Feasibility Study of Friction Stir Welding Application for Kevlar Material
Ahmet Taşan, Süha Tirkeş, Yavuz Öztürk, Zafer Bingül

Abstract—Friction stir welding (FSW) is a joining process in the solid state, which eliminates problems associated with the material melting and solidification, such as cracks, residual stresses and distortions generated during conventional welding. Among the most important advantages of FSW are; easy automation, less distortion, lower residual stress and good mechanical properties in the joining region. FSW is a recent approach to metal joining and although originally intended for aluminum alloys, it is investigated in a variety of metallic materials. The basic concept of FSW is a rotating tool, made of non-consumable material, specially designed with a geometry consisting of a pin and a recess (shoulder). This tool is inserted as spinning on its axis at the adjoining edges of two sheets or plates to be joined and then it travels along the joining path line. The tool rotation axis defines an angle of inclination with which the components to be welded. This angle is used for receiving the material to be processed at the tool base and to promote the gradual forge effect imposed by the shoulder during the passage of the tool. This prevents the material plastic flow at the tool lateral, ensuring weld closure on the back of the pin. In this study, two 4 mm Kevlar® plates which were produced with the Kevlar® fabrics, are analyzed with COMSOL Multiphysics in order to investigate the weldability via FSW. Thereafter, some experimental investigation is done with an appropriate workbench in order to compare them with the analysis results.

Keywords—Analytical modeling, composite materials welding, friction stir welding, heat generation.

I. INTRODUCTION

Friction stir welding (FSW) is particularly suitable for the non-ferrous metals which have low melting point. Additionally, some compound materials such as aluminum alloys and steels can also be readily welded. During welding, a rotating cylindrical pin is traveled throughout joint line of the materials and resulting from heating the materials to a plasticized state and stirring the workpieces together, a joint is formed.

Thanks to advances in FSW, hardly weldable steels or dissimilar materials such as aluminum, magnesium, copper, and titanium can be welded to each other. This technology is can be applied in many industries such as automotive, aviation, defense and electronics.

II. PROCESS REVIEW

Fig. 1 shows that the process applies plunge force, torque and traverse force on the workpieces to be welded via a nonconsumable rotating tool with a specially designed pin and shoulder [1].

Fig. 2 illustrates that along the joint line, two square butt grooved plates without any welding groove preparation can be welded via a tool with a specially designed pin and shoulder under applied specific process parameters such as tilt angle (θ), plunge force (F), rotating speed (ω) and travelling speed (υ) [1].
Compared to fusion welding, some benefits of FSW are summarized as described:

i. No loss of alloying elements.
ii. Dimensional stability and repeatability.
iii. Excellent mechanical properties.
iv. Avoiding porosity and cracks in the welding area.
v. Consumable materials saving such as wire, shielding gas.
vi. Welding compound and alloy steels such as: Al, Ti, Cu, Ni, Mg.
vii. No harmful emissions.
viii. Minimizing grinding wastes.
ix. Reduced weights (40% less than fusion welds).

According to the literature researches, compared to metal inert gas welding (MIG), FSW is 4 times faster than for 5 mm thick AA6062-T6 and 2 times for 10 mm thick AA6062-T6, as seen in Fig. 3. As mentioned before, the reasons of this time saving are, elimination of welding groove preparation, surface cleaning before and after welding and consumable materials replacement during welding [2].

### Joint Configurations

Among many advantages over to other fusing welding methods, as seen in Fig. 4, FSW also facilitates welding materials with the other joint configurations [3].

![Possible joint configurations for FSW. (a) Square butt groove, (b) Edge butt groove, (c) T-butt groove, (d) Lap groove, (e) Multiple lap groove, (f) T-lap groove, (g) Fillet groove.](image)

### Microstructure Zones

Due to the fact that FSW has many variable parameters including plunge force, rotating force, traverse force, tool geometry and material, the microstructure of the process can be changeable. Fig. 5 illustrates the microstructure and regions of FSW which are accepted by TWI [3].

![Schematic of the various microstructure regions of FSW.](image)

The microstructure includes distinct regions into the weld zone as follows:

i. **A**: Unaffected parent metal: This region is material that has not been deformed and not affected by the heat in terms of the microstructure or mechanical properties.

ii. **B**: Heat affected zone (HAZ): This is the region that is closer to the weld-center, although the mechanical properties or the microstructure has been modified, there is no plastic deformation occurring in this region.

iii. **C**: Thermomechanically affected zone (TMAZ): The microstructure and the mechanical properties have been changed and in contrast to the HAZ zone, the FSW tool has plastically deformed the material. Between the TMAZ zone and the recrystallized side (weld nugget), there is a distinct boundary [3].

iv. **D**: Weld nugget: The area which is called the stir zone, is a totally recrystallized region. Since the grain structure is 10 times smaller than the parent material, the mechanical properties and the fracture strength are significantly changed. The diameter of the zone is a little greater than the pin diameter, but significantly smaller than the shoulder diameter [4].

Fig. 6 represents the weld zone and region nomenclatures in a friction stir welded Al alloy, as mentioned above [3].

![Micrograph viewing the weld zones and regions.](image)

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well as the linear and rotational motion of the tool. In this respect, the shoulder diameter, shoulder surface angle, pin diameter and height are the important parameters [5].

D. Shoulder Types

1. Scroll Shoulder and Applications

Fig. 7 represents the applications of scroll shoulder and experimented welding parameters used for FSW and FSWW of several alloy materials [3]-[5].

2. Convex Shoulder and Applications

Fig. 8 represents the applications of scroll shoulder and experimented welding parameters used for FSW of several alloy materials [3]-[5].

E. Pin Types

1. Cylindrical Pin and Applications

Fig. 10 represents the applications of cylindrical pin and experimented welding parameters used for FSW and FSWW of several alloy materials [3]-[5].
3. Whorl Pin and Applications

Fig. 12 represents the applications of whorl pin and experimented welding parameters used for FSW of several alloy materials [3]-[5].

