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Weld Formation Investigations of FSW of Al 6061-T6 Lapped Workpieces Using Dual Shoulders Tool

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ABSTRACT

In present paper, dual shoulders friction stir welding (DSFSW) tools were used for friction stir welding of lapped Al 6061-T6 workpieces (152 mm X 102 mm X 3 mm) in open air-cooling conditions using different tool rotational speeds and tool feeds. A total of 17 experiments were performed using seven differently designed DSFSW tools, two different fixtures, and two different vertical milling machines to investigate the effect of tool parameters on weld formations with different processing parameters window. Some of the initial tools produced ineffective material flow due to insufficient amount of frictional heat generation and inadequate stirring action, which hindered the material movement towards the horizontal interface of lapped workpieces and reduced intermixing of workpieces material at there. Based on investigations of weld formations, a series of experiments was subsequently performed using the redesigned and modified DSFSW tools with optimized combinations of tool rotational speed and feed rate which was finally resulted in improved frictional heat generation, enhanced plasticized material flow, and sufficient material intermixing at weld interface, thereby producing improved weldments. These experiments demonstrated a progressive improvement in weld quality, ranging from unwelded joints to sound weldments, although a few hole/porosity defects were observed on the advancing side of the weld nugget zone. The investigation led to the successful development of practical DSFSW tool designs capable of producing sound friction stir welds in lapped Al 6061-T6 workpieces.

Keywords: lap welding; bobbin tool; frictional heat generation; advancing side; retreating side

INTRODUCTION

Al 6061 alloys known for their high strength-to-weight ratio are extensively used in various engineering applications. There is growing demand for "green welding" techniques in different joining situations and friction stir welding (FSW) is at the forefront. Modern applications such as military/defense industries, high-speed ground and aviation mobility [1] require such materials to be welded precisely and efficiently in different joint configurations such as butt, lap, fillet, or corner edge joints, depending on the structure, assembly, or component needs. The innovation of FSW lies in its ability to join a wide range of materials, whether similar [2], [3], [4] or dissimilar [5], [6], [7], [8] with the same or different thicknesses [9]. These materials include aluminum and its alloys, copper and its alloys [10], magnesium alloys [7], [11], [12], [13], titanium [5], [14], [15], [16], [17] steel [6], [17], [18], metal composites [19], [20], [21], [22], polymers [8], [23], [24], [25], [26] and even wood-plastics [27]. Since its invention by TWI [28], FSW has evolved from conventional tool friction stir welding (CTFSW) to more advanced techniques such as floating bobbin tool friction stir welding (FBTFSW) and differential rotation bobbin tool friction stir welding (DRBTFSW), among others.

Conventional tool FSW (CTFSW)

In FSW, the workpiece materials are mixed by the rotation and string action of the shoulder and pin. The areas where the material is stirred include the shoulder, the interface between the materials, and the pin interface, as shown in Figure 1. The movement of the tool causes a horizontal flow of material. There is very little vertical movement of the material because of the pressure applied by the shoulder and the design of the tool. Compared to the lap configuration, which has a horizontal interface between the base materials, the limited material flow in the butt configuration is less of a problem due to the presence of a vertical interface between the base materials. This is because the lap configuration requires both vertical and horizontal material flow, whereas the butt configuration only requires horizontal material flow as a result of the vertical separation surfaces of the workpieces. Because of this, FSW in the lap configuration is more difficult than in the butt configuration [29], [30], [31]. The horizontal interface in lap welding is associated with the "*hooking*" effect, inevitably results in the formation of crack-like unbonded regions at the mating surface of the workpieces [32]. The hooking effect occurs on both sides of the weld and is referred as *hooking* at the advancing side (AS) and referred as *cold lap* at the retreating side (RS) of the weld. This phenomenon contributes to the thinning or thickening of plates in welded lap joints.

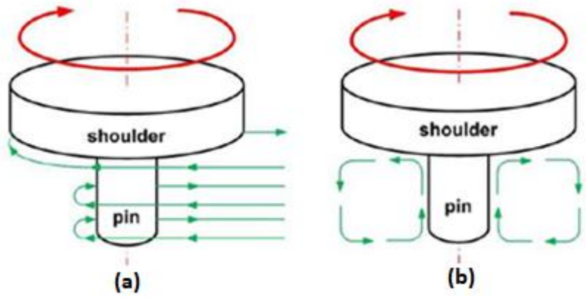

Figure 1: Material flow in FSW (a) horizontal, (b) vertical [20]

Dual shoulders FSW (DSFSW)

To address and reduce the issues caused by CTFSW, TWI had developed a variant of FSW, called dual shoulders friction stir welding (DSFSW) which is also termed as bobbin tool friction stir welding (BTFSW) or self-reaction friction stir welding (SRFSW) [33]. This technique provides multiple advantages, such as eliminating root defects, reducing under welding problems, avoiding weld roots, removing the requirement for a back plate, and lowering Z forces [34], because it uses a double-sided friction stir tool with more interfacing with workpiece material and effective control of frictional heat generation.

Kissing bond, joint line defect, and residual oxide defect (ROD), and cold lap are additional issues associated with the FSLW. In lap welding, residual oxide defects (ROD) occur when oxide layers from the bottom surface of the top plate and the top surface of the bottom plate trapped between the two surfaces that are joined. These defects contribute to increased stress concentration and are primarily responsible for the failure of lap joints [9], [34], [35], [36].

It is very needed to examine the effect on weldments of DSFSLW, by redesigning dual shoulders tool dimensions and features, and synchronizing tool speed and feed with the identical workpiece materials. It is highly valuable to determine the dimensions and features of dual shoulders FSW tool (now onwards it will be termed as tool only) for good quality weldments of lapped workpieces. This paper presents the results of several experiments conducted to achieve these objectives.

MATERIALS AND METHODS

The workpiece materials, 3 mm thick rolled Aluminum alloy 6061-T6 plates of 152 mm X 102 mm, were used for investigation of dual shoulders friction stir lap welding (DSFSLW). Table 1 shows the chemical compositions and mechanical properties of used base metal (BM). Differently designed seven, tools were experimented for DSFSLW as shown in Table 2 and hardened H13 tool steel material was used in all tools.

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Tool design variations includes, (i) change in shoulders diameter, (ii) change in shoulders height, (iii) change in pin diameter, (iv) change in shoulders primary features, (v) change in shoulders secondary features, (vi) change in pin shape (vii) change in primary feature of pin (viii) change in secondary features and profiles of pin which all are shown in subsequent figures in 2D sketch and actual images of tool. In all experiments, DSFSLW was performed along the longitudinal direction of the workpiece plates and perpendicular to rolling direction of workpiece plates. Oxide layers on the top and bottom surfaces of the workpieces were removed with light rubbing and acetone to overcome/reduce ROD defect. Components involved in DSFSLW are jointly responsible for quality of weldments which are shown in Figure 2. Figure 3 shows experiment flow diagram and concepts applied in DSFSLW. Control of generated frictional heat not eligible for further investigation is also important as generation of frictional heat in FSW and here, fixture plays a major role in this direction, considering this fact, specially designed and fabricated two types of fixtures were used for FSW lap joint as shown in Figure 4. An overlap of 72 mm was used in all experiments as shown in Figure 5.

Table 1: Chemical composition and mechanical properties of base metal.

Chemical Composition (wt. %)								**Mechanical Properties**		
Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Al**	**UTS (MPa)**	**Elongation (%)**	**Hardness (HV)**
0.457	0.553	0.173	0.106	0.937	0.266	0.01	Bal	282	21	80-90

Table 2: Process parameters and tool variants used in DSFSLW.

