameter (mm)	7
Dwell time (s)	15
Tilt angle (°)	0
Backing plate	Mild steel

Figure 1 shows the usual practice to carry out FSW in butt joint configuration. Several possible ideas or experimental cases are prepared methodically to find out an appropriate starting location and eliminate the end hole, which are described below in details. The proposed ideas are assessed experimentally in a vertical milling machine, but the results of this research should be applicable to other commercial FSW machine also. Although, the vertical machine has a few drawbacks such as, process forces cannot be controlled during the welding and the machine is less rigid.

Case 1 This is regular practice of carrying out FSW at the usual start and stop positions as shown in Fig. 1 in the "Introduction" section. In this case, some offset distance was provided both at the starting and ending of the joint. It avoids material deformation from both the ends or edges. This case is considered as reference to compare all other considered cases.

Fig. 3 FSW tool

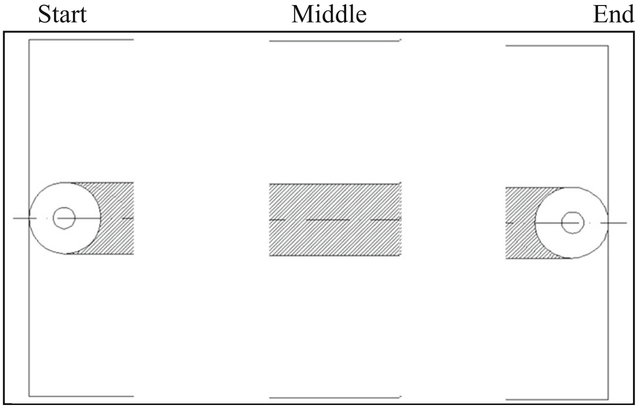


Fig. 4 Case 2

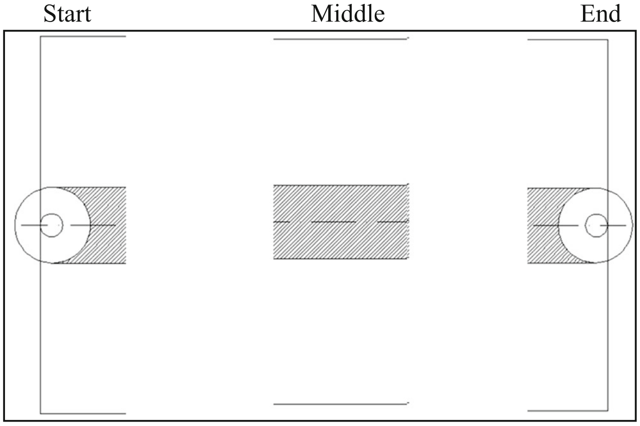


Fig. 5 Case 3

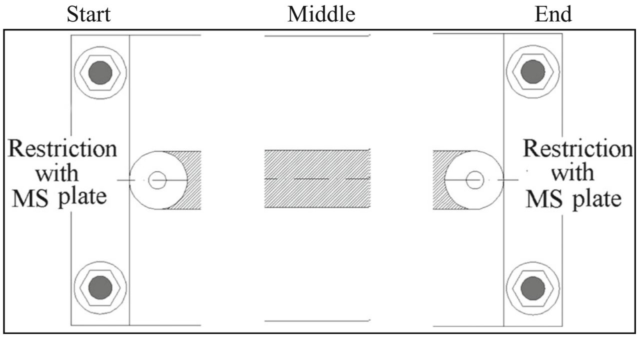


Fig. 6 Case 4

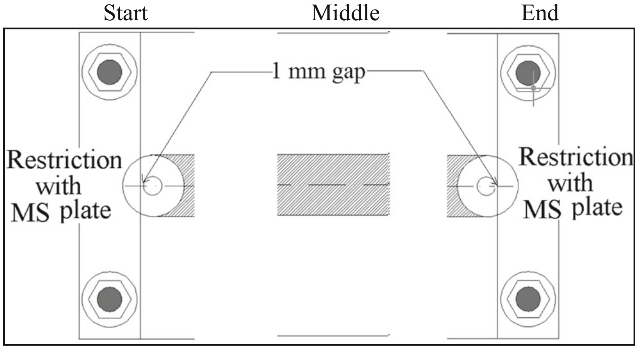


Fig. 7 Case 5

Case 2 In this case, the welding was started and stopped exactly by aligning the tool shoulder with the starting and ending edges of the workpiece material. It is shown in Fig. 4. This case was carried out without any restriction at the start and end faces of the workpiece.

Case 3 The welding was started and stopped exactly by aligning the periphery of the tool pin with the starting and ending edges of the workpiece material. No restriction was provided either at the start or at the end of the weld as shown in Fig. 5.