<table>
<thead>
<tr>
<th>Workpiece Material</th>
<th>Alloys</th>
<th>Material Thickness</th>
<th>Welding Parameters</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Schematic View</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 5xxx (Mg alloy) series (AA 5754 - FSW; friction stir spot welding)</td>
<td>1.32 mm</td>
<td>1500 rpm, dwell time; 2 s, plunge rate; 20 mm</td>
<td>* This shoulder produces quality welding and decreases significantly welding mistakes in the microstructure and geometry</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Al 6xxx (Si + Mg alloys) series (AA 6061-T6)</td>
<td>6.3 mm</td>
<td>286-1150 rpm, 30-210 mm/min</td>
<td>* It improves the max plunge force and plunge depth.</td>
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</tr>
<tr>
<td>Al 7xxx-Zn alloy series (AA 7020-T6)</td>
<td>4 mm</td>
<td>300-1620 rpm, 100-900 mm/min, dwell time; 2 s, FSW lap 200 mm, 50 mm/min, under Ar shield</td>
<td>* Simply designed.</td>
<td></td>
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</tr>
<tr>
<td>AA 1050 with 22MnB5 steel</td>
<td>3 mm</td>
<td>1000-2000 rpm, dwell time; 2 s, FSW lap 200 mm, 50 mm/min, under Ar shield</td>
<td>* Proper operation of this shoulder design requires tilting the tool 2 to 4° from the normal of the workpiece away from the direction of travel; this is necessary to maintain the material reservoir and to enable the trailing edge of the shoulder tool to produce a compressive forging force on the weld.</td>
<td></td>
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</tr>
<tr>
<td>Ti alloy (cp-Ti, commercially pure Ti)</td>
<td>1.8 mm</td>
<td>800 rpm, 80 mm/min</td>
<td>* It produces moderate the flush and welding mistakes.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2024-T3 Al with Ti-6Al-4V alloy</td>
<td>2 mm</td>
<td>150 rpm, dwell time; 1 s</td>
<td></td>
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<tr>
<td>SAF 2507 super duplex stainless steel</td>
<td>4 mm</td>
<td>450 rpm, 60 mm/min</td>
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</tr>
<tr>
<td>Stainless Steel 15-5PH (martensitic, precipitation-hardening material with chromium, nickel and copper)</td>
<td>2.6 mm</td>
<td>300-450 rpm, 60-350 mm/min</td>
<td></td>
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<tr>
<td>DP 780 carbon steel (Dual phase, for the automotive industry, consists of a soft ferrite phase with dispersed islands of a hard martensitic phase)</td>
<td>1.5 mm</td>
<td>800-1600 rpm, dwell time; 1-2 s</td>
<td></td>
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</tr>
<tr>
<td>Advanced High-Strength Steels (AHSS)</td>
<td>1.2 mm</td>
<td>3000 rpm, under Ar shield, FSW lap welding</td>
<td></td>
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</tr>
</tbody>
</table>

Fig. 9 Concave shoulder and experimented applications

4. MX Triflute Pin and Applications

Fig. 13 represents the applications of MX Triflute pin and experimented welding parameters used for FSW of several alloy materials [3]-[5].

5. MX Trivex Pin and Applications

Fig. 14 represents the applications of MX Trivex pin and experimented welding parameters used for FSW of several alloy materials [3]-[5].

6. Threadless Pin and Applications

Fig. 15 represents the applications of threadless pin and experimented welding parameters used for FSW of several alloy materials [3]-[5].

III. KEVLAR MATERIAL PROPERTIES AND APPLICATIONS

Kevlar® is a class strong and synthetic fiber which has a unique combination of characteristics such as high strength, toughness and thermal stability, is characterized from other commercial fibers [6].

Kevlar® is a registered trademark of E. I. Du Pont de Nemours and in the aromatic polyamide (aramids) family. It was developed for aerospace, defense and military industries for demanding applications [6].

There are two types of Kevlar®, Kevlar® 29 and Kevlar® 49 and especially Kevlar® 49 is widely used in aerospace industry [7]. Major applications of Kevlar® are cut, heat, and bullet-fragment resistant apparel, brake and transmission friction parts, gaskets, ropes and cables, composites, fiber-optic cables, circuit-board reinforcement, sporting goods, tires, automotive belts and hoses.

Continuous filament yarn, staple, wet and dry pulp floc, cord are the major forms of Kevlar® [7]. When we look to the properties of special interests of Kevlar®, we can see that how
Kevlar® is important for many industries [7]:

i. High tensile strength at low weight.

ii. Low elongation to break.

iii. High modulus (structural rigidity).

iv. Low electrical conductivity.

v. High chemical resistance.

vi. Low thermal shrinkage.

vii. High toughness (work-to-break).

viii. Excellent dimensional stability.

ix. High cut resistance.

x. Flame resistant.

xi. Self-extinguishing.

Table I illustrates the mechanical properties of fiber materials including Kevlar® 29 and Kevlar® 49 [8].