Experiment		**Process parameters**		**Tool Variant**	**Weld quality index (Min-0, Max-5)**	**Remarks**
Sr.	**Code**	**Tool rotation speed (RPM)**	**Tool feed (mm/min)**			
1	TA	-	-	1	Not Started	Tool Failed
2	TB			2		
3	TC			3		
4	T0	445	26	4	1	Not eligible for further investigation
5	T1	445	33		1	
6	T2	445	26		1	Experiment repeated (T0) Not eligible for further investigation
7	T3	640	26		2	
8	T4	515	31		2	
9	T5	445	31	5	0	
10	T6	445	31	6	2	
11	T7	445	16, 65		1	
12	T8	350	16	7	4	Eligible for further

13	T9	445	16		4	investigation
14	T10	280	16		4	
15	T11	350	33		4	
16	T12	350	54		3	
17	T13	350	43		3	

Schematic diagram of workpieces plates overlap is shown in Figure 5. Sheets overlap was kept 72 mm and 30 mm width kept for holding purpose in both the top and bottom workpiece plates. Two types of vertical milling machines were used for DSFSLW. Experiments-1 to 3 were performed on computer controlled VMC and other experiments were performed on heavy duty vertical milling machine – Sigma model, Geeta Machine Tools, Rajkot, Gujarat, India as shown in Figure 15.

Experiment set-up of DSFSLW with SS fixture is shown in Figure 6. Process parameters and tool variants used in experiments are shown in table 2. To compare quality of weldments, weld quality index rubrics (minimum-0 and maximum-5) was considered as follows. 0 indicates no weld formation, 1 indicates high flash formation, course weld surface, surface defect and weld formation can be easily tear by twisting the welded plates, 2 indicates moderate flash formation, smaller weld length, course weld surface, surface defect and little more force needed to break weldments, 3 indicates less flash formation, course tool marks, longer weld length, no visible surface defect and cannot break weldments easily, 4 indicates less flash formation, longer weld length, fine tool marks, no surface defects but defect may be below surface and 5 indicates very few flash formation or no flash formation, fine tool marks, higher weld length and no defect on and below surface.

From the investigated experiments, weldments having weld quality index 4 or higher were cut in transverse direction of the weldments for the metallographic study and mechanical testing using wire EDM. Investing results of Metallographic study and mechanical testing of weldments samples are beyond the scope of paper as the major objective of the present work is to decide appropriate tool dimensions; primary and secondary features, and process parameters (tool speed, tool feed) window by investigation of weld formations in DSFSLW of the Al6061-T6 workpiece material plates.

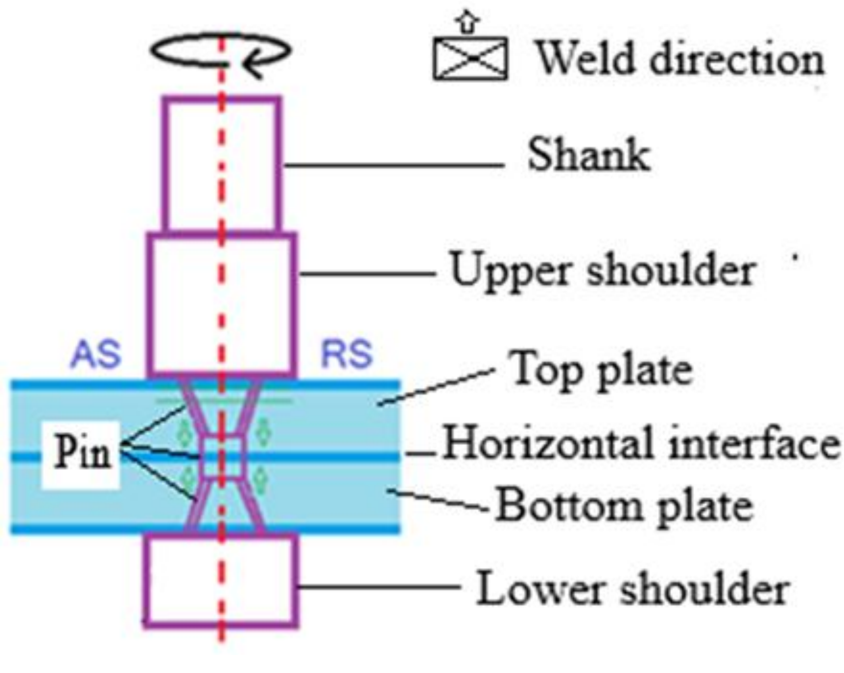

Figure 2: BTFSLW components

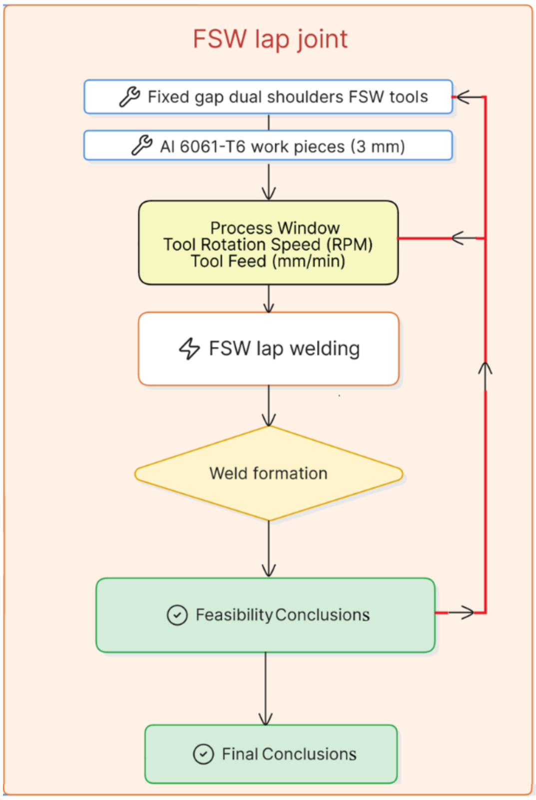

Figure 3: BTFSLW flow diagram

Figure 4: Fixtures, SS fixture (left), MS fixture (right)

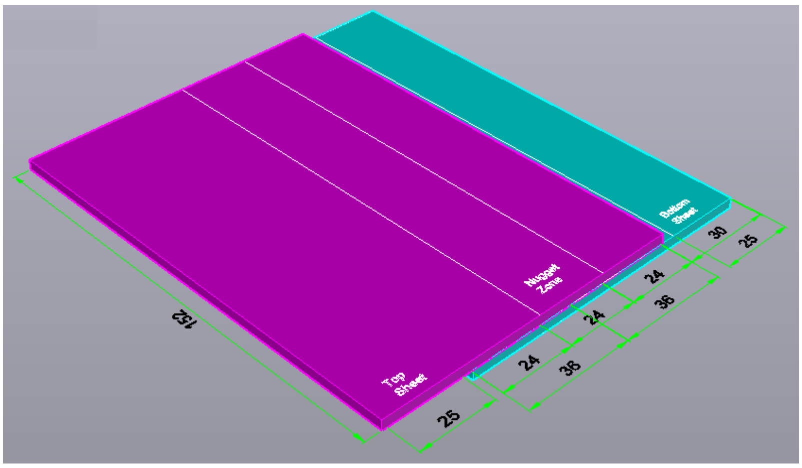

Figure 5: Sketch of workpiece plates overlaps

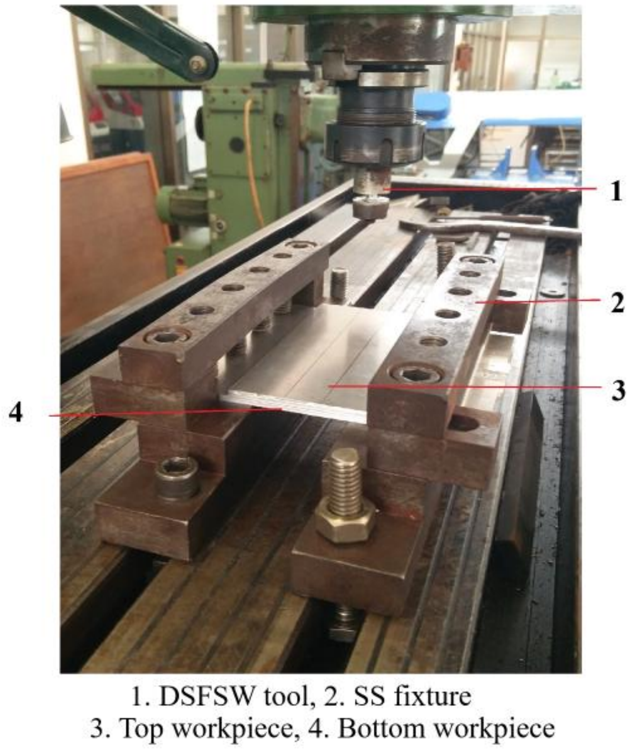

Figure 6: Experiment setup of DSFSLW

Weld formations were visually checked after each experiment and modifications/updating in tool dimensions, features and process parameters (as tool speed and tool feed) value were decided accordingly for successive experiments based on the investigations, observations and conclusions as indicated in Figure 3.