Case 4 This includes implementation of restriction both at the start and end of the weld. The plates used for restriction are made of mild steel having slightly lesser thickness than the workpiece material. The restricting plates were fixed with the backing plates by means of nut and bolt at two points to ensure the rigidity. Again, the tool shoulder was aligned with the starting and ending edges of the workpiece material as shown in Fig. 6. The restrictions are maintained in such a way that there should be no visible

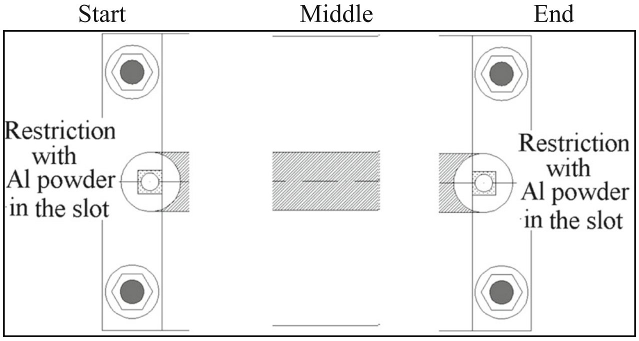


Fig. 8 Case 6

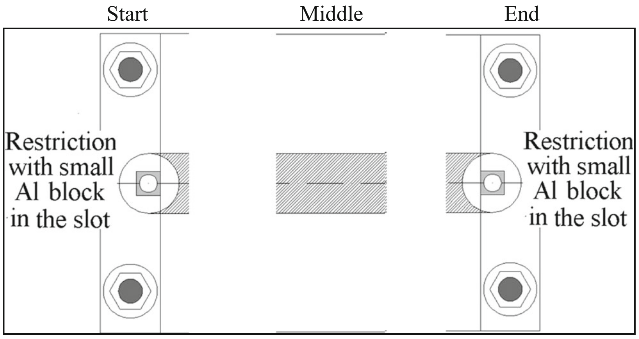


Fig. 9 Case 7

air gap between the mild steel and aluminum plates both at the start and end.

Case 5 Same restriction was provided as of case 4. The tool pin can neither be started nor ended by exactly aligning the periphery of the tool pin with the edges of the workpiece material. This may lead to tool wear by rubbing with the restriction plate. So the welding was started and stopped at a distance of 1 mm away both from the starting and ending edges of the workpiece material as shown in Fig. 7.

Case 6 In this case, two slots were provided, one at the start and another at the end of the plates. The slots were made in the restriction plates. The size of the slots is slightly higher than the tool pin diameter and packed with aluminum powder. The welding was carried out from the starting slot to the end slot. The detail arrangement is shown in Fig. 8.

Case 7 In this case, all the arrangements are similar to case 6 except the aluminum powder in the slots was replaced by solid rectangular aluminum blocks as shown in Fig. 9. The blocks are fitted in the slots in such a manner that there was no visible air gap between the side walls of the slot and aluminum blocks.

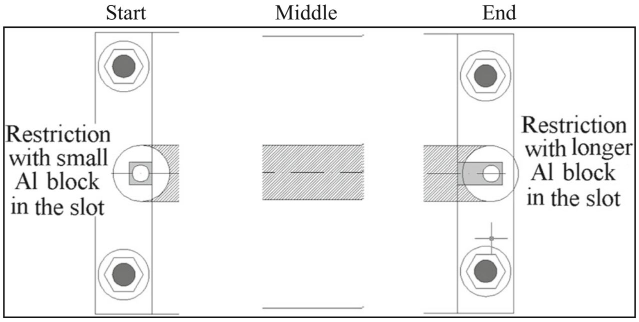


Fig. 10 Case 8

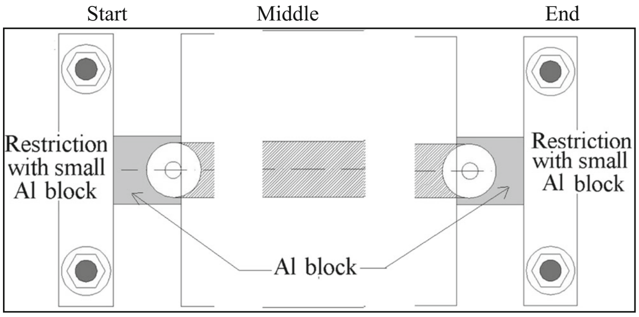


Fig. 11 Case 9

Case 8 In this case, the starting condition was kept the same as in case 7. But the lengths of the end slot as well as the aluminum block were increased as shown in Fig. 10. This is in view to move the tool completely outside the workpiece.

