Effect of Tool Pin Profile and Dwell Time on Friction Stir Spot Welding of Similar AA5083-T6 Sheets

Nipen M Khirsaria, Vivek V Patel, Jay J Vora, Darpan P Antala and Rushabh A Patel

Abstract— Friction stir spot welding (FSSW) is a solid-state metal joining process derived from friction stir welding. In this study, FSSW of similar AA5083-T6 sheet is performed at three different dwell time of 5s, 10s, and 20s with two different tool geometries i.e. circular and triangular shoulder as well as pin. Tool rotation speed, tool tilt angle, and plunge rate were held constant to investigate the combined effect of dwell time and tool geometry. All the samples were produced without any defect. The peak temperature of 289.4 ^{0}C was observed for tool with circular pin and shoulder at 20s dwell time, whereas that of triangular pin and shoulder was 269.9 ^{0}C at 20s dwell time. The maximum tensile shear load of 4020N was observed for tool with circular pin and shoulder at 10s dwell time, whereas that of triangular pin and shoulder was 3900N at 5s dwell time.

Keywords—AA5083-T6, Circular Pin and Shoulder, FSSW-similar, Triangular Pin and Shoulder

I. INTRODUCTION

There is increasing demand of light-weight materials in automotive and aerospace industries in order to have high performance of structural component, lower vehicle mass, green gas emissions, fuel consumption and to additionally reduce consumption of energy for vehicle production[1].

The traditional joining method used in automotive industry is Resistance Spot Welding (RSP), which works well for steel but is not suitable for Al or Mg Alloys [2]. Nowadays, about 2000-50000 spot welds are used in the car bodies; most of them are applied by resistance spot welding (RSW)[2, 3]. So, there is a new method known as FSSW, variant of FSW. FSW has received considerable attention because it offers various advantages such as good retention of base line mechanical properties, little distortion, low residual stress and few weld defects. Since FSSW has same advantages as FSW, this technique is expected for extensive application for joining of Body parts made of aluminum alloy sheets in automotive industries.

FSSW can be used as an alternate method for RSW. Comparing to RSW, the FSSW can lead to about 90% saving in the energy and approximately 40% saving in the equipment costs. It is also an environmentally friendly (green) process [4-6]. The FSSW process mimics the resistance spot welding (RSW) process and can be used in place of RSW, riveting, clinching or any other single point joining process in many application[7].

In FSSW (solid-state welding technique), the non-consumable rotating tool is used[8]. Tool consists of two main parts: shoulder and pin out of which pin is plunged into two overlapping sheets at a predefined position as shown in Fig.1. The shoulder of the tool creates a compressional stress generating the frictional heat and makes the material soft this heated and soften material below the tool deform plastically to very high strains, disrupting the oxides at the joint interface, so that a solid state bond can be formed between upper and lower sheets[9]. The major regions of FSSWed joints include (i) stirred zone (SZ) (ii) thermo-mechanically affected zone (TMAZ) (iii) heat affected zone (HAZ) and (iv) base metal (BM)[2, 10]. Similar to friction stir processing SZ in FSSW is characterized by recrystallized grain structure due to sever plastic deformation by tool pin[11-13]. The pin assists in material flow between the work pieces. A keyhole is created at circular stir zone when the rotating tool is retracted back from the stir zone after a predefined dwell time.

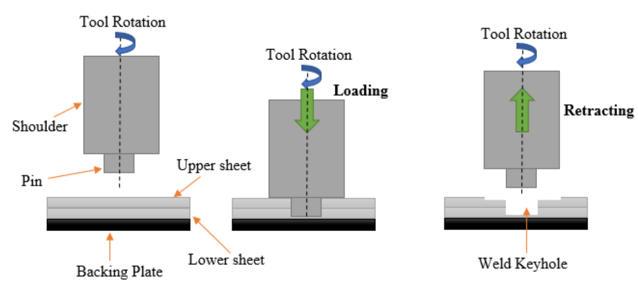

Fig.1: FSSW Process

Before any successful engineering application, it is necessary to have a detailed understanding of the material flow behavior during the FSSW process. However, experimental investigation always helps in clearly clarifying the material flow behavior. For example, in different components, the embed trace material unavoidably changes the flow mechanism of the base material. A stir zone where dynamic recrystallization occurs, a thermo-mechanically affected and heat affected zone are formed, directed from weld key hole towards parent material. Temperature plays one of the major role when different tool pin