<table>
<thead>
<tr>
<th>Workpiece Material</th>
<th>Alloys</th>
<th>Material Thickness</th>
<th>Welding Parameters</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Schematic View</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31 Mg (Al with Mg alloy for the aviation industry)</td>
<td>1.5 mm</td>
<td>3D: 3 mm, PD: 4 mm, PL: 1.8 mm, PS: straight circular threaded, 3 flats with M4 threads, 1000-2000 rpm, tool: 1.4 s, plunge rate: 0-10 mm/s, TIG weld at 0.8 mm/min</td>
<td>* By means of the thread, it enables to transport material from the shoulder to the pin bottom.</td>
<td>* A larger round-bottom pin radius will reduce the velocity differential.</td>
<td>* The flat bottom pin needs much more plunge force than others.</td>
<td>Fig. 10 Cylindrical pin and experimented applications</td>
</tr>
<tr>
<td>Mg AZ31 B-02</td>
<td>2 mm</td>
<td>PD: 3.15 mm, PL: 1.65 mm, PS: straight circular, left (right handed thread, 1000-2000 rpm, 300-800 mm/min</td>
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<tr>
<td>Al alloys 5 mm</td>
<td>5 mm</td>
<td>SD: 1.5 mm, PL: 4.7/6.6 mm, PS: concave, triangular circular threaded, 600-1500 rpm, 25-1000 mm/min</td>
<td>* By means of the thread, it enables to transport material from the shoulder to the pin bottom.</td>
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<tr>
<td>60Si2-Ti Al 1.5 mm</td>
<td>1.5 mm</td>
<td>PD: 1.7 mm, PL: 1.2 mm, 110 rpm, 400 mm/min</td>
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<tr>
<td>6061-T6 Al 6.3 mm</td>
<td>6.3 mm</td>
<td>SD: 2.6 mm, PD: 4.6 mm, PL: 3.5 mm, PS: straight circular threaded, 280-1150 rpm, 30-210 mm/min</td>
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<tr>
<td>Al 7000-T6 Al 4 mm</td>
<td>4 mm</td>
<td>SD: 1.5 mm, PS: straight circular; PL:3.19 mm, PD: 5 mm, 300-160 rpm, 100-900 mm/min</td>
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<tr>
<td>51-T6 Al 20% Al2 5.6 mm</td>
<td>5.6 mm</td>
<td>SD: 1.5 mm, PS: straight circular threaded, PD: 6.5 mm, 550-2600 rpm, 60-540 mm/min</td>
<td></td>
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<tr>
<td>9 + 20% SiC (for castings) 4 mm</td>
<td>4 mm</td>
<td>SD: 1.9 mm, PS: straight circular threaded, PD: 6.3 mm, PL: 3 mm, 300-1000 rpm, 300 to 600 mm/min</td>
<td></td>
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<tr>
<td>Composite Al-10 wt% Ti6B (with %10 Al, Al with TiB2 alloy) 6 mm</td>
<td>6 mm</td>
<td>SD: 1.6 mm, PS: square, circular; 1000 rpm, 30 mm/min</td>
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<tr>
<td>Ti 3 mm</td>
<td>3 mm</td>
<td>SD: 1.8 mm, PS: straight circular; PD: 5 mm, PL: 2.55 mm, 1250 rpm, 32 mm, 1500 rpm, 40 mm/min</td>
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<tr>
<td>Workpiece Material</td>
<td>Alloys</td>
<td>Material Thickness</td>
<td>Welding Parameters</td>
<td>Advantages</td>
<td>Disadvantages</td>
<td>Schematic View</td>
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<tr>
<td>7020-T6 Al</td>
<td></td>
<td>4 mm</td>
<td>SD: 13 mm; PS: straight circular, tapered circular with those flaps (PL: 0.3–1 mm; PD: 5 mm; 300–1600 rpm; 100–900 mm/min)</td>
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<tr>
<td></td>
<td>AA 1050-22MnB5 (Al alloy and hot stamped boron steel)</td>
<td>1.8 mm</td>
<td>SD: 12 mm; PS: Conical shoulder; PD: 2 mm; PL: 2.7 mm; FSSW (friction stir spot welding) lap joint welding; 1000–2000 rpm; dwell time: 2 s</td>
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<tr>
<td></td>
<td>AA 6061–1 (5–7)% T4 (Al-8011, abrasion and wear resistance and improved damping capabilities with T4)</td>
<td>6 mm</td>
<td>PS: square, hexagonal, tapered hexagonal, tapered octagonal, 30–135 mm / min</td>
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<tr>
<td>2024-T3 Al with Tr-6Al–4V alloy</td>
<td></td>
<td>2 mm</td>
<td>SD: 18 mm; PS: threaded and tapered; PD: 6 mm; 800 rpm, 80 mm/min</td>
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<tr>
<td>Mg</td>
<td>AZ31B (Mg alloy)</td>
<td>6 mm</td>
<td>SD: 15.18.21 mm; PD: 6 mm; PL: 5.7 mm; PSt: triangular and square, straight circular threaded, tapered circular, 1600 rpm; 40 mm/min</td>
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<tr>
<td></td>
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<td></td>
<td>This design allows to weld the material over 12 mm thick</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>This pin has lower traverse loads compared to a cylindrical pin</td>
<td></td>
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<tr>
<td>cp-Ti (commercially pure Ti)</td>
<td></td>
<td>3 mm</td>
<td>SD: 15 mm; PS: tapered at 45 deg and truncated; PL: 1.7 mm; PD: 5.3 mm; 200 rpm; 50 mm/min, under Ar shield</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ti-6Al–4V</td>
<td></td>
<td>3-12 mm</td>
<td>SD: 19–32 mm; PS: tapered; PL: 2.8–13.5 mm, 150–750 rpm, 50–200 mm/min</td>
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<tr>
<td></td>
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<td></td>
<td>The increased surface velocity at the bottom of the pin would increase the bursting power of the pin, or the ability of the pin to affect metal below the root of the joint</td>
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<td></td>
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<td></td>
<td>High temperature and hydrostatic pressure can increase the tool wear</td>
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<tr>
<td>Ti-5111 plate</td>
<td></td>
<td>12.7 mm</td>
<td>PL: 12.7 mm; PD: 25.4 mm; PS: 5.4 mm; 140 rpm, 51 mm/min</td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>The stepped spiral tools enable to weld high temperature rotating steel (i.e. Ni-Al boron, survived at 100°C temperature)</td>
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</tr>
<tr>
<td>Ti-15V–3Cr–3Al–3Sn</td>
<td></td>
<td>3 mm</td>
<td>SD: 15 mm; PD: 5.1 mm; PD: 3 mm; 400 rpm, 60 mm/min, under Ar shield</td>
<td></td>
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</tr>
<tr>
<td>Boron</td>
<td>Hot stamped boron steels</td>
<td>1.4 mm</td>
<td>SD: 10.2 mm; PL: 2.3 mm; PS: tapered circular with three flaps; 800–2000 rpm, 1.8–10.5 x welding time. Lap welding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP 600 carbon steel (Dual phase for the automotive industry, composites of a soft ferrite phase with dispersed islands of a hard martensitic phase)</td>
<td></td>
<td>1.22 mm</td>
<td>SD: 10 mm; PS: straight circular; PL: 1.7 mm; PD: 4.3–5.3 mm; Flange rate: 3000 rpm, 30–60 mm / min (FSSW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA2124 / S6p2 / 25-T4</td>
<td></td>
<td>3 mm</td>
<td>SD: 20 mm; PL: 23 mm; PS: tapered threaded; PD: 6 mm; 4mm 900 rpm, 100 mm/min</td>
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</tr>
<tr>
<td>Composite</td>
<td>Al–15 wt % Mg2Ni (or 95% Al, Al with Mg2Ni alloy)</td>
<td>6 mm</td>
<td>SD: 18 mm; PS: tapered circular threaded; PL: 5.7 mm; 710–1400 rpm; 125 mm / min</td>
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</tbody>
</table>