Case 9 In this case, solid aluminum pieces were provided at the start and end of the plates. These pieces act as the restricting plate and the size of the pieces are higher than the size of the tool shoulder with thickness same as the workpiece thickness. Also, the tool pin was aligned with the start and end edges of the workpiece in such a way that the pin will be outside the workpieces. The complete arrangement is shown in Fig. 11. Instead of stopping the tool exactly at the interface of the tool pin periphery and outside edge of the workpiece, it has been moved slightly some distance away. This is to avoid the chance of formation of minute defects at the trailing side of the pin hole as shown in Fig. 21b.

Case 10 This case also includes the restriction of workpieces by means of aluminum pieces at both the ends. But the size of the plates is bigger than the previous case. Also the welding operation was started and stopped at some distance away from the edges of

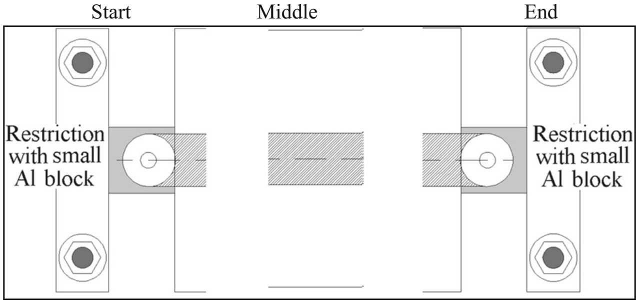


Fig. 12 Case 10

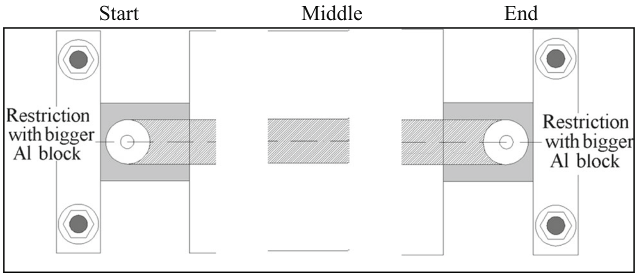


Fig. 13 Case 11

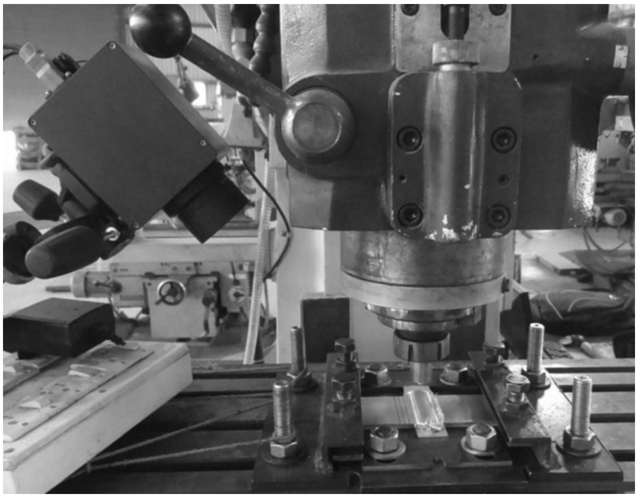


Fig. 14 Experimental set up with IR camera

the workpiece. The complete arrangement is shown in Fig. 12.

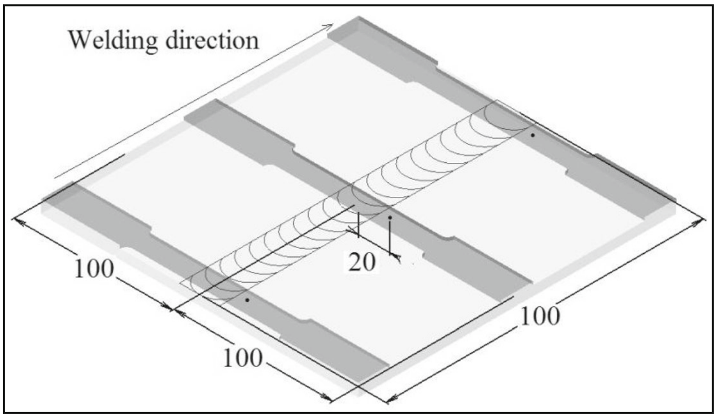
Case 11 All the arrangements are similar to case 9 except the tool shoulder was aligned with the start and end edges of the workpiece in such a way that the complete tool shoulder will be outside the workpieces as shown in Fig. 13.

In addition to the above 11 cases, some more experimental cases were considered. These are the extended cases of case 5 in which the distance of the tool pin periphery from the start edge of the workpiece was varied from 2 to 7 mm (case 12 to case 17). This is to check the optimum distance of the tool pin periphery from the start edge of the workpiece that can be considered for good joining.