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profiles are used. According to one study pentagonal pin profile generated maximum temperature of 373^0C when 6.35 mm thick 7075Al-T651 rolled plates were subjected to FSP[14]. Process condition including tool penetration and dwell essentially determines heat generation and material plasticization which further establish microstructure, macrostructure and texture in spot weld as well as weld strength[15].

In FSSW important process parameters are tool rotational speed, dwell time and tool profile which determine mechanical properties by influencing material flow and heat generation[16]. Despite various studies, the influence of shoulder geometry on the mechanical properties of FSSW joints has not been clarified completely. FSSW of Al 2024 T3 of 1.6mm at 1600rpm with cylindrical shoulder and cylindrical pin tool, triangular shoulder and cylindrical pin tool and cylindrical shoulder and triangular pin tool results in tensile shear load of 7900N, 5400N and 8000N respectively[16]. In one study Tozaki have reported that increasing pin length can improve weld shear strength in 6061 alloy(2 mm thick sheet) which agrees with a previous claim that the pin needs to penetrate the bottom sheet by ~25% of it's thickness to obtain maximum joint strength[17]. Zhang et al [18] observed that the weld shear strength decreased with increasing the rotational speed and was not influenced by the dwell time on the other hand Pathak et al [19] reported that increase in rotational speed and plunge depth strengthened the joint. However, Yuan et al [20] found the weld strength initially increased with the rotational speed and plunge depth. But is has been also noted that deep plunge depth may lead to decreased weld strength due to excessive thinning of top sheet[21, 22]. One study shows that FSSW of Dissimilar Aluminum Alloys AA5052-H32 and AA6082-T6 gives highest tensile strength of 56MPa at 1500rpm with Truncated tool pin profile[23].

II. Experimental Procedure

AA5083-T6 sheets having thickness of 2mm were used for FSSW. The chemical composition of AA5083-T6 is listed in TABLE I. Physical and Mechanical properties are listed in TABLE II.

TABLE I:
CHEMICAL COMPOSITION OF BASE METAL (wt.%)

Al	Mn	Fe	Zn	Cu
99.33	0.402	0.188	0.033	0.038

TABLE II:
PHYSICAL AND MECHANICAL PROPERTIES

Density	2660kg/m^3
Tensile Yield Strength	228MPa
Ultimate Tensile Strength	317MPa
Modulus of Elasticity	70.3GPa
Poisson's Ratio	0.33

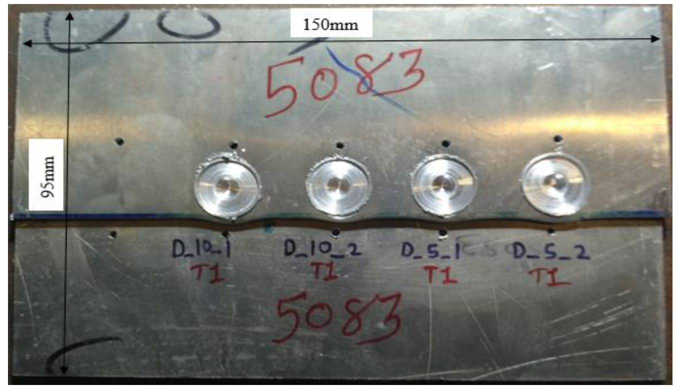


Fig.2: Lap Joint Specimen

Aluminum sheets of dimensions 150 x 110 mm^2 with overlap of 25 mm were used for FSSW as shown in Fig.2. One Aluminum sheet was overlapped on other and 5 spots per specimen were made with help of Vertical Milling Machine (Fig.3). The arrangement for FSSW is shown in Fig.4. Temperature measurement was carried out by using k type thermocouples. Out of various parameters, effect of tool pin geometry and effect of dwell time is to be studied. Hence two different types of tools are used in this study and Tool Geometry and dimensions with designation are listed in TABLE III. Both FSSW tools were made of H13 tool steel. Fig.5 depicts FSSW tools used in this study.