Dual shoulders FSW tools

Initial experiment was performed with the tool-1 as shown in Figure 7. Diameters of both the shoulders were 18 mm and heights 20 mm and 15 mm for upper shoulder and lower shoulder, respectively ass shown in Figure 7 (a). Dumbbell or hour glass shaped pin was used which connects both the shoulders, having maximum diameter of 12 mm towards shoulders and minimum diameter of 9 mm towards the center of pin. As shown in Figure 7, LH threads on conical shape of upper pin part and RH threads on conical shape of bottom pin part were used as secondary features of tool pin to force the material towards common horizontal interface of both the lapped workpieces (as shown in Figure 2).

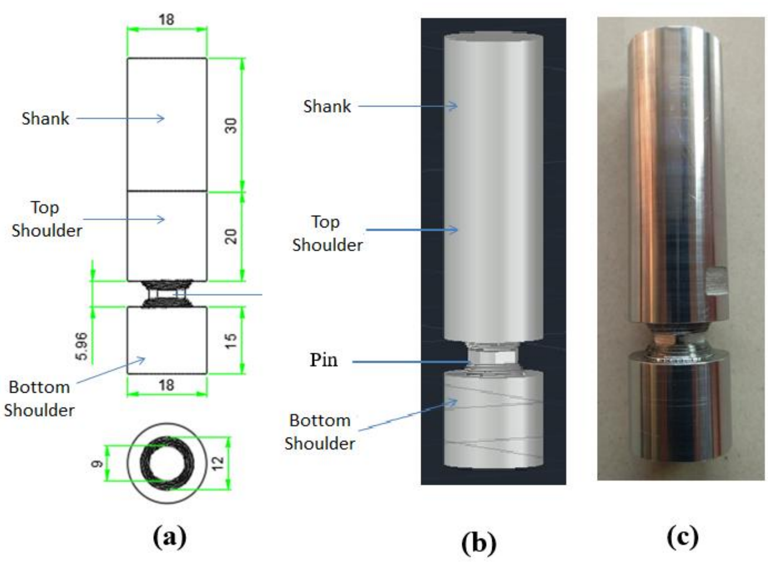

Figure 7: Tool-1, (a) 2D sketch, (b) 3D rendering, (c) actual

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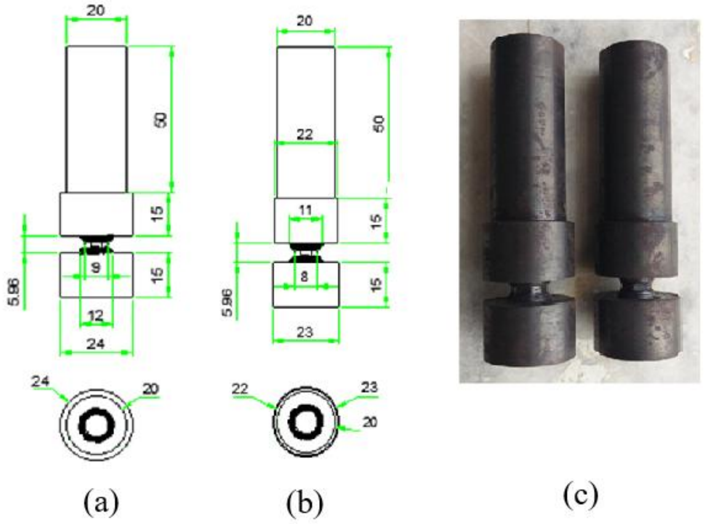

Figure 8: Tool-2 and 3, (a) Tool-2, 2D sketch, (b) Tool-3, 2D sketch, (c) Actual

Figures 8 shows, 2D sketches and actual images of the tool-2 and 3, which were used in second and third experiments. As shown in Figure 8 (a), diameters of both the shoulders were increased from 18 mm to 24 mm with 15 mm shoulders heights. In tool-2, dumbbell or hour glass shaped pin having maximum diameter of 12 mm towards shoulders and minimum diameter of 9 mm towards the center of pin was used and for the tool-3, maximum diameter of 11 mm towards shoulders and minimum diameter of 8 mm towards the center of pin was used. As shown in Figure 8, LH threads and RH threads were used as described before. Due to these modifications, frictional volume of the workpiece material was increased and increased frictional heat generation and embodies stirring action.

Figures 9 shows, tool-4 which was used in experiments-4 to 8. As shown in Figure 9 (a), diameters of both the shoulders were kept 24 mm with heights of 20 mm and 15 mm for upper and lower shoulder respectively. As shown in figure 9, a flat surface towards pin, as a primary feature and three spirals machined on it as secondary feature were used on both the shoulders to enhance plasticized material flow to wards canter of pin that reduces flash formation. Cylindrical pin having 8 mm diameter and two opposite flats/flutes on cylindrical surface as a secondary feature was used. Flats/flutes improves material shearing and mixing of workpiece materials in weldments.

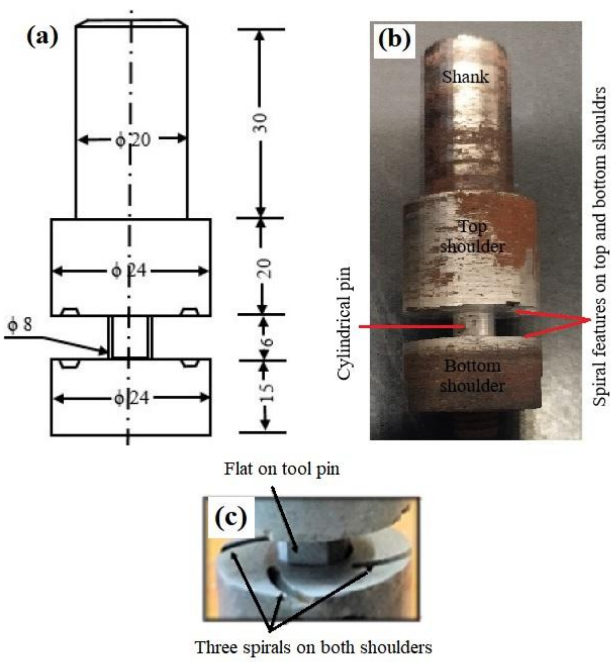

Figure 9: Tool-4, (a) 2D sketch, (b) Actual, (c) Spirals on shoulders [19], [37]

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In the experiment-9, tool-5 was used which is shown in Figure 10 (a) and Figure 11 (a). Hour glass shaped threaded pin was used in tool-5. As shown in Figure 12, flat surface as primary feature and four spirals on it as a secondary feature on both the shoulders surfaces towards pin were used in tool-5. Three flats/flutes as secondary feature on pin were used with maximum diameter of 10 mm and minimum diameter of 8 mm on tapered pin.