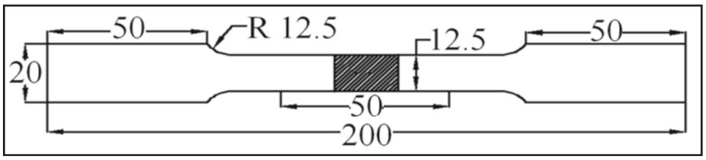
The workpieces to be joined were clamped to completely restrict its movement under both plunging and translational forces of the FSW tool. The tool rotation speed and traverse speeds of the bed were set prior to each experimental run. For temperature measurement, an infrared (IR) camera was used. Before welding, the camera was mounted in an appropriate location to capture thermal images. The complete experimental setup with the IR camera is shown in Fig. 14. At all the three positions, the temperature data were taken at a distance of 20 mm away from the joint line in the advancing side as shown in Fig. 15a.

At each experimental condition, three tensile specimens were prepared one from the start, one at the middle, and one at the end of the weld as shown in Fig. 15a. The welded joints

Fig. 15 Schematic diagrams. **a** Position of specimen extraction for tensile tests. **b** Dimensions of tensile specimens (all the abovementioned dimensions are in mm)



(a)



(b)

were cut by using a saw. Then, the tensile specimens were machined to the required dimensions as per the American Society for Testing of Materials (ASTM E8) guidelines. The dimension of the tensile specimen is shown in Fig. 15b. Each experiment was repeated two times to minimize the experimental error.

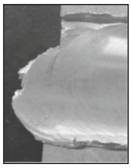
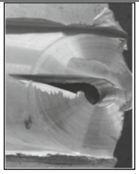
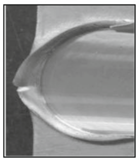
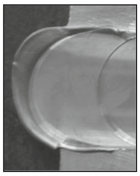
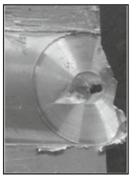
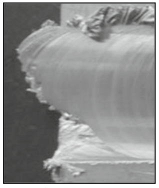
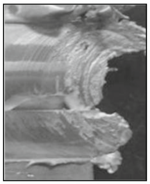
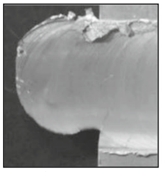
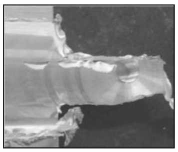
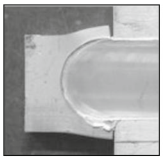
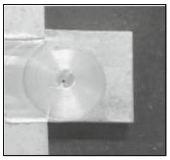
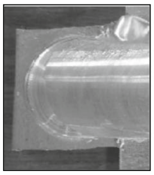
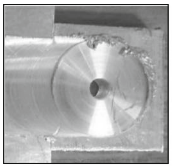
Cases	Weld bead appearance	
	Start portion of the weld	End portion of the weld
Case-3	 **Fig. 16(a)** start	 **Fig. 16(b)** end
Case-4	 **Fig. 17(a)** start	 **Fig. 17(b)** end
Case-5	 **Fig. 18(a)** start	 **Fig. 18(b)** end
Case-6	 **Fig. 19(a)** start	 **Fig. 19(b)** end
Case-7	 **Fig. 20(a)** start	 **Fig. 20(b)** end
Case-8		 **Fig. 21(a)** end
Case-9	 **Fig. 22(a)** start	 **Fig. 22(b)** end
Case-10	 **Fig. 23(a)** start	 **Fig. 23(b)** end

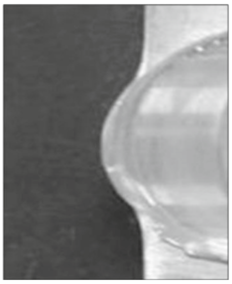
Fig. 16–23 Weld bead appearance for different cases. **a** Start portion of the weld. **b** End portion of the weld. **16** Case 3. **17** Case 4. **18** Case 5. **19** Case 6. **20** Case 7. **21** Case 8. **22** Case 9. **23** Case 10

3 Results and discussions

The appearance of weld bead at the start and end portion of the joint for selective cases are shown in Figs. 16–23. Some of the weld beads of the extended cases for case 5 are shown in Figs. 24–25. Being the usual practice, there was no distortion and outward flow of material for case 1 both at start and end. This can be observed in Fig. 1b. For case 2 and case 3, as no restriction was provided, the plasticized material tends to flow out from the weld zone both at the start and end position. Case 2 is shown in Fig. 2b and case 3 is shown in Fig. 16. Case 4 and case 5 are similar to case 2 except being provided with restrictions both at start and end of the weld. So, the outward material flow at the start and end portion is at surface level only. It is shown in Figs. 17–18. For case 6 to case 8, slots of different sizes are provided in the restriction plate both at the start and end. In all these cases, welding was started and finished outside the workpiece material. It can be seen from Figs. 19–21 that in all the three cases, there was material flashing at the surface level as the rotating tool shoulder tries to push the plasticized material behind the tool. Cases 9, 10, and 11 showed defect-free portions on visual basis both at start and end position which can be seen from Figs. 22–23.