* SD: shoulder diameter, PL: pin length, PD: pin diameter, PS: pin shape, PSt: pin diameter at the top (larger diameter) for tapered pin, PDt: pin diameter at the bottom (smaller diameter) for tapered pin
### Fig. 12 Whorl pin and experimented applications

<table>
<thead>
<tr>
<th>Workpiece Material</th>
<th>Alloys</th>
<th>Material Thickness</th>
<th>Welding Parameters</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Schematic View</th>
</tr>
</thead>
<tbody>
<tr>
<td>6082 T6 Al</td>
<td>1-50 mm Single pass</td>
<td>* This design reduces the displaced volume of a cylindrical pin of the same diameter by 60%. It also decreases the traverse loads, which enables faster tool travel speeds. * The difference from the truncated cone pins is that the helical ridge on the pin surface. * The significant advantages of this pin is the ratio of the volume swept by the pin to the pin volume. This ration is 1:1:1 for a cylindrical pin, while for whorl pin is 1:8:1.</td>
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</table>

### Fig. 13 MX Triflute pin and experimented applications

<table>
<thead>
<tr>
<th>Workpiece Material</th>
<th>Alloys</th>
<th>Material Thickness</th>
<th>Welding Parameters</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Schematic View</th>
</tr>
</thead>
<tbody>
<tr>
<td>7075-T7351 Al</td>
<td>6.35 mm</td>
<td>394 ve 457 rpm, 300-540 mm/min</td>
<td>* This pin is a further refinement of the Whorl pin by TWI. Its three flutes reduce the displaced volume of a cylindrical pin by 70% and supply additional deformation at the weld line. * This designed pin has a pin volume swept to pin volume ratio of 2.6:1 (for 25 mm thick plate). * Experimental research of cast A356 Al to demonstrate that a modified Triflute pin (cylindrical pin with three flutes) is more effective in breaking up silicon particles and healing casting porosity than either cylindrical or truncated cone pins.</td>
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</tbody>
</table>

| 6082 T6 Al         | 1-50 mm Single pass | | | | |
In this study, as seen in Fig. 16, Twaron CT 736 PHF Kevlar® resin material was used which is a registered trademark of SAATI S.p.A. [7].

Table II illustrates the mechanical properties of Twaron CT 736 PHF compared to Kevlar® 29 and Kevlar® 49 [6], [7]. It can be seen that they have similar mechanical properties.

Table III makes a comparison between the mechanical properties comparing some other material with Kevlar®.
TABLE III
SOME OTHER MATERIALS COMPARED TO KEVLAR

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength to weight KN/m/kg.</th>
<th>Ultimate Strength MPa</th>
<th>Density g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar® (ARAMID)</td>
<td>2514</td>
<td>2757</td>
<td>1.44</td>
</tr>
<tr>
<td>Steel alloy</td>
<td>254</td>
<td>400</td>
<td>7.8</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>222</td>
<td>248-483</td>
<td>2.63 - 2.8</td>
</tr>
<tr>
<td>Spider Silk</td>
<td>1069</td>
<td>1000</td>
<td>1.3</td>
</tr>
<tr>
<td>Oak</td>
<td>87</td>
<td>65</td>
<td>0.75</td>
</tr>
</tbody>
</table>

IV. MODEL ANALYSIS OF HEAT GENERATION IN FSW

In recent years, analytical models based on a cylindrical pin structure were developed [9]. Since the tapered pin has better mechanical properties than straight the cylindrical pin, in this study, as seen in Fig. 17, a tapered circular pin with 3 flat layers was used and the analytical model was developed accordingly.

Fig. 17 A tapered circular with 3 flats pin used in this study

A. ESTIMATION OF THE HEAT GENERATION MODEL

As shown in Fig. 18, heat generation occurs at three different regions where \( Q_1 \) is under the tool shoulder, \( Q_2 \) is at the pin side surface and \( Q_3 \) is at the pin tip. The total heat generation is obtained via \( Q_{total} = Q_1 + Q_2 + Q_3 \) [9].