As shown in Figure 10 (b) and Figure 11 (b), a tool-6 having 2° concave shoulders and a cylindrical pin with two flats/flutes on pin was used for the experiments-10 to 11. Concave shaped surface of the shoulders works as a reservoir for plasticized material during welding, reduces flash formation and tool marks on weld surface.

Tool-7 having 2° concave shoulders and hour glass shaped pin without threads was used for the experiments-12 to 17, as shown in Figure 10 (c) and 11 (c). Maximum and minimum diameters of the pin were 10 mm and 8 mm respectively as tool-5. As in Figure 13 and Figure 14, experiments-1 to 3 were performed on computer controlled vertical milling machine and other experiments were performed on heavy duty milling machine which is shown in Figure 15.

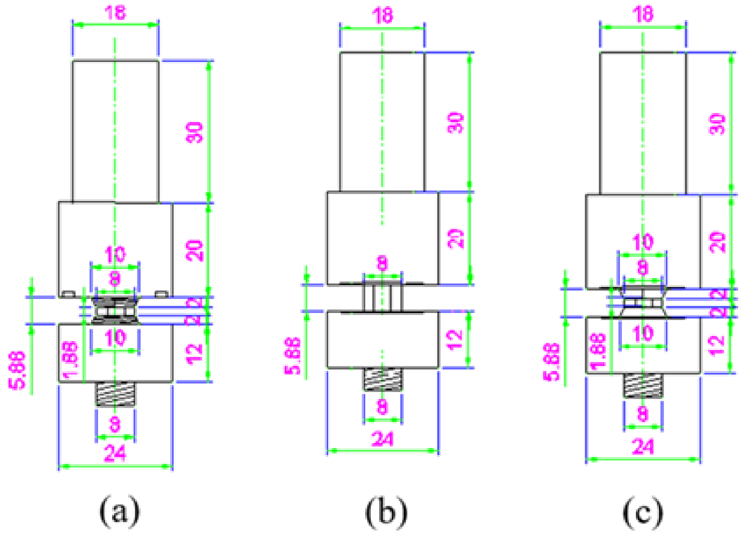

Figure 10: 2D sketches, (a) Tool-5, (b) Tool-6, (c) Tool-7

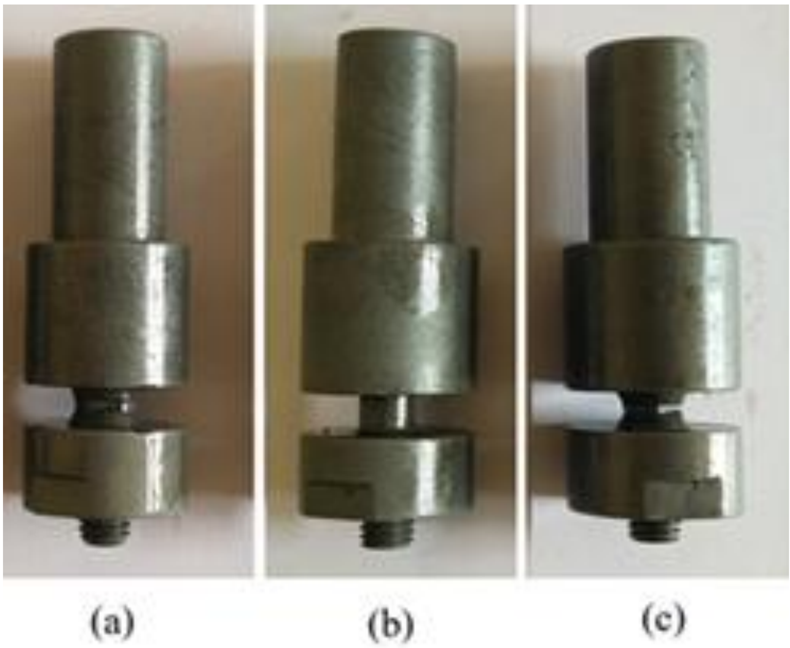

Figure 11: Actual images, (a) Tool-5, (b) Tool-6, (c) Tool-7

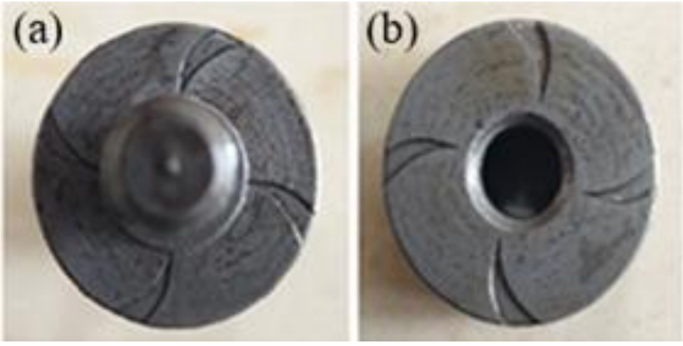

Figure 12: Tool-5, (a) 4 spirals on pin faced surface of top shoulder, (b) 4 spirals on pin faced surface of bottom shoulder

RESULTS AND DISCUSSION

The major objective of the present work was to design and investigate a dual shoulders FSW tools for lapped workpieces of Al6061-T6 material which produce defect free weldments. Comparison of weld formations investigated in experiments may not be feasible as very few literature is available for DSFSLW specifically of Al6061-T6 material plates in research community, so comparison of results with peer reviews is out of scope of the paper.

As shown in Table 2, minimum tool rotational speed was 280 RPM and maximum was 640 RPM. Minimum tool feed was 16 mm/min and maximum was 54 mm/min. Total seven tools were experimented for the weld formation investigation in DSFSLW, mentioned as 1 to 7 in table 2. Due to large variations in these parameters, various kinds of weldments were formed which are discussed as follows.

In experiment-1, tool rotational speed was varied from 350 RPM to 1550 RPM in various steps to soften weld area during dwelling (in several trials) but weld formation could not start and tool was broken as shown in Figure 13. From the experiment-1, below observations were useful in redesigning of tool.

1) Plate material was softened at entry hole and material flow was observed due to frictional heat generation.

2) Material flow in horizontal as well in vertical direction towards common horizontal interface of the plates was observed due to tool pin design.

3) Less amount of frictional heat generated due to insufficient tool shoulder surface area in contact with workpieces. (Although tool is designed based on literature reviews).[33]

4) Due to good thermal conductivity of aluminum alloy, generated heat was rapidly transferred to fixture made of mild steel. (Measured temperature of fixture was higher than the temperature workpieces).

5) Tool vibration observed due to little long shoulder length and lower shank length. (Longer shank length provides more rigid holding).

6) Sufficient piercing of both the shoulders in to workpieces plate surface was observed due to proper pin length.

7) Fixture held the workpieces plates very rigidly. No sliding or any movement of plates was observed during experiment.

8) Tool was broken at pin portion (at minimum diameter) due to high thermal and shear stress at the tool rotational speed of 1550 RPM.

Following modifications were identified based on the observations of experiment-1.

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1) Upper and bottom shoulder diameters should be increased and pin diameter should be decreased to increase frictional surface area. (Decrease in pin diameter reduces tool strength and may break at the stressed area).

2) Sufficient provision or restriction should be made in between Aluminum plates and fixture to prevent large amount of heat dissipation though conduction.

3) Tool shank diameter should be increased to dissipate more amount of heat.

4) Tool shank length should be increased to increase peripheral griping area in collate.

5) Upper shoulder length should be decreased to reduce tool vibrations.

In experiment-2 and 3, redesigned tool-2 and 3 were used as shown in Figure 8. Due to insufficient load bearing capacity of computer controlled vertical mailing machine, machine vibrated and tool was broken during experiment as shown in Figure 14. Following modifications were identified based on the observations of experiment-2 and 3.

1) Total tool length should be decreased to reduce tool vibrations.

2) Tool should be designed in two parts for secondary features on tool shoulders and easy machining.