Each experimental case was repeated two times and the average tensile properties (ultimate tensile strength, yield strength, and ductility) at three different positions, namely start, middle, and end of the joint are given in Tables 3, 4, and 5. From the tested joints, it was seen that for usual practice, i.e., case 1, the presence of offset distance at both start and end locations lowers the weld strength at the respective positions. As the workpiece materials within the offset distance are not plasticized by the joining process, the strengths are low in these regions. Due to absences of restrictions for both case 2 and case 3, the plasticized material at the start and end edges escapes from the weld region as shown in Fig. 2b and Fig. 16a, b, respectively. It leads to defect at both the positions with an additional keyhole at the end. Therefore, in these two cases, the strengths at the start and end of the joint were low. From the recorded temperature data as shown in Figs. 26 and 27, it can be seen that the peak temperature at the start position is little lower in case 1 compared to other two cases due to the presence of offset distance, but the thermal histories at the end position are almost similar.

Fig. 24–25 Weld bead appearance (at start) for extended cases of case 5. **24** Case 12. **25** Case 17

Weld Bead Appearance at Start	
Case-12	Case-17
	
Fig. 24 start	**Fig. 25** start

As the restriction was provided both for case 4 and case 5, the plasticized material could not escape from the weld zone, which can be seen in Fig. 17a, b. Due to less material flow out, sufficient heat generation, and proper material mixing, the strength at the starting portion of the joint in case 5 was good. Although, the material flashing was low and heat generation was slightly higher in case 4 as compared to case 5, the strength of the starting portion was low. Because, in this case, the welding was started by aligning the periphery of the tool shoulder with the starting edge of the workpiece which mixes the material in the surface level only. The material mixing in the thickness direction was inadequate. The strength of the end part in both the cases was poor due to improper material mixing and the presence of keyhole. The recorded thermal histories at start and end positions shown similar trends as case 1 to case 3.

The next three cases (cases 6, 7, and 8) are based on starting and stopping of the process outside the workpiece material. The welding was started in a slot provided in the restriction plate and filled with aluminum (Al powder for case 6 and Al blocks for cases 7 and 8). Similar provisions were provided at the end position except for case 8 in which the length of the block was more. In case 6, it was seen that the Al powder in the slot tried to come out both at the start and end of the joint.

Table 3 Measured ultimate tensile strength at different positions of a joint for different cases

Cases	Ultimate tensile strength of welds at different positions in MPa								
	Start			Middle			End		
	Trial 1	Trial 2	Avg.	Trial 1	Trial 2	Avg.	Trial 1	Trial 2	Avg.
Case 1	54.21	43.65	48.93	139.15	129.25	134.2	51.09	43.21	47.15
Case 2	25.29	31.37	28.33	135.58	139.26	137.42	29.04	35.74	32.39
Case 3	36.6	30.46	33.53	140.41	137.11	138.76	11.62	6.7	9.16
Case 4	97.38	84.88	91.13	134.73	144.67	139.7	77.8	89.92	83.86
Case 5	136.42	145.28	140.85	138.9	144.62	141.76	59.19	48.95	54.07
Case 6	55.18	63.8	59.49	81.6	97.66	89.63	25.1	17.44	21.27
Case 7	92.48	110.6	101.54	131.81	133.09	132.45	103.88	109.48	106.68
Case 8	101.86	106.56	104.21	139.59	129.85	134.72	100.03	94.31	97.17
Case 9	132.7	129.84	131.27	130.25	134.39	132.32	127.4	137.5	132.45
Case 10	138.19	133.52	135.85	137.80	134.01	135.09	142.74	129.98	136.36
Case 11	123.09	140.37	131.73	135.20	129.23	132.26	137.62	138.10	137.86
Extended cases of case 5									
Case 12	144.19	138.45	141.32						
Case 13	135.95	141.23	138.59						
Case 14	138.27	142.53	140.4						
Case 15	140.97	131.61	136.29						
Case 16	100.5	105.7	103.1						
Case 17	94.22	107.58	100.9						

