An experimental investigation of the effect of tool rotational speed on the force, torque and mechanical behaviour of friction stir welded PVC sheets

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Abstract: In this investigation, an attempt has been made to join the polyvinyl chloride (PVC) sheet of 3mm thickness with a taper cylindrical pin tool. They are butt welded under different weld parameters by Friction Stir Welding. This study is focused on the effect of tool rotational speed on the force, torque and mechanical behaviour of friction stir welded polyvinyl chloride sheets. The welding parameters are the tool rotational speed; varied between 1500 and 1800 RPM and the traverse speed; varied between 0.3 and 0.7 (mm/sec) with a constant tilt angle of 1°. It is observed that the spindle torque is first increasing then decreasing with increasing tool rotational speed whereas in some cases the spindle torque is also found to decrease with increase in traverse speed. Z-force is found to reduce as the tool rotation speed increases. With a change in traverse speed inconsistent variation of Z-force is observed causing disturbed material flow and weld irregularities. Minimum micro-voids and blisters are observed in Scanning Electron Micrographs of the nugget zone of the specimen welded at 1600 RPM and 0.3 mm/sec traverse speed. The specimen with least micro-voids also exhibits highest ultimate tensile strength.

Keywords: PVC, Z-force, Torque, Taper Cylindrical, UTS.

1. Introduction

In the year 1991, The Welding Institute first introduced Friction stir welding (FSW) which is a solid-state welding process capable of producing high-quality welds [1]. Initially, FSW was proposed for welding soft metallic materials such as aluminium alloys which are strenuous to weld by the conventional techniques. Presently it is being used for the purpose of joining non-metallic material as plastic. On the basis of wide application in industry its demand is very high. Several authors have reported its effectiveness for welding of different lightweight materials especially aluminium alloys and characterised the process parameters like traverse speed, rotational speed and the tilt angle in respect to final weld quality [2-4]. In the year 1997, this joining technique was applied to plastic [5]. FSW has emerged as a new technique for joining of different thermoplastic materials since the last few decades. Thermoplastic polymers have huge applications in the present industry because they offer excellent physical and corrosion properties [6]. FSW has proven to be an efficient technique to achieve successful welding of various similar and dissimilar thermoplastics like acrylonitrile butadiene styrene (ABS), polymethyl methacrylate (PMMA), polypropylene (PP), polyvinyl chloride (PVC), polyamide (Nylon, PA), polycarbonate (PC), polyethylene (PE), polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE) and polymer composites.

FSW tool consists of a shoulder and pin. The rotating tool rubs against the workpiece and the friction between tool and workpiece causing the heat generation. FSW process is accomplished by plunging a rotating tool pin into the workpiece (into the line where two surface of the plate to weld meets) followed by the advancement of the tool along the line to be joined. Due to the solid-state nature of
this process, it aids in the preservation of material properties and also reduces greenhouse gas emission [7]. Figure 1 shows a typical schematic diagram of FSW.

Strand et al. [8] claimed that due to the different chain lengths and molecular weights in polymers, Friction Stir Welding of polymeric materials is not a pure solid-state process. During the welding of polymers, the shorter chains might attain melting temperature, but in the case of longer chains, the required temperature might not be achieved. Inaniwa et al. [9] in their study regarding the weldability evaluation for PVC observed a reduction in nugget zone hardness for all welding and an increase in tensile properties with decreasing revolution pitch. They also observed most of the voids formed at the retreating side where fracture initiated. During the welding of ABS and PE with different tool pin profile Givi et al. [10, 11] concluded that compared to the other pin profiles, cylindrical pin tool exhibits better result in terms of mechanical properties. However in case of welding of PP, Jaiganesh et al. [12] observed that the tapered cylindrical tool produced best welded joint.

Figure 1. Schematic representation of friction stir welding.

2. Experimental procedure

In the present investigation, rigid polyvinyl chloride (PVC) sheet was used as the parent material. The mechanical and physical properties of PVC are listed in Table 1. FSW on PVC specimens with dimension of 100×60×3 mm (length×width×depth) was carried out for butt joint configuration. Welding of PVC sheets were conducted on a 3T Friction Stir Welding machine.

The FSW tool was made from HCHCr steel (HSN 7228). The tool has a shoulder diameter of 12 mm, pin diameter of 2.5 mm and pin length of 2.6 mm (figure 2).

| Properties                      | Value          |
|---------------------------------|----------------|
| Tensile strength                | 65MPa          |
| Hardness                        | 16 HV          |
| Thermal conductivity            | 0.16-0.17 W/m k|
| Glass transition temperature    | 87℃            |
| Melting temperature             | 200-220℃       |
In this study, the welding parameters were selected after performing several trial experiments. After evaluating the range of process parameters welding was performed in various parametric combination. All the experiments were performed with 1° tilt angle. The traverse speed (TS) and tool rotation varied from 0.3, 0.5, 0.7 mm/sec and 1500, 1600, 1800 RPM respectively.

The Scanning Electron Microscope (SEM) was used for investigation of the cross-section weld joint microstructure. The effects of the process parameters on weld stir zone formation were investigated.

For evaluation of the strength of the welded joints, the tensile test was carried out on Instron machine at a constant crosshead speed of 0.5 mm/min at room temperature. The tensile samples were prepared according to the ASTM D638-14 standard. For each parametric setting, three samples were considered for tensile tests and the average value is reported.

