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# FRICTION STIR WELDING OF NYLON -6: EFFECT OF PROCESS PARAMETERS ON MECHANICAL AND MICROSTRUCTURAL PROPERTIES

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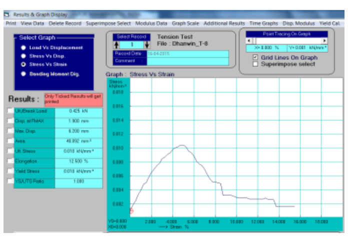
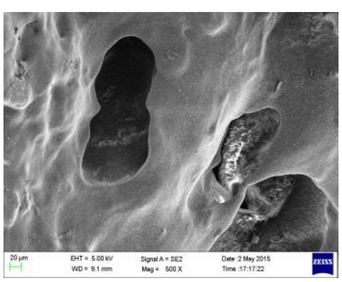
**Graphical abstract**





**Abstract**

Friction stir welding (FSW) is solid state joining process with more advantages than that of fusion welding. Nylon -6 is one of the engineering plastics used widely in various industrial applications. The main aim of this research work is to investigate the effect of tool rotational speed and tool traversing speed on the mechanical and microstructural properties of the nylon-6 butt welded joints made by FSW. The FSW process was performed in a computer numerically controlled (CNC) vertical milling machine using a cylindrical tool with threaded pin made of heat treated high carbon high chromium (HCHCr) steel. The tensile testing and microscopic examinations were carried out to study the mechanical and microstructural properties of the welded joints. In visual inspection, it is observed that the excessive flashes are observed on either sides of the weld line in all cases. From the results, it is observed that the maximum tensile properties are achieved in a joint made which is approximately 18% and 26% of the parent material's ultimate tensile strength (UTS) and yield strength (YS) respectively with the tool rotational speed 1200 rpm and the tool traversing speed of 30 mm/min within the experimented process parameters. Overall, the tensile properties of the welded joints made using the experimented process parameters are very much lower than the parent material.

*Keywords*: Friction stir welding, nylon-6, process parameters, mechanical properties, microstructural properties



## 1.0 INTRODUCTION

The Friction Stir Welding, an innovative joining technology [1], was developed and patented by Thomas *et al*. of The Welding Institute (TWI), United Kingdom in 1991. In FSW, the materials to be joined are not 'melted' but 'plasticized' by the heat generated by the friction developed between the rotating tool and the workpiece material and the plasticized material is stirred for thorough mixing to form a defect free welded joint. FSW can avoid or restrict the solidification problem that are encountered in fusion welding and also produces a defect free welded joint with good properties even in those materials which are inappropriate for fusion welding [2]. FSW process has wider applications in automobile, aeronautics, aerospace and marine industries.

Nylon-6 is one of the most widely used engineering thermoplastics. This Polymer is an excellent replacement for a wide range of different materials like metals and rubber due to its toughness, lighter weight, low coefficient of friction and abrasive resistance properties. It has limitations in usage because of high water/moisture absorption characteristics and poor chemical resistance to strong acids and bases.

In the past, many researchers have performed investigation on FSW of similar or dissimilar metals like Magnesium alloys [1,2] Aluminium alloys[3],Steel[4], Titanium alloy[5,6], Composite [7], Titanium and Steel [8] and Al alloy and Metal matrix composite [9] etc. But, very few researchers have carried out FSW of polymeric materials [10-20] and investigated the performance of the process. Simões and Rodrigues [10] performed FSW of Polymethyl methacrylate (PMMA) and analysed for the material flow in polymers. It was concluded from the study that the formation of important discontinuities, at the retreating side of the welds, is one of the main weldability problems for polymers.

Mendes *et al*. [11, 12] studied the influence of tool rotational and traversing speeds and axial force on the FSW quality on the Acrylonitrile butadiene styrene [ABS]. It was found that the welded joints with high strength efficiency and strain at break were achieved at higher tool rotational speed and high axial force. Also, it was observed that the appearance of good weld crown when sufficient heat is supplied during welding process [11]. Welds made using robot were compared with the welds performed in a conventional FSW machine for the joint characteristics [12] and observed similar or slightly better mechanical properties than the welds made by conventional method.