Table 4 Measured yield strength at different positions of a joint for different cases

Cases	Yield strength of welds at different positions in MPa (gage length 50 mm)								
	Start			Middle			End		
	Trial 1	Trial 2	Avg.	Trial 1	Trial 2	Avg.	Trial 1	Trial 2	Avg.
Case 1	45.12	37.05	41.08	69.73	74.00	71.87	41.02	39.87	40.44
Case 2	22.35	24.95	23.65	78.14	67.92	73.03	22.88	27.34	25.11
Case 3	24.01	27.04	25.52	70.01	77.01	73.51	5.26	8.19	6.73
Case 4	59.84	52.80	56.32	68.95	78.76	73.85	47.95	59.44	53.69
Case 5	71.42	77.11	74.27	66.91	82.28	74.60	39.34	46.54	42.94
Case 6	41.19	48.61	44.90	58.60	52.96	55.78	20.01	16.19	18.10
Case 7	62.95	57.20	60.08	71.08	71.39	71.23	61.80	62.06	61.93
Case 8	66.81	55.27	61.04	68.51	75.59	72.05	60.94	56.06	58.50
Case 9	72.14	69.48	70.81	70.13	72.25	71.19	72.55	69.91	71.23
Case 10	69.58	73.27	71.42	74.30	70.51	72.40	63.91	74.45	69.20
Case 11	66.20	70.01	68.12	72.87	77.05	74.96	75.50	70.10	72.80
Extended cases of case 5									
Case 12	74.99	73.88	74.44						
Case 13	70.91	75.99	73.45						
Case 14	68.43	79.78	74.10						
Case 15	78.79	66.45	72.62						
Case 16	60.01	61.27	60.64						
Case 17	54.64	65.05	59.84						

Specifically, it was more prevalent at the starting point due to the plunging of the rotating tool. This leads to lesser heat generation and inadequate material availability at the start as well as at the end of the joint which leads to poor weld strength

Table 5 Measured ductility at different positions of a joint for different cases

Cases	% elongation of welds at different positions (gage length 50 mm)								
	Start			Middle			End		
	Trial 1	Trial 2	Avg.	Trial 1	Trial 2	Avg.	Trial 1	Trial 2	Avg.
Case 1	4.65	6.27	5.46	12.89	13.77	13.33	3.98	5.01	4.50
Case 2	2.95	3.66	3.30	11.99	11.42	11.71	5.28	7.25	6.27
Case 3	5.17	5.56	5.37	10.87	14.14	12.51	6.21	8.3	7.25
Case 4	8.00	7.70	7.85	14.68	14.00	14.34	5.99	7.79	6.89
Case 5	15.24	14.80	15.00	12.90	16.04	14.47	4.90	7.70	6.30
Case 6	3.02	4.92	3.97	8.219	7.602	7.911	1.99	2.52	2.25
Case 7	7.68	9.12	8.40	12.05	10.39	11.22	5.88	7.20	6.54
Case 8	7.01	8.22	7.62	14.29	16.5	15.40	8.89	9.00	8.94
Case 9	12.59	12.3	12.5	13.03	10.98	12.00	12.00	10.4	11.2
Case 10	14.18	11.59	12.89	10.69	13.52	12.10	9.76	12.23	10.99
Case 11	13.03	11.31	12.17	11.78	15.61	13.70	11.42	14.10	12.76
Extended cases of case 5									
Case 12	14.19	16.50	15.30						
Case 13	14.86	13.30	14.10						
Case 14	15.99	16.70	16.40						
Case 15	15.01	20.1	17.6						
Case 16	14	15.4	14.7						
Case 17	7.01	5.72	6.36						