![Fig. 18 Schematic view of heat generation regions at a tapered pin](image)

In Fig. 19, the nomenclature is listed that is used during estimation [9]. For the analytical model, the following assumptions were made and accepted [9]:

i. The estimation based upon uniform contact shear stress \( \tau_{contact} \) was considered.

ii. The shearing takes place at the contact interface during sliding.

iii. Deformation mechanism was not considered.

iv. Since friction interface mechanism, the friction shear stress \( \tau_{friction} \) was considered. For the sliding condition, the friction shear stress was estimated via \( \tau_{contact} = \mu \tau_{friction} = \mu \sigma \).

\[
\begin{align*}
Q_1 & \quad \text{heat generation from shoulder surface} \\
Q_2 & \quad \text{heat generation from pin surface} \\
Q_3 & \quad \text{heat generation from pin tip surface} \\
\mu & \quad \text{friction coefficient} \\
\omega & \quad \text{tool angular rotation speed (rpm)} \\
\alpha & \quad \text{pin taper angular (°)} \\
\vartheta & \quad \text{tool speed (mm/min)} \\
\sigma & \quad \text{contact pressure (Pa)} \\
\tau_{contact} & \quad \text{contact shear stress (Pa)} \\
R_{PT} & \quad \text{pin tip radius (mm)} \\
R_{PS} & \quad \text{pin bottom radius (mm)} \\
R_{shoulder} & \quad \text{tool shoulder radius (mm)} \\
Q_{total} & \quad \text{total heat generation (W)} \\
H_{probe} & \quad \text{pin length (mm)}
\end{align*}
\]

Fig. 19 Nomenclature

A tool with flat shoulder, taper circular pin and flat probe tip is accepted which is a modified version of the one given by [9]. The tapered pin surface is indicated by the taper angle \( \alpha \). The general heat generation equation is:

\[
dQ = \omega . dM = \omega . r . dF = \omega . r . \tau_{contact} . dA
\]  

(1)

Fig. 20 illustrates the contact surface between tool and workpiece given by position and orientation with regard to rotation axis [9].
area provides an infinitesimal force of \( dF = \tau_{\text{contact}} \cdot dA \) and torque of \( dM = r \cdot dF \). Thereby, the heat generation of the area is achieved;

\[
dQ = \omega \cdot r \cdot dF = \omega \cdot r^2 \cdot \tau_{\text{contact}} \cdot d\theta \cdot dr
\]

where \( \omega \) is the angular velocity, \( r \) is the distance to the center of rotation, \( r \cdot d\theta \) and \( dr \) are the segment dimensions [9]. Integrating (2), the heat generation is achieved from \( R_{\text{PS}} \) to \( R_{\text{shoulder}} \) and thereby, it gives that [9]:

\[
Q_1 = \int_0^{2\pi} \int_{R_{\text{PS}}}^{R_{\text{shoulder}}} \omega \cdot r^2 \cdot \tau_{\text{contact}} \cdot d\theta \cdot dz
\]

\[
Q_1 = \frac{2}{3} \pi \cdot \omega \cdot \tau_{\text{contact}} \cdot (R_{\text{shoulder}}^3 - R_{\text{PS}}^3) \quad (3)
\]

2. Heat Generation of the Tapered Pin Surface
Equation (4) expresses the heat generation of the tapered pin surface over the probe side area [9];

\[
Q_2 = \int_0^{2\pi} \int_0^{R_{\text{PS}}} \omega \cdot r^2 \cdot \tau_{\text{contact}} \cdot d\theta \cdot dz
\]

\[
Q_2 = \frac{2}{3} \pi \cdot \omega \cdot \tau_{\text{contact}} \cdot \frac{(R_{\text{PS}}^2 + R_{\text{PS}}R_{\text{shoulder}} + R_{\text{shoulder}}^2)}{2}
\]

\[
Q_2 = \frac{\pi \cdot \omega \cdot \tau_{\text{contact}} \cdot \rho_{\text{probe}} \cdot \cos \alpha}{2} (R_{\text{PS}} + R_{\text{PS}}^2) \quad (4)
\]

3. Heat Generation of the Pin Tip Surface
Integrating (1) and assuming a flat pin tip, it gives (5) as follows [9];

\[
Q_3 = \int_0^{2\pi} \int_0^{R_{\text{PS}}} \omega \cdot r^2 \cdot \tau_{\text{contact}} \cdot d\theta \cdot dz
\]

\[
Q_3 = \frac{2}{3} \pi \cdot \omega \cdot \tau_{\text{contact}} \cdot R_{\text{PS}}^3
\]

Now, \( Q_{\text{total}} \) can be calculated using (3)–(5) as follows:

\[
Q_{\text{total}} = Q_1 + Q_2 + Q_3
\]

\[
Q_{\text{total}} = \frac{2}{3} \pi \cdot \omega \cdot \tau_{\text{contact}} \cdot \left( \frac{R_{\text{shoulder}}^3 - R_{\text{PS}}^3}{2} + \frac{\pi \cdot \omega \cdot \tau_{\text{contact}} \cdot \rho_{\text{probe}} \cdot \cos \alpha}{2} (R_{\text{PS}} + R_{\text{PS}}^2) \right)
\]

However, since \( R_{\text{PS}} = R_{\text{PT}} - H_{\text{probe} \cdot \text{tana}} \), \( Q_{\text{total}} \) becomes;

\[
Q_{\text{total}} = \frac{2}{3} \pi \cdot \omega \cdot \tau_{\text{contact}} \cdot R_{\text{shoulder}}^3 \left( R_{\text{shoulder}}^3 - R_{\text{PS}}^3 + \frac{3}{4} \cdot \frac{H_{\text{probe} \cdot \text{tana}}}{\cos \alpha} \left( 2 \cdot R_{\text{PT}} - H_{\text{probe} \cdot \text{tana}} \right)^2 \right)
\]

If requested, the energy input per unit length of the weld can be achieved by dividing (6) by the transverse velocity as [9];

\[
Q_{\text{energy/length}} = \frac{2}{3} \cdot \frac{\omega \cdot F_P}{\tau_{\text{shoulder}}} \left( R_{\text{shoulder}}^3 - R_{\text{PS}}^3 + \frac{3}{4} \cdot \frac{H_{\text{probe} \cdot \text{tana}}}{\cos \alpha} \left( 2 \cdot R_{\text{PT}} - H_{\text{probe} \cdot \text{tana}} \right)^2 \right)
\]