TABLE III:
WELDING TOOL GEOMETRY AND DIMENSIONS WITH DESIGNATION

Tool Designation	Tool Geometry and Dimensions
Tool_1	Circular shoulder with 14mm diameter and 10^o concave; circular pin with 5mm diameter and 3mm pin length
Tool_2	Triangular shoulder with 14mm diameter; triangular pin with 5mm diameter and 3mm pin length

Fig.3: Verticle Milling Machine

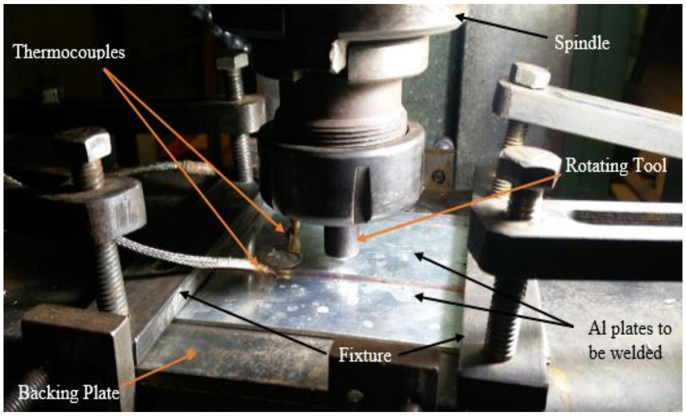


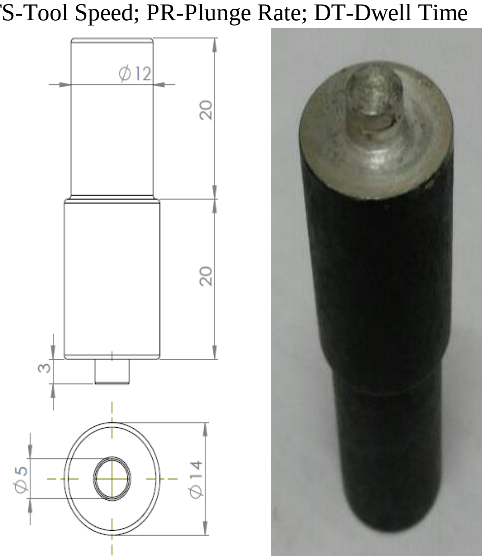
Fig.4: Experimental Setup

Two different sets were made in order to study effect of Tool pin geometry and Dwell Time. In Set_1, Tool_1 was used for dwell time of 5s, 10s and 20s at 1500rpm and 0.1mm/s plunge rate. Two spots for each dwell time with Tool_1 were made in order to carry out Shear-Tensile Test and Macrograph. Thus 6 spots for each Set were made. Similarly, Tool_2 was used in Set_2. Both Sets are listed in TABLE IV.

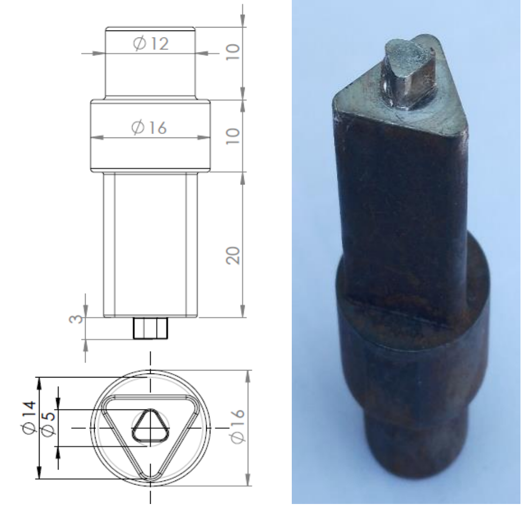
TABLE IV:
DESIGN OF EXPERIMENT

Experiment No.	**Tool**	**Thickness of sheet**	**Tool rotation**	**Process Parameters**
Set_1	Tool_2	2mm	Clockwise	TS=1500rpm PR=0.1mm/s DT=5,10,20s
Set_2	Too_4	2mm	Clockwise	TS=1500rpm PR=0.1mm/s DT=5,10,20s

TS-Tool Speed; PR-Plunge Rate; DT-Dwell Time



(a)



(b)

Fig.5: (a) Tool_1 (b) Tool_2

After all spots were made, Shear-Tensile Test specimens of dimension 95 x 25 mm^2 were prepared by cutting on wire EDM (Electro Discharge Machine) as shown in Fig.6. Shear-Tensile Tests were conducted at room temperature on Universal Testing Machine.