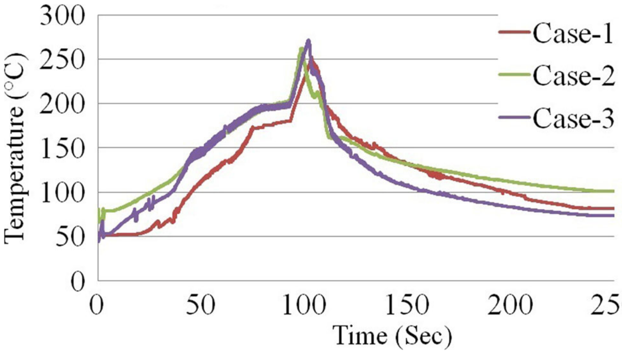


Fig. 26 Thermal histories at start position of the joints from cases 1 to 3

at both the ends. Also, inappropriate material mixing due to inadequate heat generation leads to defect formation lowering the strength at the middle portion of the joint. In case 7 and case 8, the Al powder was replaced by small rectangular Al blocks to improve the heat generation and material availability. The sizes of the blocks were slightly bigger than the size of the tool pin. These rectangular blocks were of same size at the start for both the cases but smaller and longer at the end for case 7 and case 8, respectively. The thermal histories recorded at start and end positions of case 6 to case 8 are shown in Figs. 28 and 29. Though in both the cases, the weld strength was improved but due to the outward material flow at the surface levels both at the start and end, weld strength was lower than the middle portion. This is due to the deformation of material around the open spaces available at the start and end. These open spaces are available at start and end because the tool was plunged into a material which size is just larger than the tool pin diameter. Due to the lack of material availability both at the start and end, the heat generation was less for case 6.

For case 9 and case 10, the size of the rectangular Al blocks were increased from tool pin size to slightly bigger than the size of the shoulder. Case 9 was found to be another appropriate condition to start the process. In this case, the end part of the joint is also having good weld strength. The process was started by aligning the periphery of the tool pin with the starting edge of the workpiece in such a way that the tool pin will be outside the workpiece. Only the tool pin was moved by a little distance from the end edge keeping the shoulder above the transition zone (from base plate to runoff plate). This results in adequate amount of heat generation and the material at the end of the joint gets sufficient time to mix. Also for both case 10 and case 11, the joint strength was found to be adequate at start as well as at the end of the welding. But particularly for these two cases, the matching surface preparation both for the workpiece and the tab material is an important issue. All the matching surfaces should be machined and polished by emery paper thoroughly. Also, there must not be any visible air gap present between the matching surfaces of the workpiece and tab material at start and end positions. The presence of a gap may lead to the formation of defects particularly at the transition positions at the start and end because the tool enters and exits the workpiece in the rotation condition for both the above cases. The recorded thermal histories at the start position for all these cases have shown similar trends as in cases 1 to 3. But at end, the temperature in case 9 is slightly higher than the two other cases as shown in Fig. 30. This is due to stopping the joining process when the tool was at the transition zone itself.