3) Number of flutes should be optimized to provide pin strength and material stirring action as a greater number of flutes will increase stirring action but reduces tool strength.

4) Heat treated hardened tool should be used to reduce failures.

5) Sufficient provision or restriction should be made in between Aluminum plates and fixture to prevent large amount of heat dissipation.

6) Heavy duty milling machine should be used to eliminate vibrations.

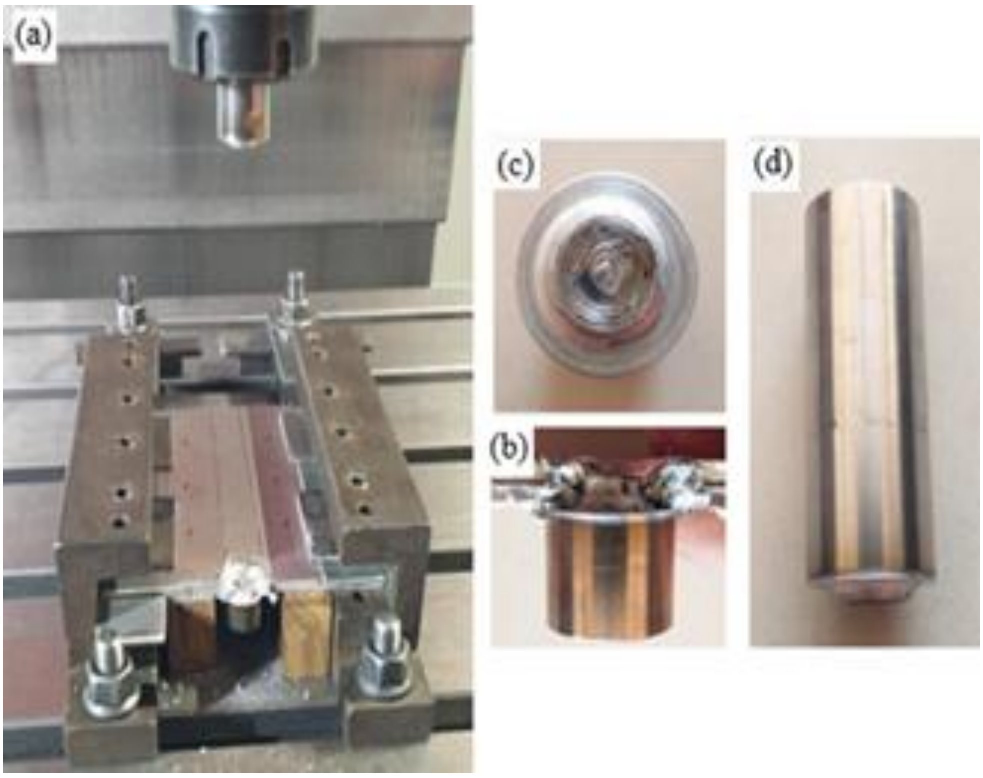

Figure 13: Experiment-1, after tool-1 was broken, (a) experiment setup, (b) view of bottom shoulder, (c) Top view of bottom shoulder, (d) Top shoulder with shank

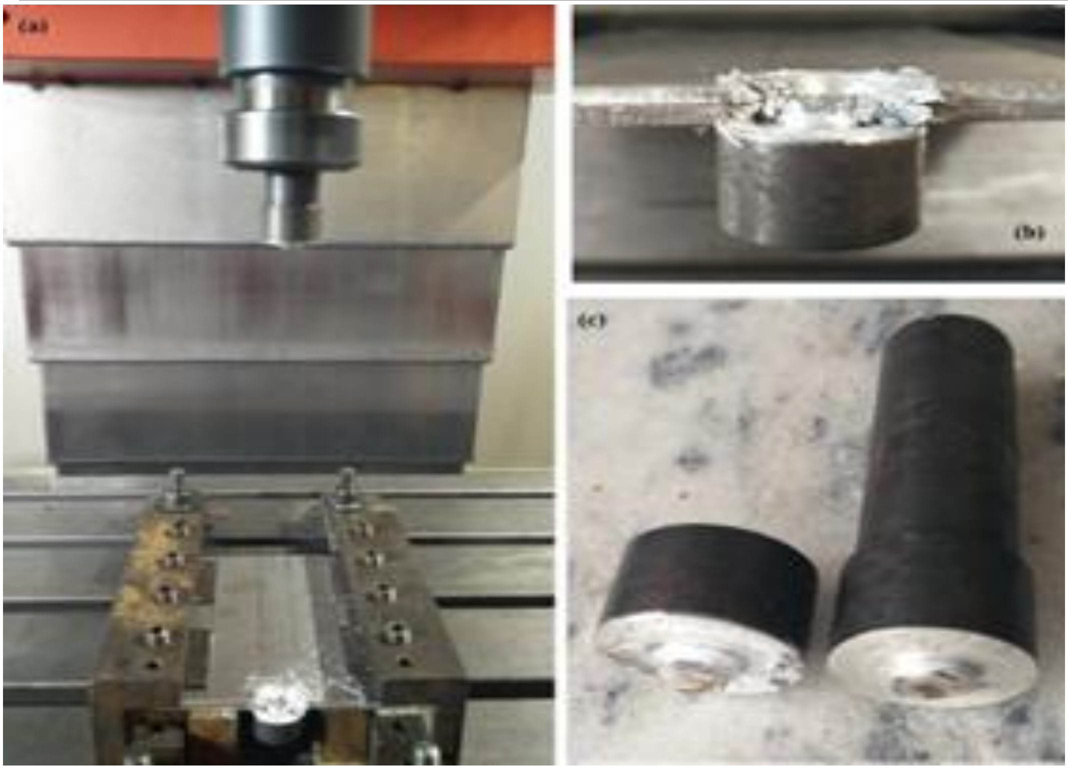

Figure 14: Experiment-2, broken tool-2, (a) experiment setup, (b) view of bottom shoulder, (c) view of broken parts of tool-2.

Figure 15: Heavy duty vertical milling machine used for FSW

The evaluation of weld formation on top and bottom surfaces was conducted through a detailed visual inspection. The assessment included weld surface appearance, flash formation, surface cracking, visible porosity, cold welding/galling defects, and other surface irregularities. In the case of DSFSLW, particular attention was given to the geometry and integrity of the entry hole and exit tail regions, as these features significantly influence weld quality and process stability.

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During the FSW process, the rotating tool initially interacts with the relatively cold material on the advancing side (AS) of the workpiece. The frictional heat generated by the tool shoulders and pin, softens and plasticizes the workpieces material, which is subsequently transported by the rotational motion of the tool from the AS toward the retreating side (RS) [19], [37], [38], [39], [40], [41] The displaced plasticized material is deposited on the RS, responsible for the flash formation in this region. As illustrated in Figure 16 (a) (left), noticeable flash formation is observed on the RS of the top weld surface in *experiment-4* performed with tool-4 (shown in Figure-9). Distinct tool marks were evident on the top surface, indicating effective material flow and tool engagement. Figure 16 (b) (left) presents the bottom surface of the weld, where surface markings resulted from the welding process can be observed. Furthermore, inadequate tool pin height or an inappropriate shoulder gap may contribute to excessive material expulsion, thereby promoting flash formation during DSFSLW.