Bilici [13] investigated the effects of tool geometry on the friction stir spot welding (FSSW) of polypropylene (PP) sheets. Four different tool pin profiles such as straight cylindrical, tapered cylindrical, threaded cylindrical and square shape were used for fabrication of the welded joints. It was concluded from the investigation that the highest tensile strength was obtained with the cylindrical threaded pin and the tool geometry affects the stir zone formation and weld lap-shear fracture load. Taguchi's approach was used to study the effect of welding process parameters on the welded joint strength by Lenin *et al*. [14]. It was evaluated that the following percentage contribution of the process parameters for obtaining the best welded joints: 50% tool pin profile, 25% tool traversing speed and 18% tool rotational speed.

Jaiganesh *et al*. [15] performed FSW of high density polypropylene (HDPP) with the aim to optimize the process parameters for the quality welded joint formation. From experiments, it was observed that a superior weld was made with the tool rotational speed of 950 to 1000 RPM, feed rate of 9 to 12 mm/min and tilt angle of $1^0$. Erica Anna Squeo *et al*. [16] examined the effect of tool profile and process parameters on the FSW of polyethylene (PE) sheets with the additional heat supplied to tool pin and the sheets. It was found that the additional heating made the process more robust and provided better joint characteristics.

Shayan Eslami *et al*. [17] conducted friction stir lap welding of dissimilar plastics,Polyethylene and Polypropylene sheets, using a specially designed stationery shoulder tool to study the effects of process parameters on the weld quality. It was concluded that the welded joints made under the same parameters that is used for welding of metals did not show a good reproducibility. Ethiraj *et al*. [18] carried out FSW of nylon-6 to investigate the mechanical and microstructural properties of the joints at different tool rotational speeds. From the results, it was noted that better mechanical and microstructural properties were obtained at a rotational speed of 1200 RPM when the tool traversing speed was kept constant at 30 mm/min. Imad M. Husain *et al*. [19] carried out the process on nylon-66 to find the optimum process parameters to produce a joint with good mechanical properties. It was stated from the experimental results that the mechanical properties of the joints are very much less than the base material. Friction stir spot welding of Polycarbonate sheets were performed by Paoletti *et al*. [20] to explore the influence of process parameters on the quality of the welds produced. It was concluded that the mechanical strength is mainly influenced by the plunge rate, rotational speed and dwell time.

From the literature survey, it is observed that lot of difficulties are encountered in FSW of polymers when compared with the metals. Also, it is noted that very extensive work have been carried out in metals rather than polymers and hence there is a need for exploring more information regarding FSW of polymers. The objective of this paper is to investigate the effect of process parameters on the mechanical and microstructural properties of friction stir welded nylon-6 butt joints. The expected outcome of this research work may reveal the friction stir weldability characteristics of nylon-6. The important methodology used for this work includes performing the FSW, studying the effect of tool rotational speed and tool traversing speed on weld quality by tensile testing and microstructural analysis

# 2.0 METHODOLOGY

## 2.1 Material and Methods

The nylon -6 sheets are supplied by M/s Kadi Enterprises, Chennai. In this experimentation, butt FSW of the Nylon-6 plastic sheets with the dimension 105 X 75 X 6 mm was carried out in the CNC Vertical Milling Machine. The tensile testing of the nylon-6 raw material was carried out in Central Institute of Plastic Engineering & Technology (CIPET), Ministry of Chemicals & Fertilizers, Government of India. The test result for the mechanical properties of the Nylon-6 sheet material is mentioned in the Table 1.

**Table 1** Mechanical Properties of Nylon-6 sheet material

| S.No. | Property | Value |
|---|---|---|
| 1 | Ultimate Tensile Strength (UTS) | 55.7 MPa |
| 2 | Yield Strength (YS) | 38 MPa |
| 3 | % Elongation | 19.3 |

## 2.2 Tool Material and Parameters

Type : Cylindrical tool with Threaded Pin
Material : HCHCr
Supplier : M/s. Madras Steels & Tubes, Chennai
Hardness : 60-62 HRc
Overall Length : 100 mm
Shoulder Diameter : 16 mm
Pin Diameter : 8 mm
Pin Length : 5.8 mm

## 2.3 Process Parameters Used

Tool Rotational Speeds:
600, 800, 1000 and 1200 RPM
Tool Traversing Speeds:
18, 21, 24, 27 and 30 mm/min
Tilt Angle of the tool : 0°

The nylon-6 sheets were cut to the above mentioned dimensions, cleaned to remove dirt, grease etc. and clamped firmly on the machine table. One set of FSW experiments were conducted by varying the tool rotational speed and other by varying the tool traversing speed while keeping the other parameters constant. Trial experiments were conducted to identify the tool rotational speed at which the successful welding is performed.