For a cylindrical pin, since \( R_{\text{PS}} = R_{\text{PT}} \), \( Q_{\text{total}} \) becomes simplified as follow [9];

\[
Q_{\text{total}} = \frac{2}{3} \cdot \pi \cdot \omega \cdot \tau_{\text{contact}} \cdot (R_{\text{shoulder}}^3 + 3 \cdot H_{\text{probe} \cdot \text{R}_{\text{PS}}}) \quad (8)
\]

B. Numerical Approach
1. Estimation of the Heat Transfer
When estimating heat transfer in the plate, (9) was based on finite element analysis;

\[
\rho C \frac{dT}{dt} + \rho C \nabla \cdot (u \nabla T) = \nabla \cdot (-k \nabla T) + Q
\]

where \( T \) is heat, \( t \) is time, \( u \) is unit vector, \( \rho, k \) and \( C \) are material parameters which represents respectively density, thermal conductivity and specific heat capacity. When fixing the coordinate system to the welding tool, (9) becomes (10) includes a convective term in addition to the conductive term, as follows [10];

\[
\nabla \cdot (-k \nabla T) = \mathbf{Q} - \rho C u \cdot \nabla T
\]

The following definition explains the boundary conditions in order to obtain heat generation between the plates, pin and the shoulder [10];

\[
Q(r, T) = \begin{cases} 
\left( \frac{F_a}{A_s} \right) \omega r; & T < T_{\text{melt}} \\
0; & T \geq T_{\text{melt}} 
\end{cases}
\]

where \( F_a \) is the nominal force, \( A_s \) is the shoulder surface area, \( T_{\text{melt}} \) is Kevlar®’s melting temperature, \( \mu \) is Kevlar®’s friction coefficient, \( \omega \) is the angular velocity, \( r \) is the pin radius.

2. Estimation of the Torque
The required torque input for the fully stick condition was estimated following the discussion by [11]. Reynolds divided the total torque into three parts as follows [12];

\[
M = M_{\text{shoulder}} + M_{\text{pin surface}} + M_{\text{pin bottom}}
\]

\[
M = \int_0^{\alpha} \int_0^{2\pi r_2 \pi r_2} + \int_0^{\alpha} \int_0^{2\pi r_2 \pi r_2} + r_1 \int_2 \pi r_1 h
\]

where \( r_1 \) is the pin radius, \( r_0 \) is the shoulder radius, \( \tau \) is the shear stress and \( h \) is the pin length. When we take \( \sigma = \frac{\tau}{\sqrt{3}} \), where \( \sigma \) presents the shear strength, the equation becomes [12];

\[
M = \frac{2\pi \sigma r_1^2 h}{\sqrt{3}} + \frac{2\pi \sigma r_1^2 h}{\sqrt{3}} + \frac{2\pi \sigma r_1^2 h}{\sqrt{3}}
\]

Equation (13) was obtained in accordance with a straight pin approach, but if the tapered part of the pin extends to the pin tip, then we can acquire 90% of the torque from (13) [13]. For this reason, we used this equation in order to estimate the torque.

Fig. 21 illustrates the dimensions of the pin used in our study where \( R_{\text{PS}} \) is the pin bottom radius, \( R_{\text{PT}} \) is the pin tip radius, \( H_{\text{probe}} \) is the pin length and \( R_{\text{shoulder}} \) is the shoulder radius;
The dimension of the pin used in our study: a) The pin length ($H_{probe} = 35\,\text{mm}$), b) The shoulder diameter ($R_{shoulder} = 7.5\,\text{mm}$), c) The pin bottom diameter ($R_{PS} = 3\,\text{mm}$, the diameter is accepted 6 mm), d) The pin tip diameter ($R_{Pt} = 1.6\,\text{mm}$)

$$\sigma = 3600 \times 10^3 \,\text{Pa}, \, R_{PS} = 0.003 \,\text{m}, \, R_{shoulder} = 0.0075 \,\text{m}, \, H_{probe} = 0.0035 \,\text{m}$$

was taken and the torque was estimated as follows:

$$M = \frac{2\pi}{3} \left[ \frac{R_{shoulder}^2 r^2}{2} + \int_{0}^{R_{PS}} r^2 \,dr + R_{PS}^2 H_{probe} \right] = 5.7 \,\text{Nm}$$

3. Estimation of the Plunge Force

In order to produce a Kevlar® plate from some Kevlar® fabrics, as seen in Fig. 22, the fabrics were pressed at 165°C temperature and 6 bar in 10 minutes. Fig. 23 illustrates the produced plates which have 150 mm x 250 mm x 4 mm dimensions.

The required plunge force during pressing Kevlar® fabrics is also used as a reference in order to estimate the plunge force for the plates. As seen below calculation, $P$ is the applied plunge force and it was calculated as follows:

$$P = 6 \text{bar} = 6 \times 10^5 \,\text{Pa}, \, A_p = 0.15 \times 0.25 \,\text{m}^2$$

$$P = \frac{F}{A_p} = 6 \times 10^5 = \frac{F}{0.15 \times 0.25} \Rightarrow F = 2250 \,\text{N}$$

According to a literature research, the plunge force is declared as a force which is applied to the workpiece by the milling machine and expressed as in (14) as follows [14]:

$$F \equiv 6\pi R_{shoulder}^2 \tau$$

Calculating the plunge force according to this equation we obtain:

$$F = 6\pi (0.0075)^2 \frac{3600 \times 10^3}{\sqrt{3}} = 2203 \,\text{N}$$

It can be seen that this value is approximately closed to the required plunge force value during pressing of Kevlar® fabrics (2250 N).

4. Estimation of Friction Coefficient

As reported by an experimental research, the friction coefficient ($\mu$) of Kevlar® for the static condition is calculated between 0.36-0.51 [15]. In this study, it was estimated theoretically as follows:

$$\mu = \frac{M}{Fx \, R_{shoulder}} = \frac{5.7}{2203 \times 0.0075} = 0.34$$

which is close to the experimental values ranging from 0.36 to 0.51 thus, $\mu = 0.35$ was accepted.