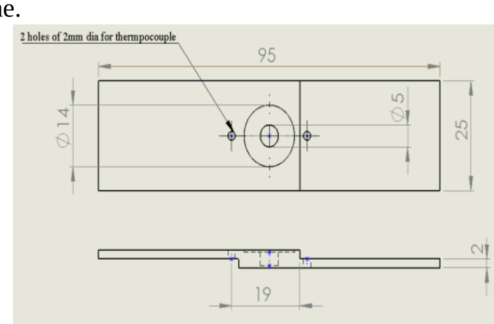
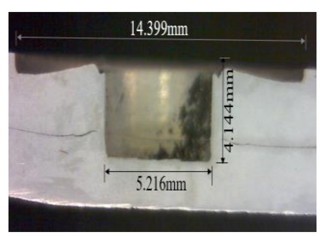


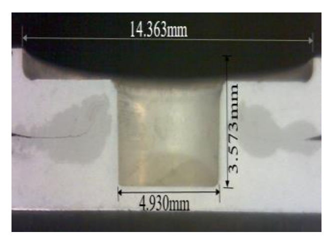
Fig.6: Tensile-Shear Test Specimen

III. Result and Discussion

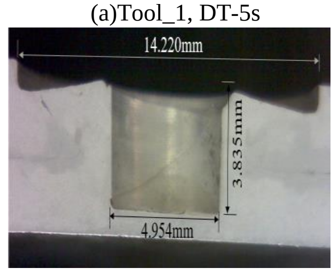
A. *Macrostructure*



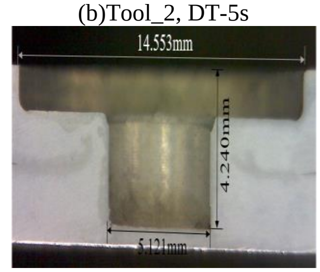
(a)Tool_1, DT-5s



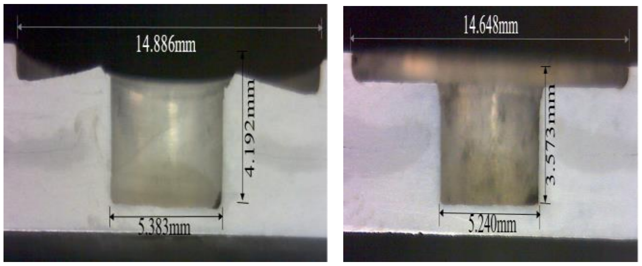
(b)Tool_2, DT-5s



(c)Tool_1, DT-10s



(d)Tool_2, DT-10s



(e)Tool_1, DT-20s (f)Tool_2, DT-20s

Fig.7: Macrostructure

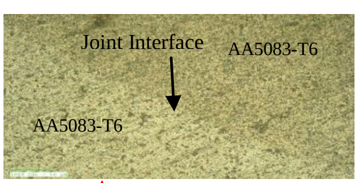
TABLE V:
DIMENSIONS OF FRICTION STIR SPOT WELD

	Tool_1			Tool_2		
	D_5	D_10	D_20	D_5	D_10	D_20
Effective Shoulder Diameter	14.399	14.220	14.886	14.363	14.553	14.648
Effective Pin Diameter	5.216	4.954	5.383	4.930	5.121	5.240
Plunge Depth	4.144	3.835	4.192	3.573	4.240	3.573

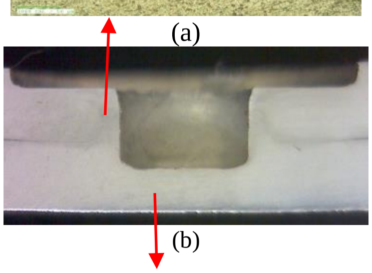
Fig.7 shows macrostructure (at 10X) of welded specimens at different dwell times with different tools. The macrostructures show proper bonding between the sheets without any defect in case for all samples. The observed macrostructure is a result of intense stirring and mixing of the sheet material around the tool pin, which resulted recrystallized grain microstructure in the stir zone (SZ) for all samples.