Firstly, the tool rotational speed is kept at 1000 rpm, welding was performed by keeping the tool traversing speeds at 18, 21, 24, 27, 30 mm/min. Initially the welded joints are visually inspected for any external defects. Similar procedure was followed for the welded joints made by keeping the tool rotational speeds at 600, 800, 1000 and 1200 rpm while maintaining a constant tool traversing speed of 30 mm/min. Four replicates of experiments were carried out for each test parameters settings. The experimental setup for friction stir welding is shown in Figure 1.

The welded joints are investigated for mechanical and microstructural properties. For mechanical testing, the specimens are cut at right angle to the direction of welding as per the ASTM D638 standard in the electrical discharge machine (EDM) or water jet cutting machine. The gauge length of 60mm is marked on the cut specimens for measuring the strain. The stress and strain values were obtained directly from the data acquisition system of computerized tensile testing machine.

**Figure 1** FSW Experimental Setup

The fractured sample specimens after the tensile testing are shown in the Figure 2.

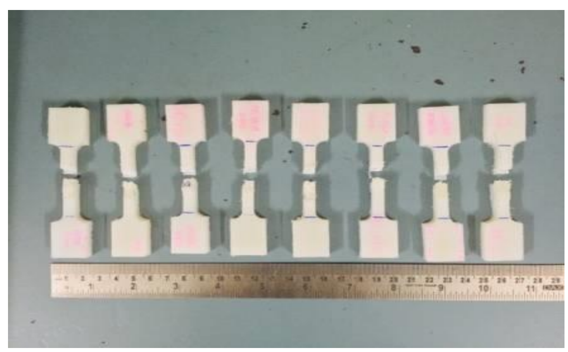


**Figure 2** Sample of Fractured Specimens after Tensile Testing

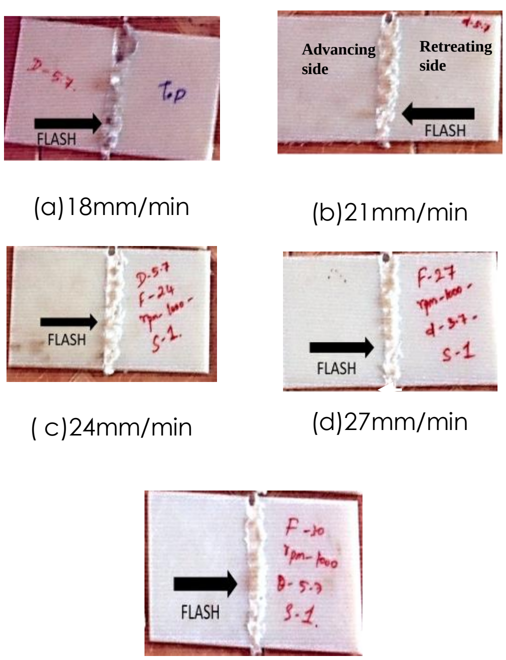
To study the microstructural properties of the welded joints, scanning electron microscopic (SEM) images were taken in the welded regions.

# 3.0 RESULTS AND DISCUSSION

Friction stir welding of nylon-6 plates are successfully performed at different tool traversing speeds and tool rotational speeds. The friction stir welded joints made using different tool traversing speeds at constant tool rotational speed and different tool rotational speeds at constant tool traversing speed are shown in Figure

3. The visual inspection of the welded joints revealed that the surface of the welded joint is very rough and excessive flashes are observed on either side of the weld line. The occurrence of excessive flashes may be due to the excessive flow of plasticized materials under the shoulder surface. Also, the heat generated on the top surface of the weld nugget is more than the bottom surface due to the additional friction developed by the rotating shoulder which plasticizes the material further more. This plasticized material is splashed out of the surface due to the rotation of the tool thus forming the flashes on either side of the weld line.

The appearance of excessive flash in the joints made at different tool traversing speeds remains the same. Also, small grooves are observed on one side of the weld joint made at a rotational speed of 600 rpm at constant tool traversing speed of 30 mm/min. This may be due to the fact that the lower rotational speed generates less frictional heat which is insufficient to plasticize the material and mix them properly. When the tool rotational speed was increased from 800 rpm to 1200 rpm, the quality of the weld surface has improved due to the proper mixing and restricted flow of plasticized material under the shoulder surface.