5. Estimation of Non-Newtonian Fluid

In a non-Newtonian fluid, the ratio between the local shear stress and the local shear rate cannot be calculated via Newton’s laws. In this condition, the fluid is not a fixed scaler, but a variable and viscosity can change when under force to either more liquid or more solid. For instance; ketchup, cream, toothpaste, blood and shampoo are non-Newtonian fluids.

In this study, Carreau model we also used Carreau model was assumed in CFD analysis. The main reason for nonlinear viscosity is the existence of high and low strain rates together around the pin and the boundary of the TMAZ [16]. Fig. 24 shows the classification of non-Newtonian fluids [17].

Based on the flow behavior index, $n$ [17]:

i. If $0 < n < 1$; the fluid shows pseudoplastic or shear thinning behavior. A smaller $n$ value means a greater degree of shear thinning.

ii. If $n = 1$; Newtonian behavior.

iii. If $1 < n$; the fluid shows dilatant or shear thickening. Comparing to pseudoplastic behavior, an increase in the fluid viscosity with an increase in the shear rate. A greater $n$ means a greater degree of shear thickening.
Fig. 24 The general types of non-Newtonian fluids and their stress-strain behavior

Carreau model is defined by;

$$
\mu = \mu_{\infty} + (\mu_0 - \mu_{\infty}) \left[ \frac{1 + \left( \frac{\dot{\gamma} \lambda \exp \left( \frac{T - T_0}{T} \right)}{T} \right)^n}{1 + \left( \frac{\dot{\gamma}}{\dot{\gamma}_c} \right)^{n-1}} \right]^{-\frac{n}{n-1}}
$$

(15)

where \( \mu_{\infty} \) is the infinite shear viscosity (kg/ms), \( \mu_0 \) is the zero shear viscosity (kg/ms), \( \dot{\gamma} \) is the shear strain rate (1/s), \( \lambda \) is the time constant, \( T \) is the melting temperature (K), \( T_0 \) is the reference temperature (K), \( n \) is the power law non-Newtonian fluid index.

In this study, the constants were found to be [18]-[20].

\( \mu_0 = 10^4 \) kg/ms, \( \mu_{\infty} = 0 \), \( \dot{\gamma} = 0.1 \) 1/s , \( \lambda = 10 \), \( T = 441 \) K (168 °C), \( T_0 = 298 \) K (25 °C), \( n = 0.2 \)

Hence, \( \mu \) was calculated as:

$$
\mu = \mu_{\infty} + (\mu_0 - \mu_{\infty}) \left[ 1 + \left( \frac{0.1\times10^3\times\exp \left( \frac{298}{441} \right)}{0.1} \right)^{9.1} \right]^{-\frac{9.1}{9.1-1}} = 0 + (10^4 - 0)\times \left[ 1 + \left( \frac{0.1\times10^3\times\exp \left( \frac{298}{441} \right)}{0.1} \right) \right]^{-\frac{9.1}{9.1-1}} = 5.32\times10^3 \text{ kg/ms}
$$

V. ANALYZING COMPUTATIONAL FLUID DYNAMICS (CFD) OF THE MODEL

The Finite Element Analysis (FEA) of the FSW system was performed by using COMSOL Multiphysics. CFD and Heat Transfer modules were employed together in a multiphysics setting. The geometry was defined as a 200 mm x 200 mm x 4 mm thick block in Fig. 25. Tip of the pin was defined as a taper shape and back of it was defined as a pillbox, as seen in Fig. 26.

Non-Newtonian Carreau model was adopted for the solution as seen in Fig. 27. The displacement of the Kevlar® material was modelled as a viscous flow. In Fig. 28, rotation of the pin was modelled as a sliding wall. Heat generated by the pin rotation was modelled as boundary sources on the shoulder and on the pin surface. Meshing has been made via tetrahedral meshing. Mesh on all domains consisted of 156154 elements with an average quality of 0.6617, which was fair enough, as seen in Fig. 29.

Calculations were performed for two parameters: \( u_{\text{weld}} \), the travelling velocity and \( w \), the rotational velocity of the pin. Required \( u_{\text{weld}} \) and \( w \) values were calculated to be respectively 80 mm/min and 300 rpm in 5 seconds. Velocity maps for two different parameter set are represented in Figs. 30 and 31. Here the translational velocity is subtracted.

It is not readily seen from the two images above whether the desired mixing was achieved. In order to do that we needed a picture which shows velocity vectors. A full circular motion is expected around the pin. Any vortex like field at either side of the pin reveals absence of the desired mixing condition. Below two figures for two set of parameters one of which exhibits a clear vortex in Fig. 32 which does not appear in the other one as given in Fig. 33.
Fig. 27 Non-Newtonian Carreau model setting in COMSOL

Fig. 28 Pin velocity and rotation setting in COMSOL

Fig. 29 Mesh structure used for the solution

Fig. 30 Velocity map for $u_{\text{weld}} = 100 \text{ mm/min}$ and $w = 400 \text{ rpm}$

Fig. 31 Velocity map for $u_{\text{weld}} = 200 \text{ mm/min}$ and $w = 400 \text{ rpm}$

Fig. 32 Velocity vectors for $u_{\text{weld}} = 200 \text{ mm/min}$ and $w = 400 \text{ rpm}$

Fig. 30 Velocity map for $u_{\text{weld}} = 100 \text{ mm/min}$ and $w = 400 \text{ rpm}$
Uniform distribution of the shear rate can be another clue for determining the mixing condition as seen in Figs. 34 and 35. Table IV shows all the parameters which were calculated. It can be seen that for welding velocities above 100 mm/min mixing does not occur. Rotation velocity must be high enough to facilitate the mixing however there is a compromise between mixing and overheating which can be elevated for increased rotational speeds.