Loading of aluminum on flat portion of triangular pin was observed. The 3 corners of triangular pin acts as single point cutting tool and aluminum material from the sheet was removed in form of chips. This highly plasticized chip gets loaded on pin periphery in form of stack as pin advances into the sheet. Hence, the shape of Tool_2 became cylindrical after FSSW, which is common for polygonal pin profiles[24]. Ideally the plunge depth for each tool should remain constant, but TABLE V shows that it is not constant, which is due to fact that the control was done manually. Hence there is maximum variation of plunge depth of 9.3% for Tool_1 and 18.7% for Tool_2.

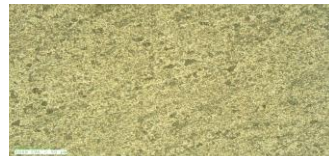
B. Microstructure



(a)



(b)

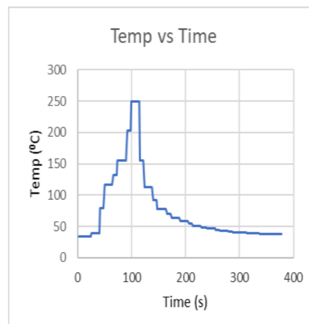


(c)

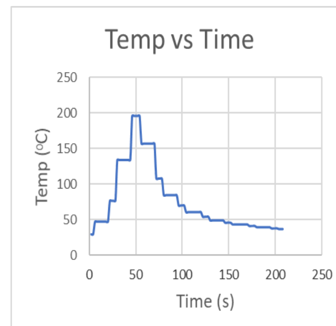
Fig.8: Microstructure

Fig.8(a) and Fig.8(c) shows Microstructure at location shown in Fig.8(b). Microstructure reveals that because of plastic deformation and proper heat generation during FSSW process of AA5083-T6 sheets, recrystallization occurred which resulted into fine grain structure. Microstructure observed were defect free, which is due to proper selection of tool.

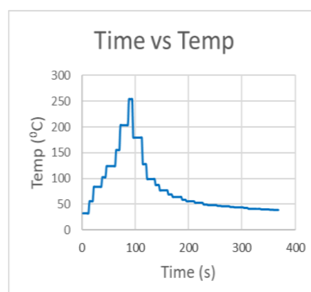
C. Temperature



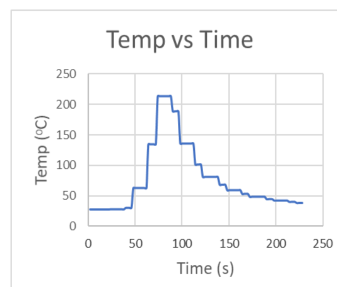
(a)Tool_1 DT – 5s



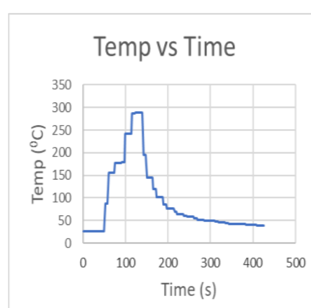
(b)Tool_2 DT – 5s



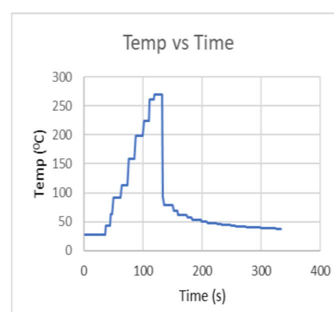
(c)Tool_1 DT – 10s



(d)Tool_2 DT – 10s



(e)Tool_1 DT – 20s



(f)Tool_2 DT – 20s

Fig.9: Temperature Profile

TABLE VI:
MAXIMUM TEMPERATURE WITH DIFFERENT TOOLS AT DIFFERENT DWELL TIME

Tool	D_5	D_10	D_20
Tool_1	248.8	254.3	289.4
Tool_2	196.4	213.2	269.9

For temperature measurement two holes of 2mm diameter were drilled on Al-5083 sheets at distance of 19mm from end of sheet as shown in Fig.6. Temperature below the tool should be high enough to soften the work piece but less than the melting temperature of work piece. Plastic flow and mixture can be analyzed using obtained temperature distribution. Fig.9 shows temperature profile at different dwell time for both tools.