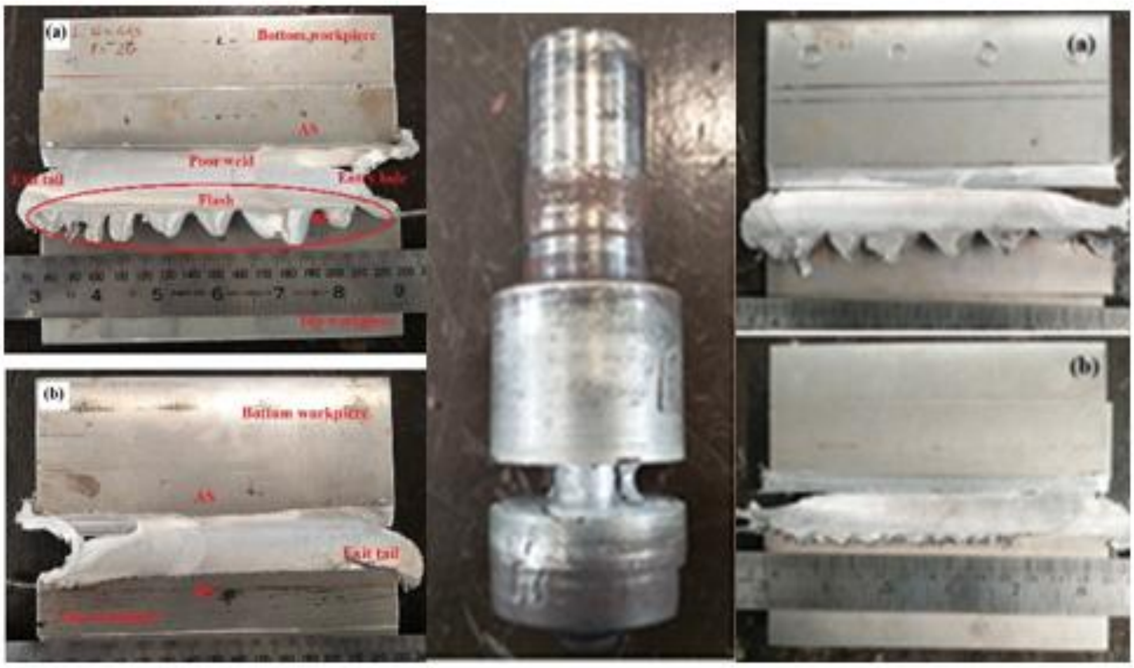

Figure 16: (left) Weld formation in experiment-4, (a) Top surface, (b) Bottom surface; (middle) Tool view after performing experiment-4; (right) Weld formation in experiment-5, (a) Top surface, (b) Bottom surface

Furthermore, the welds displayed a distinct entry hole, an extended unwelded region along the lap interface, and a noticeable exit tail, as illustrated in Figure 16 (left). These defects can be attributed to insufficient frictional heat generation, inadequate material mixing during the welding process and, linear and rotation forces generated by tool. Figure 16 (middle) shows, tool condition after experiment finished, showing adhesion of workpiece material to the tool pin and adjacent shoulders surfaces, indicating poor material flow behavior and increased sticking tendency of substrate. Nearby unbonded weld formation and course tool marks were observed in *experiment-5* as shown in Figure 16 (right). In the experiment, too-4 was used and tool feed was increased to 33 mm/min, resulted in poor intermixing of workpieces materials.

Figures 17 (a) (left) and 17 (b) (left) illustrate the weld morphology observed on the top and bottom surfaces of the weld specimen, respectively in *experiment-6*. The weld was produced at a tool rotational speed of 445 rpm and a welding feed of 26 mm/min (repeated experiment-4 and repeated tool-4). The weld exhibited negligible lap joint formation, with joint quality nearby same that was obtained in the experiment-4. This deterioration in weld integrity can be attributed to the increased tool feed rate, which reduced the interaction time between the tool and workpiece, thereby limiting heat generation and material mixing. As a result, the plasticized material was transported away from the weld zone without adequate intermixing at the faying interface, leading to material tearing and insufficient metallurgical bonding between the overlapping plates.

Figures 17 (a) (middle) and 13(b) (middle) show the weld morphology on the top and bottom surfaces, respectively in *experiment-7*. Tool-4 was used in experiment at rotational speed of 640 rpm and feed of 26 mm/min. Compared with the previous investigation, a slight improvement in joint formation was observed. The increase in tool rotational speed enhanced frictional heat generation, resulting in greater softening of the

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workpieces materials and a reduction in the viscosity of the plasticized zone. Consequently, material flow around the rotating tool was improved, promoting better mixing at the weld interface.

However, the selected feed rate was not adequately balanced with the increased rotational speed. The relatively high traverse rate tended to drag the plasticized material along the welding direction, limiting its effective deposition and consolidation at the lap interface. As a result, the weld quality remained unsatisfactory, and the joint was considered as unacceptable for further investigations due to insufficient bonding and poor lap joint formation.

Figures 17 (a) (right) and 17 (b) (right) depict the weld morphology observed on the top and bottom surfaces respectively in *experiment-8.* Tool-4 was used in the experiment at rotational speed of 515 rpm and a feed of 31 mm/min. Under these processing conditions, no effective lap joint formation was achieved. The absence of bonding can be attributed to inadequate frictional heat generation resulting from the relatively low tool rotational speed, combined with the comparatively high traverse rate. These conditions limited the material softening and plasticization, thereby restricting material flow and intermixing at the faying interface. Consequently, insufficient consolidation occurred between the overlapping sheets, leading to the failure of joint formation.

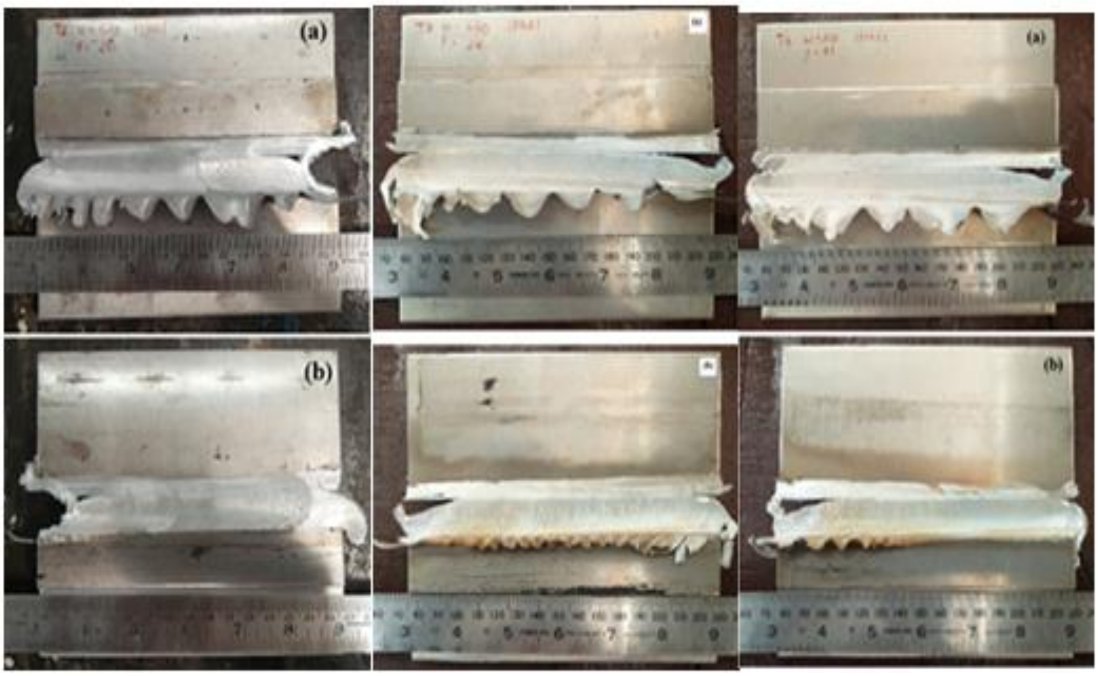

Figure 17: (left) Weld formation in experiment-6, (a) Top surface, (b) Bottom surface; (middle) Weld formation in experiment-7, (a) Top surface, (b) Bottom surface; (right) Weld formation in experiment-8 (a) Top surface, (b) Bottom surface

Figures 18 (a) (left) and 18 (b) (left) illustrate the weld morphology on the top and bottom surfaces, respectively in *experiment-9*. Tool-5 (shown in Figure 10 (a)) was used in the experiment at rotational speed of 445 rpm and a welding feed of 31 mm/min. Unwelded formation was observed as compared with the previous trial performed under identical processing conditions and different tool. This result may be attributed to the complex thermo-mechanical nature of the FSW process in association with the primary and secondary features of tool-5 may not be suitable for lapped workpieces.