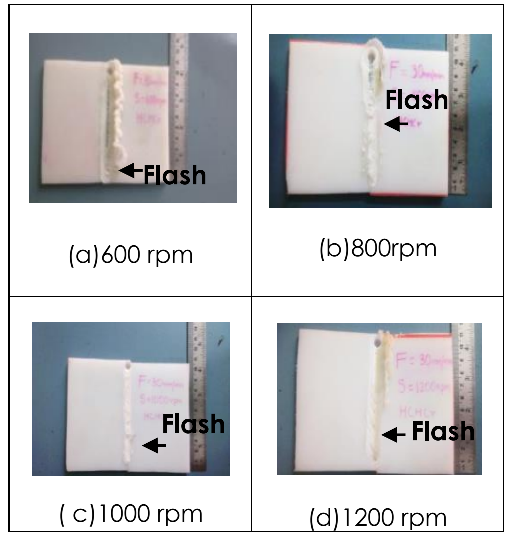



(a)18mm/min (b)21mm/min

( c)24mm/min (d)27mm/min

(e)30mm/min

**(i)**



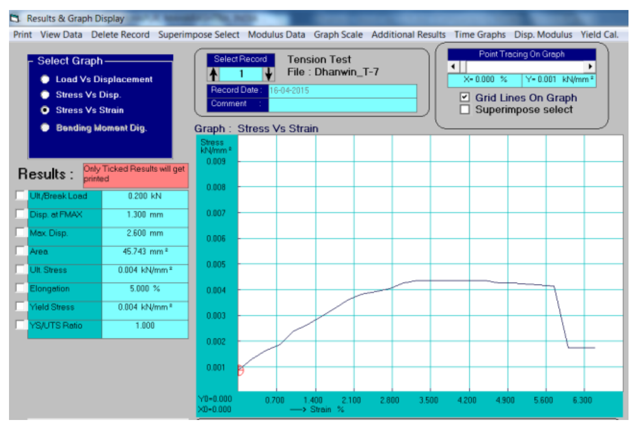

(a)600 rpm (b)800rpm

( c)1000 rpm (d)1200 rpm

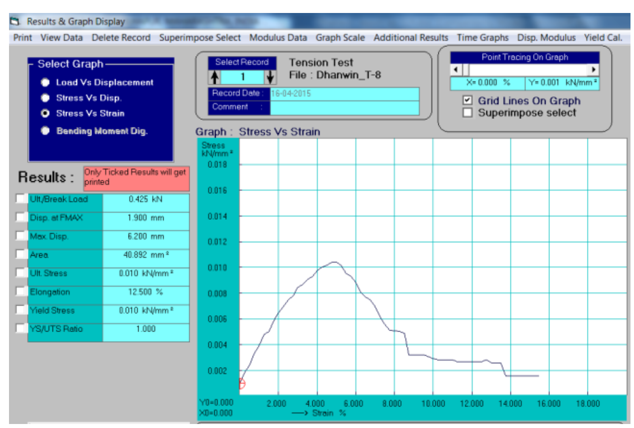
**(ii)**

**Figure 3** Friction Stir Welded Joints at (i) Different Tool Traversing Speeds (ii) Different Tool Rotational Speeds

The two sample stress strain curves, one for constant tool rotational speed and other for constant tool traversing speed, for the welded joints made are shown in Figure 4.




**(a)**




**(b)**

**Figure 4** Stress-Strain curve of the welded joint made at (a) tool rotational speed of 1000rpm and tool traversing speed of 21mm/min; (b) at tool rotational speed of 1200rpm and tool traversing speed of 30mm/min

The mechanical properties such as yield strength, ultimate tensile strength and percentage elongation of the friction stir welded joints fabricated using different tool traversing speeds and different tool rotational speeds while keeping other parameters constant are shown in Figure 5(a) and (b) respectively. It is observed from the values obtained that the ratio between the yield strength and the ultimate tensile strength is unity in all cases. This indicates that once the material starts yielding, the stress required for further yielding remains constant until the fracture occurs as seen in the Figure 4(a).