![FSW tool with Taper cylindrical (TC) pin.](image)

**Figure 2.** FSW tool with Taper cylindrical (TC) pin.

3. Result and discussion

3.1. Variation of spindle torque

Spindle torque is the response of a solid state material upon deformation applied by the tool. From figure 4 it is observed that initially with the increase in rotational speed, spindle torque increases and with further increase in rotational speed, spindle torque decreases. The initial increase in spindle torque may be due to the increased slip condition which reduces heat input. At higher rotational speed i.e. at 1800 RPM; material gets more softened with the increase in frictional heat input thereby causing
suitable material flow felicitating easy movement of the tool. Also here it can be seen that spindle torque is decreasing with increased traverse speed. Though the heat input decreases with increase in traverse speed since the material is a polymer (comparatively softer), the friction between the tool–workpiece interface is less. So it can be said that the decrease in spindle torque may be occurring due to improved material flow.

![Graph](image)

**Figure 4.** Variation of spindle torque with rotational speed.

### 3.2. Variation of Z-force

Axial force (Z-Force) is the response of the tool to the deformed material which helps it to consolidate the material behind the tool. The variation of axial force (Z-force) with different rotational speed and with different traverse speed is shown in figure 5. It is well established in the literature that the axial force is a function of the welding parameter [4]. It can be seen from figure 5 that at 1500 RPM Z-force variation is irregular and higher due to insufficient heat generation, because of inadequate friction between tool and workpiece. But with the increase in rotational speed at 1600 RPM showing comparatively smoother appearance, because the heat input increases with increase in rotational speed causing more material deformation and getting better with wider bandwidth depicting a less viscous state of material and better flow. With further increase at 1800 RPM, Weld surface gets severely deteriorated due to lack of sufficient available mass of material during welding as soft material carried away from the welded zone due to higher rotational speed (figure 3(c)).
Figure 5. Z-Force during welding: (a) 0.3 mm/sec traverse speed, (b) 0.5 mm/sec traverse speed, (c) 0.7 mm/sec traverse speed.
At high travel speed, i.e. 0.7 mm/sec the variation of axial force is found to be inconsistent for all tool rotational speed. This may be due to the reason that at high traverse speed less material deformation is taking place thereby causing an irregular material flow which further causes slip and obstruction to the movement of the tool. However, a decreasing trend of axial force is observed at the higher rotational speed of 1800 RPM.

3.3. Morphological analysis of welded joint

In the present investigation, the effects of the parameters on the weld quality were studied. For examining the effect of tool traverse speed and tool rotational speed on the weld microstructure, the SEM images of the weld cross-section of the prepared samples with the rotational speed of 1500, 1600 and 1800 rpm with traverse speed of 0.3 mm/sec are shown in the figure 6. It is observed that the weld structure is regular and uniform at 1600 rpm. It is also seen to be comparatively free from defects such as voids, blisters and splits perhaps due to the achievement of balanced heat input.

In addition, at high rotational speed, the material flow becomes turbulent resulting defects in the welded joint. It can be seen that blisters and micro-voids are present in the weld joint especially at higher rotational speed due to more heat generation and turbulent flow of the polymer under the tool shoulder. The joint formed with low rotational speed shows a significant material loss, chip formation, lack of fusion due to lack of heat at the weld zone (figure. 3(a)).

3.4. Tensile properties

The effect of the traverse speed and tool rotational speed on the joint strength is shown in figure 7. According to the resulting tool for the combination of medium tool rotational speed and lower traverse speed (1600 RPM, 0.3 mm/sec) considering the present study shows an increased value of tensile strength and joint efficiency (27.86MPa, 43 %). From SEM image (figure. 6(b)) it can be seen that the specimen welded with rotational speed of 1600 RPM and 0.3 mm/sec traverse speed is defect free. The defect free morphology suggests well mixing of two PVC sheets at the weld joint which results in high UST. Whereas with an increase in traverse speed a gradual reduction in the UTS value is observed because of the lack of sufficient time to make soft material flow below the tool, that results in defects in the welding zone. Similar joint efficiency for welding of PVC was obtained by Inaniwa et al. [9]. It also can be observed that at 1800 RPM the variation in UTS value is not very significant due to excessive welding heat input.
Figure 7. Variation of ultimate tensile strength values for different rotational speeds and traverse speeds.

4. Conclusions

1. Spindle torque first increases then decreases with an increase in rotational speed of the tool. Also, it is observed that a spindle torque decrease with increase in traverse speed, which may be due to better material flow has been achieved for less traverse speed.

2. Z-force decreases with an increase in rotational speed of the tool. At lower rotational speed less material deformation is taking place due to less heat input, thereby causing an irregular material flow. This results in inconsistent variation of Z force with the change in traverse speed. However, at higher rotational speed Z force decreases with an increase in traverse speed.

3. The SEM analysis reveals the presence of less micro-voids and less blisters formation in the welding zone for the samples having higher Ultimate Tensile Strength. At 1600 RPM and 0.3 mm/sec traverse speed better material flow and proper material mixing takes place resulting in better mechanical property in terms of Ultimate Tensile Strength.

4. At 1500 RPM rotational speed the ultimate strength reduces with increase in traverse speed because of low heat generation. As traverse speed increases the tool-workpiece interaction time becomes less resulting in low heat generation and less softening of the material and improper mixing of material at weld line. But at 1600 RPM rotational speed heat generation in the tool – work interface is more which assist good mixing of material and better mechanical properties of the welded joint.

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