Thus, the translational velocity must not be too high to prevent the mixing. But on the other hand, in case the welding velocity is very low this will cause overheating of the sample and will burn it. In order to check this, temperature map of the system was also calculated. It is required not to exceed 170°C. An isothermal surface map around the pin for a certain set of parameters can be seen in Fig. 36.

VI. EXPERIMENTAL PROCEDURES

A. Setup

In order to perform friction stir processing (FSP), Smart XL6036 horizontal knee-type milling machine was used, as seen Fig. 37.

To check the temperature and investigate the thermal situation during FSP, FLIR T450sc thermal camera was used, as seen in Fig. 38.
Fig. 38 FLIR T450sc thermal camera

Fig. 39 illustrates the setup of the milling machine and the name of the parts used in FSP.

![Setup of milling machine and parts](image)

**B. Friction Stir Processing and Results**

1. Processing Without Joint

In this section, during all process, only one plate was tried to weld in order to investigate the weldability of the Kevlar® plate as seen in Fig. 39. Due to the fact that COMSOL could not create any solution over 500 N plunge force, the plunge force was ignored during analysis.

As seen in Fig. 40, welding was processed at 1800 rpm and 65 mm/min, respectively, rotation speed and welding speed.

![Processing at 1800 rpm and 65 mm/min](image)

After 168°C, the temperature went up to max 328°C and then some imperfections, cluster pulp burning (like volcanic eruption) were occurred, as seen in Fig. 41.

![Welding results at 1800 rpm and 65 mm/min](image)

As seen in Fig. 42 welding was processed at 720 rpm and 65 mm/min.

![Processing at 720 rpm and 65 mm/min](image)

After reaching 165°C, the temperature quickly rises to 391°C and cluster pulp burning and spattering were observed (pulp burning was started at 213°C) and the temperature went up to max 481°C. Then, again some imperfections such as cluster pulp burning, spatter and lack of fusion were occurred, as seen in Fig. 43.

![Welding results at 720 rpm and 65 mm/min](image)

As seen in Fig. 44, welding was processed at 390 rpm and 100 mm/min.

![Welding results at 390 rpm and 100 mm/min](image)
Fig. 44 Processing at 390 rpm and 100 mm/min, welding was started at 83°C (a) and reached to 165°C (b) in 6 seconds.

After 165°C, some pulp burning was started at 288°C and reached at max 298°C, again some imperfections like cluster pulp burning, spatter and lack of fusion were occurred, as seen in Fig. 45.

Fig. 45 Welding results at 390 rpm and 100 mm/min; (a) Pulp burning and spatter, (b) Max reached temperature and again cluster pulp burning and spatter, (c) Imperfections such as lack of fusion, staple fiber deformation and cluster pulp burning.

2. Processing on a Lap Joint

As seen in Fig. 46 welding was processed at 1800 rpm, 65 mm/min on a lap joint. The thickness of one plate was approximately 2 mm and totally ~4 mm. At 168°C, pulp burning was occurred, as seen in Fig. 46 (b).

After reaching at 166°C, in a short time, the temperature was escalated to max 354°C and then, more cluster pulp burning was observed as seen in Fig. 47 (a). Fig. 47 (c) illustrates that throughout the joint line, the upper plate was sheared and as seen (d), on the surface of lower part, only deformation was observed.

Fig. 47 Welding results at 1800 rpm, 65 mm/min on a lap joint; (a) At max 354°C, more cluster pulp burning, (b) During welding, the position of the lap joint, (c) On the upper plate, lack of fusion throughout the joint line, (d) On the lower plate, no fusion, only deformation was observed.

3. Processing on a Butt Joint

As seen in Fig. 48 (c), welding was processed at 1800 rpm, 100 mm/min on a butt joint. Two 4 mm thick plates were used. After processing, no fusion was observed, only edge burning and staple fiber deformation were occurred as seen in Fig. 48 (d).

As seen in Fig. 49 (c), welding was processed at 720 rpm,
65 mm/min on a butt joint. Two 4 mm thick plates were used. After processing, no fusion was observed; only staple fiber deformation was occurred as seen in Fig. 49 (d).

Consequently, as seen in Fig. 50, Kevlar® material losses weight in large amount after 200°C [21]. Due to the weight loss from both the fiber and the resin-, the void volume of the composite increases and the shear stress is affected negatively because of this change. Aramid is very tough allowing significant energy absorption but, compared to carbon, it is lower in compressive strength and has poorer adhesion to the matrix. Twaron CT 736 PHF Kevlar® product contains phenolic resin and it chars when heated to temperature greater than 250°C. The thermal conductivity of the phenolic resin is lower in compressive strength and has poorer adhesion to the matrix. Twaron CT 736 PHF Kevlar® product contains phenolic resin and it chars when heated to temperature greater than 250°C. The thermal conductivity of the phenolic resin is 451 W/mK and it is too high compared to that of Kevlar® (0.04 W/mK).

Due to above results, during welding process, when heated to temperature greater than 250°C, many imperfections such as cluster pulp burning, lack of fusion, spatter and staple fiber deformation were observed.

VII. CONCLUSION

Thanks to its light weight, ability to absorb large impact energies and its good ballistic protection including stab and knife resistance, Kevlar® is a widely preferred material in aerospace and defense industry. According to the technical guide of Kevlar®, it neither burns nor melts, however, over long periods of time at elevated temperatures (exceeding 250°C), it can suffer degradation, which in this study, were observed in form of cluster and/or pulp burning, edge burning and spattering.

For the complex shapes designed by modern industries especially in automotive and aerospace industries, two or more layers of Kevlar® are needed to bond together. As a general rule, synthetic fabrics such as polyester, nylon or polyamide can be welded using electromagnetic waves, but Kevlar® cannot be welded with FSW and via using a tapered circular with 3 flats pin, as it does not melt and there is immediate weight reduction. It can be suggested that during the manufacturing process of Kevlar®, the thermal conductivity of the resin should be selected closer to Kevlar® and by this way, the resin could protect the fibers and keep them together during the welding process.

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