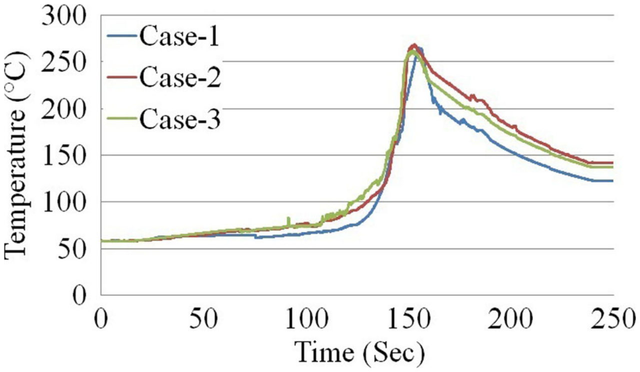


Fig. 27 Thermal histories at end position of the joints from cases 1 to 3

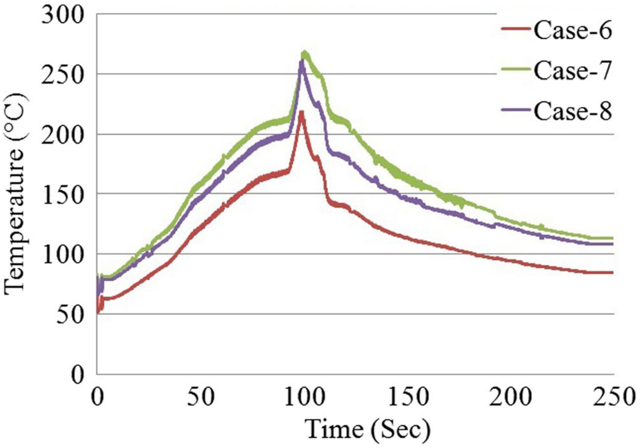


Fig. 28 Thermal histories at start position of the joints from case 6 to case 8

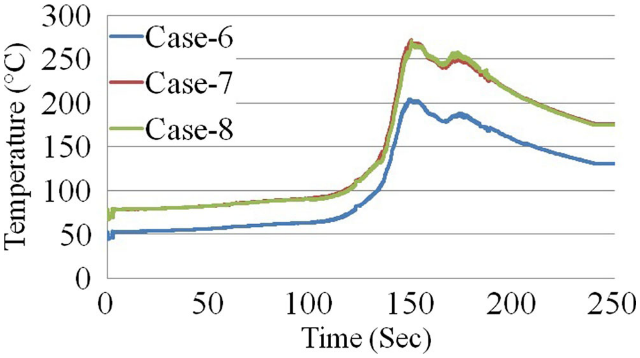


Fig. 29 Thermal histories at end position of the joints from case 6 to case 8

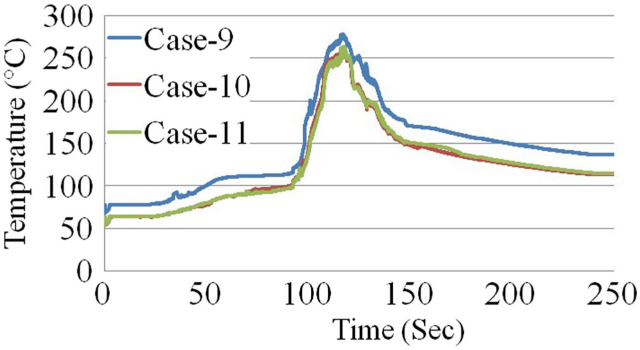


Fig. 30 Thermal histories at end position of the joints from case 9 to case 11

From the aforementioned case studies (case 2 to case 11), it is found that only case 5 and case 9 result in weld strength nearly equivalent to that of middle part of the joint except that the strength at the end of case 5 was reduced due to the presence of the pin hole. Therefore, any of these two cases can be considered as an appropriate starting condition. In case 9, a solid aluminum block is used as a restricting plate which became integral part of the workpiece. After welding, the block has to be separated from the workpiece using some machining operation. Both the use of aluminum block and separation from the workpiece will increase production time and cost. Therefore, case 5 is relatively better as a starting condition. In case 5, the periphery of the tool pin was aligned with the edge of the workpiece material. In order to find out the range of exact starting location that can be considered for case 5, six more cases (case 12 to case 17) were investigated. These cases are considered to check whether there is any flexibility to choose a starting location. In case 12 to case 17, the welding was started at a distance varying from 2 to 7 mm from the starting edge in an increment of 1 mm, respectively. The thermal plots at start position for all these cases have shown similar trend as in cases 1 to 3. From the tensile test data, given in Table 3, it can be seen that up to a distance of 5 mm from the starting edge of the workpiece to the tool pin periphery, the joint strength is adequate. Then, the strength decreases as shown in Fig. 31. This is due to inadequate material plasticization at the starting edge. The results of this research apply quantitatively only to the welding parameters and plate thickness used in the investigation, but the concepts should be applicable to other FSW joints.

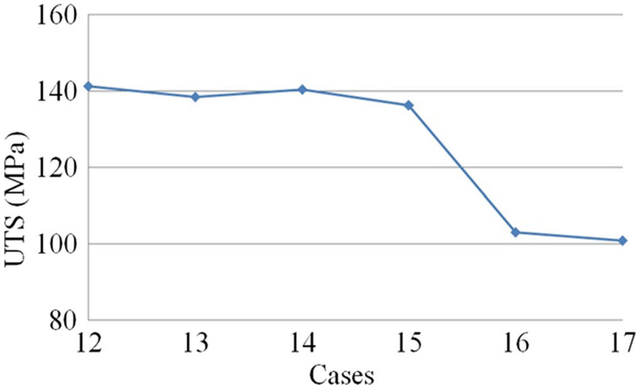


Fig. 31 Strengths at the start from case 12 to case 17

4 Conclusions

The present investigation aimed to obtain an appropriate starting position and elimination of end hole defect for maximizing the effective joint length in FSW process. Seventeen different experimental cases were investigated for that. From the experimental results, it was seen that the weld quality at the starting portion of the joint for cases 5, 9, 10, and 11 are same as that of the middle portion of the joint. So these cases can be implemented to resolve the starting issue. Among these cases, case 5 is relatively a better approach to resolve the starting issue as in this case extra material or tab material is not required which eliminates post welding machining work. Cases 9 to 11 can be used for elimination of the end hole defect. The tab material for cases 10 and 11 has to be prepared carefully and there must not be any visible air gap between them and the workpiece to obtain good weld quality. Out of all the considered cases, case 9 was found to be the best approach to eliminate the exit hole defect. The appropriate distance from which the welding can be started was found to be from 1 to 5 mm for the 6-mm-thick plates, beyond which the joint strength diminishes. So from this investigation, the following rules of thumb can be followed during FSW for maximizing the joint length by minimizing the material wastage and post-weld machining work.

- In linear FSW, the starting issue can be eliminated by using an appropriate non-consumable restriction plate and commencing the welding up to 5 mm away from the starting edge of the workpiece.
- The end hole defect can be resolved by providing a small rectangular piece with a size of little bigger than the shoulder diameter and by moving the tool pin to some distance away from the end edge of the workpiece.

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