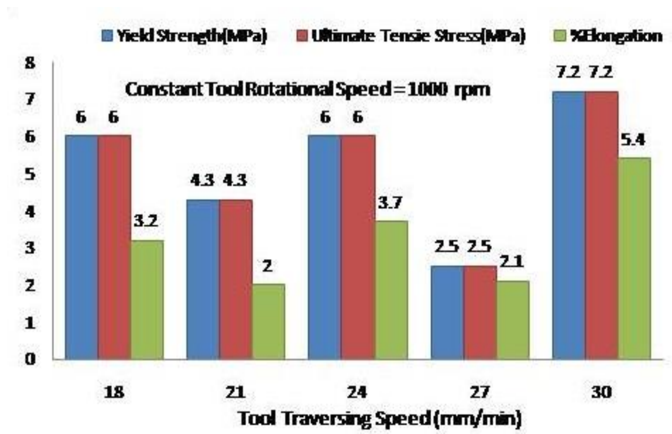
It is seen from the Figure 5(a) and (b) that the values obtained are summarized as follows:

The joints made at different tool traversing speeds exhibit (i) minimum yield strength of 6.6% to maximum of 19% of parent material(Mean=5.2; Standard Deviation(SD)=1.83); (ii) minimum ultimate strength of 4.5% to 13% of parent material(Mean=5.2; SD =1.83); and (iii) % elongation ranging from 10.4% to 28% of the parent material (Mean=3.28; SD =1.39). Whereas, the joints made at different tool rotational speeds exhibit (i) minimum yield strength of 10.5% to maximum of 26.3% of base material(Mean=6.25; SD =2.87); (ii) minimum ultimate strength of 7.2% to 18% of base material(Mean=6.25; SD =2.87); and (iii) % elongation ranging from 25.9% to 64.8% of the base material(Mean=8.13; SD =3.15). The reasons for such low values of mechanical properties are attributed to the following reasons: (a) the frictional heat generated is insufficient to plasticize the material and improper mixing due to the stirring action of the pin; and (b) more rapid moisture absorbing characteristics of Nylon-6 and the moisture acts as a plasticizer which reduces the tensile strength. Since there is no pre heating was done on raw material, there is a possibility of absorbing the moisture from atmosphere by nylon 6 during storage and handling

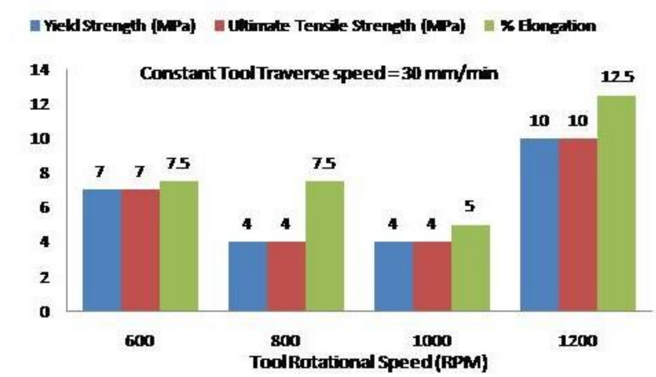
The tool rotational speed is the most significant parameter influencing the weld quality. Increasing the tool rotational speed from 800 to 1200 rpm increases the tensile strength of the welded joint due to the higher frictional heat generation and proper mixing of material by the stirring action of the rotating pin. But In general, it is very difficult to establish the exact relation of tensile properties with the tool rotational speed. It may be due to the non homogeneity of the plates welded. This is similar to the results obtained by Mendes *et al.* [12] incase of friction stir welding of ABS.

Whereas, the values of the tensile properties fluctuate when increasing the tool traversing speed. In general, lower traversing speed generates more heat which is sufficient for proper mixing. Also, lower traversing speed provides sufficient time for proper mixing and homogenization[19]. From Figure 5(a) and (b), it is observed that the value of tensile properties fluctuate incase of constant tool rotational speed and constant tool traversing speed. It may be due to the non homogeneity and direction of flow lines of the samples used. Accurate prediction of relation between the tensile properties with the tool rotational speed and tool traversing speed is complex and needs further study. The ratio of rotational / traversing speed more than 10 was recommended for good welded joint in case of FSW of ABS by Mendes *et al*. [11].

The joints made with the ratio less than 10 fractured by the hand force itself. Too much of increase in rotational speed and decrease in traversing speed may increase enormous amount of frictional heat generation leading to the burning of the material. Also, the excessive tool rotational speed will separate the plasticized material from the parent material which reduces the thickness of the plate at the weld zone and hence reduces the tensile properties of the welded joints. Higher traversing speed spill the plasticized material out of the weld area due to the higher tangential force by the rotating tool on the material and reduces the thickness of the plate in the welded region. The appearance of excessive flash on either side of the weld line, shown in Figure 3, shows that the material is separated from the weld area and hence the reduction of thickness in the weld region