Figures 18 (a) (middle) and 18 (b) (middle) illustrate the weld morphology on the top and bottom surfaces respectively in *experiment-10.* Tool-6 (shown in Figure 10 (b)) was used at rotational speed of 445 rpm and feed of 31 mm/min. A slight improvement in joint formation was observed compared with the previous experiment performed under identical processing conditions, but non-acceptable for further investigation.

Figures 18 (a) (right) and 18 (b) (right) illustrate the weld morphology on the top and bottom surfaces respectively in *experiment-11*. Tool-6 was used at rotational speed of 445 rpm and feed of 16 mm/min initially

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and changed to 65 mm/min. Compared with the previous experiment performed under identical process parameters, decrement in joint formation was observed and non-acceptable for further investigation.

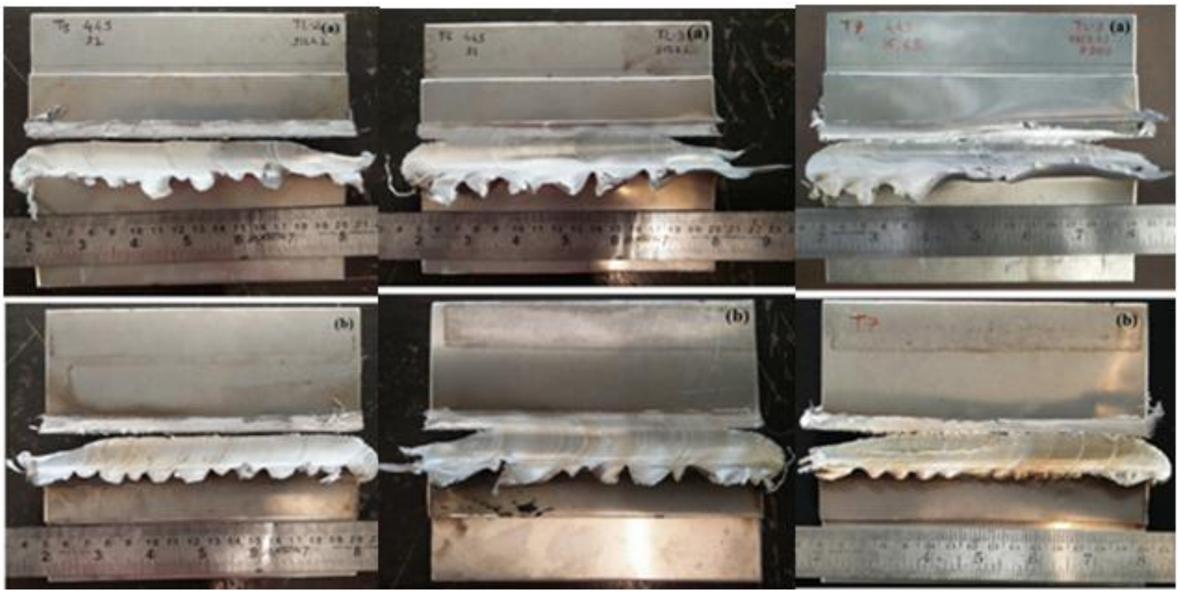

Figure 18: (left) Weld formation in experiment-9, (a) Top surface, (b) Bottom surface; (middle) Weld formation in experiment-10, (a) Top surface, (b) Bottom surface; (right) Weld formation in experiment-11, (a) Top surface, (b) Bottom surface

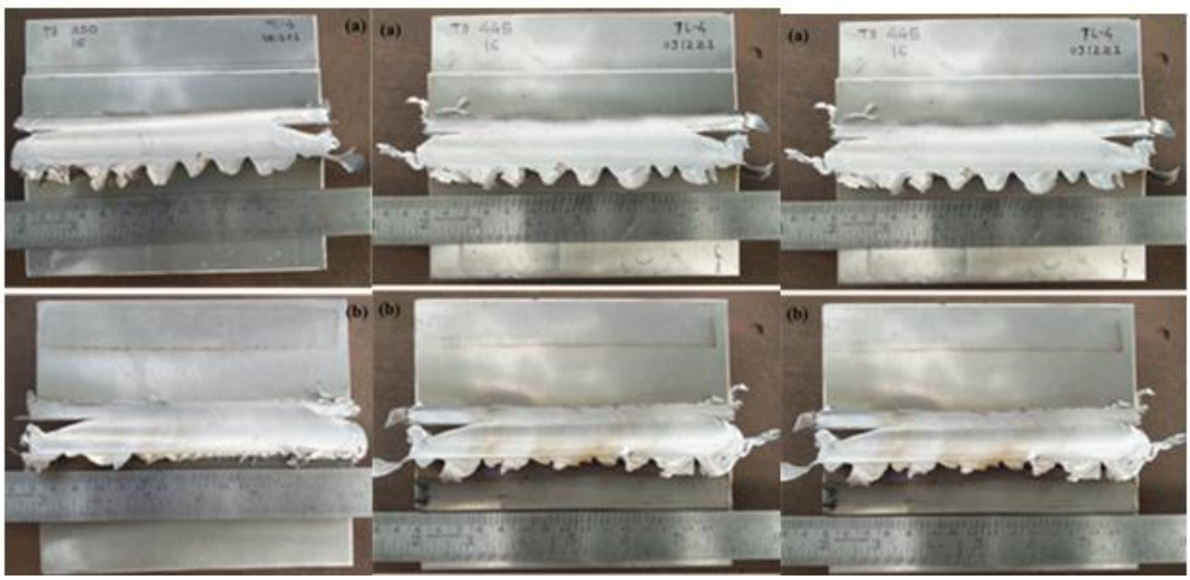

Figure 19: (left) Weld formation in experiment-12, (a) Top surface, (b) Bottom surface; (middle) Weld formation, in experiment-13, (a) Top surface, (b) Bottom surface; (right) Weld formation in experiment-14, (a) Top surface, (b) Bottom surface

As presented in Table 2, weld generated from the experiments corresponding to serial numbers 4–11 exhibited weld quality index, 0 or 1 or 2 in all DSFSLW trials due to lack of needed features in tool responsible for efficient frictional heat generation and intermixing of heated and plasticized embodies in lapped workpieces. Non-synchronized process parameters (tool rotation speed and tool feed) with the tool features proved inefficiency in weld formations. All weldments were characterized by significant flash formation on the RS of the top surface, pronounced tool marks on the bottom surface, and inadequate lap joint integrity. The excessive flash indicates insufficient confinement between the tool shoulder and substrate, which limited the effective transport of frictionally softened material. Consequently, inadequate material flow and bonding occurred at the weld interface.

Tool-7 (shown in Figure 10 (c)) was applied in experiments-12 to 17 at rotation speed of 280, 350 and 445 RPM; and feed of 16, 43 and 45 mm/min as shown in Table-2, serial number 12 to 16. Figure 19 represents welds achieved on top and bottom surfaces in *experiments-12 to 14* with weld quality index 4 (shown in Table-2). Figure 20 shows welds achieved on top and bottom surfaces in *experiments-15 to 17* with weld quality index 3 or 4 (shown in Table-2).