As the dwell time increases the maximum temperature also increases due to fact that more time is allowed for welding. This is clear from TABLE VI. Also, maximum temperature reached is lower in case of tool with triangular pin and shoulder then in tool with cylindrical pin and shoulder i.e. Tool_1 have lower temperature when compared to Tool_2 at corresponding dwell time.

The maximum temperature of 289.4^0C is achieved when tool with cylindrical pin and shoulder is used at 20s dwell time. Whereas minimum temperature of 196.4^0C is achieved when tool with triangular pin and shoulder is used at 5s dwell time.

D.Tensile-Shear Load

Dwell Time is one of the deciding parameter for obtaining good tensile shear strength of Lap joint of metal sheets. Fig.10 illustrates results of tensile shear test of specimens joined under different welding parameters.

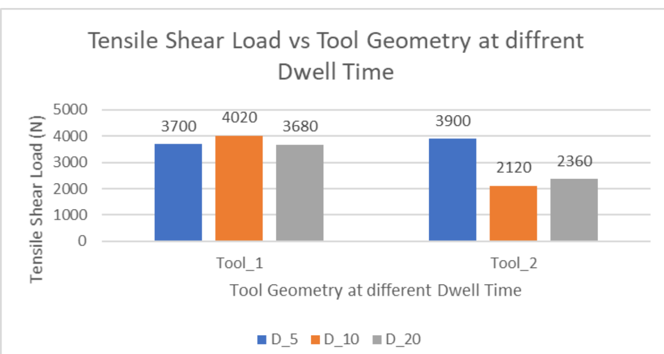


Fig.10

The maximum tensile shear strength of 4020N was obtained at 10s dwell time for Tool_1. For Tool_2 the maximum tensile shear strength of 3900N was obtained at 5s dwell time.

For 5s dwell time Tool_2 (3900N) has higher Tensile-Shear Load then that of Tool_1(3700N). For 10s dwell time Tool_1 (4020N) has higher Tensile-Shear Load then that of Tool_2 (2120N). For 20s dwell time Tool_1 (3680N) has higher Tensile-Shear Load then that of Tool_2 (2360N). Hence Optimum dwell time for Tool_1 is 10s and that of Tool_2 is 5s resulting in highest Tensile Shear Strength.

By comparing maximum value of Tensile-shear load of Tool_2(3900N) with that of Tool_1(4020N), there is decrease in it by 2.99%, with decrease in dwell time by 50%. Taking strength and productivity into selection criteria Tool_1 is to be selected under strength criteria at cost of productivity and Tool_2 is to be selected under productivity criteria at cost of strength.

IV. Conclusion

In this study FSSW welds were made on lap configuration of AA5083-T6 with both aluminum sheets being 2mm thick. FSSW was carried out at different dwell time (5s, 10s and 20s) with two tool pin profiles (circular and triangular) at constant tool rotation of 1500rpm and manual plunge rate of 0.1mm/s. Comparison of the parameters selected for study were carried out by investigating results obtained from Tensile-shear, macrostructure, microstructure and temperature profile. After comparison it was observed that tool with circular pin and shoulder gives maximum tensile-shear load of 4020N at 10s dwell time and tool with triangular pin and shoulder gives maximum tensile-shear load of 3900N at 5s dwell time. Temperature during FSSW process was increased with increase in dwell time. It was also observed that temperature generated by tool with triangular pin and shoulder was less compared to tool with circular pin and shoulder at corresponding dwell time. Microstructure revealed that FSSWed specimens were free from defects with fine grain structure.

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