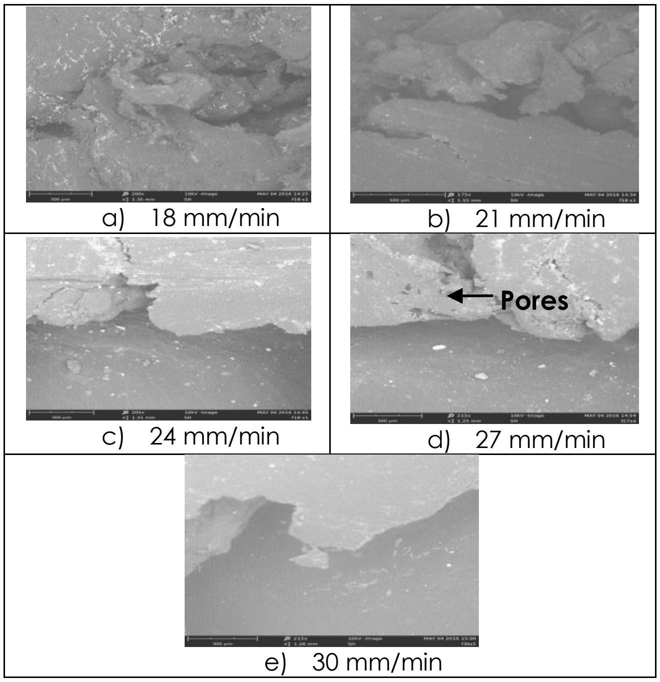

(a)



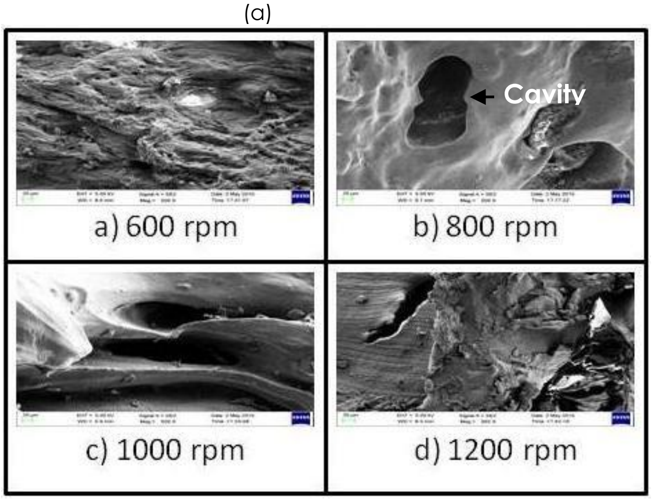

(b)

**Figure 5** Mechanical Properties of Welded Joints Produced at (a) different traversing speeds; (b) different Rotational speeds

The scanning electron microscopic (SEM) images of the welded joints made at different process parameters are shown in Figure 6. The microstructures reveal the presence of pores and cavities in most of the joints made. This may be due to the fact that the heat generated is not sufficient enough to help the proper bonding. Also, in the stir zone, an asymmetrical material flow may cause the cavities to form i.e., the material flow may not be uniform in advancing side and retreating side. The cavities may also be formed due to the different thermal shrinkage occurring in the top and bottom of the weld surface and due to the presence of entrapped air. The presence of cavities is also responsible for the decrease in mechanical properties of the joints made when compared with the parent material.




(a)




(b)

**Figure 6** SEM Images of the welded joints made at (a) different traversing speeds; (b) different rotational speeds

## 4.0 CONCLUSION

The friction stir welding of nylon-6 plates were made successfully at different tool rotational and traversing speeds while other parameters are kept constant. Based on the above results and discussion, the following conclusions can be drawn accordingly:

(1) Excessive flashes are observed on both sides of the weld line due to the flow of plasticized material under the shoulder surface.

(2) The weld surface is very rough at lower tool rotational speed and improved as the speed is increased.

(3) The Ultimate Tensile Strength, Yield Strength and percentage elongation of the welded joints are very much lower than the parent material in all experimented process parameters. The welded joint produced at the tool rotational speed of 1200 rpm and 30 mm/min tool traversing speed has maximum tensile properties within the experimented values. The maximum Ultimate Tensile Strength and Yield Strength of the welded joint is approximately 18% and 26% respectively of the parent material. The maximum percentage elongation is approximately 65% of the base material.

4) The SEM images reveal the presence of cavities and discontinuities in most of the joints made which reduced the tensile properties of the weld.

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