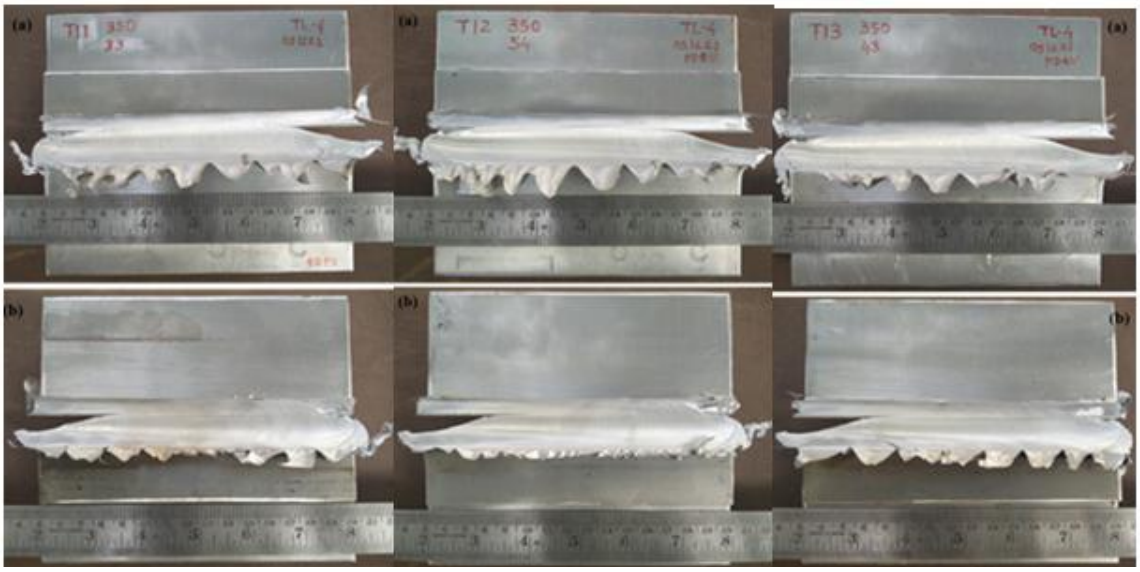

Figure 20: (left) Weld formation in experiment-15, (a) Top surface, (b) Bottom surface; (middle) Weld formation, in experiment-16, (a) Top surface, (b) Bottom surface; (right) Weld formation in experiment-17, (a) Top surface, (b) Bottom surface

These variations in the weld formation may be attributed to design features of tools and synchronized tool rotational speed and feed and these are highly responsible for complex thermo-mechanical effects in FSW process, as well as reduced heat dissipation through the machine structure and fixture system with the application of heat restricted material plates at abutting surfaces of workpieces and fixture during subsequent welding runs. These resulting in enhanced thermal control and likely enhanced material plasticization and improved dynamic material flow in horizontal and vertical direction towards the weld interface.

Good welds were generated with use the application of tool-7 at tool rotation feed of 280, 350 and 445 RPM and feed of 16 mm/min. Another combination for good weld was a tool rotation speed of 350 RPM and 33 mm/min with the application of tool-7. No defects were observed either on top or bottom surfaces of the weld and acceptable for further testing/investigations. These investigations demonstrated that the tool features were well aligned with the characteristics of DSFSLW, resulted in weld formations from no weld (0) to good weld (4).

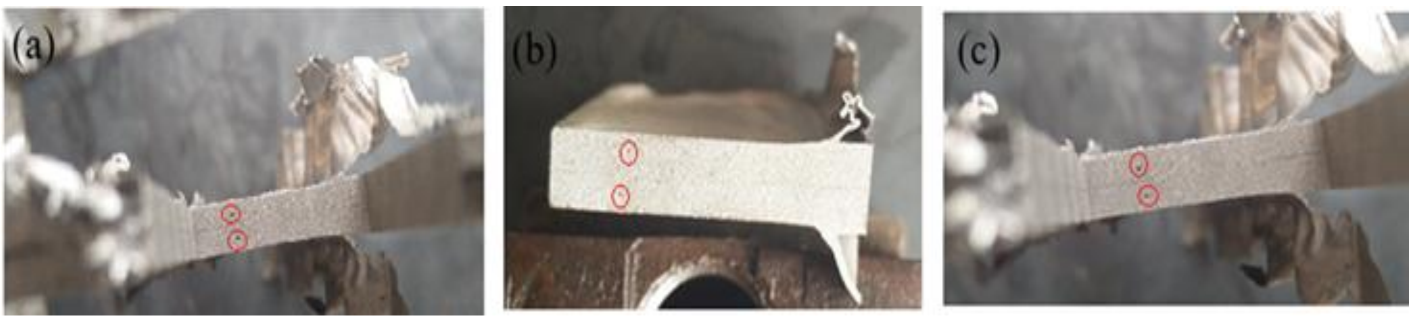

Figure 21: Cross section of weldments, (a) experiment-12 (T8), (b) experiment-13 (T9), (c) experiment-14 (T10)

Nevertheless, the improvement was not practically applicable as hole(s) or no metal volume defects observed in cross sections of weld of experiments-12 to 17. Figure 21 shows holes or no metal volume defects in cross section of weld at AS and no defect at RS. It can be attributed to missing forging force, less than the needed force at AS. As a FSW characteristics workpieces materials shift from AS to RS due to tool rotational speed. Little less frictional heat and material flow at AS resulted in hole (s) or no metal volume defects. Figure 21 (a), (b) and (c) shows hole defects in weld of experiments-12, 13 and 14 respectively. These defects can be eliminated by synchronized tool rotation speed and tool feed with controlled net effective frictional heat accumulation in heated and plasticized embodies and dynamic intermixing by controlled stirring of embodies.

CONCLUSION

After investigations of weld formations in DSFSLW of Al 6061-T6 workpieces material by applying different DSFSW tools, and varying tool rotation speed (RPM) and tool feed (mm/min), following conclusions can be made.

In DSFSLW, un-successful welds (weld quality index, 0 or 1 or 2) were generated in initial experiments-4 to 8 with the application of tool with cylindrical and fluted pin. In one case, weld formation was not generated. Cylindrical fluted pin is successful in DSFSW in butt configuration but not useful in lap configuration.

Successful weld (weld quality index, 3 or 4) was achieved at lower welding speed of 16 mm/min with designed dual shoulders tool-7 in DSFSLW.

Higher rotational speed and welding speed resulted poor weld in DSFSLW.

Experiments with conductive heat flow restriction approach resulted in requirement of low tool rotational speed (RPM) for successful welds.

Weld quality and higher strength (manual check) was observed with increase in tool rotation speed from 280 to 445 RPM.

Successful weld formations were observed in which experiments were performed with the tool having 2° concave shoulders surface towards pin and hour glass shaped pin without threads and 3 flutes on mid part surface of pin.

Characteristics of weld formation of lapped workpieces is different that the butted workpieces due to horizontal separation surface in lapped workpieces, is aligned with the presented tool features may cumulatively generate effect to forge intermixed and stirred workpiece material towards common horizontal interface of lapped workpieces for defect free weld.

Author’s Contribution

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Discussion of results: Modi Vijaykumar Natvarlal, Kishan Fuse

Writing – Original Draft: Modi Vijaykumar Natvarlal

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Supervision: Anishkumar H. Gandhi, Vishvesh J. Badheka

Approval of the final text: Anishkumar H. Gandhi

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Appendix -1 (Abbreviations and full term)

Abbreviations	**Full Term**
FSW	Friction Stir Welding
CTFSW	Conventional Tool Friction Stir Welding
FSLW	Friction Stir Lap Welding
BTFSW	Bobbin Tool Friction Stir Welding
DSFSW	Dual Shoulders Friction Stir Welding
SRFSW	Self-Reacting Friction Stir Welding
DSFSLW	Dual Shoulders Friction Stir Lap Welding
BTFSLW	Bobbin Tool Friction Stir Lap Welding
SRFSLW	Self-Reacting Friction Stir Lap Welding
LH	Left Hand
RH	Right Hand
BM	Base Material
AS	Advancing Side
RS	Retreating Side
ROD	Residual Oxide Defect
UTS	Ultimate Tensile Strength