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Loadability of Friction Stir Welded joints of High Density Polyethylene

Ebtisam F. Abdel-Gwad [1], Abu-Bakr M. Omar[2] and Ahmed H. Radwan[3]

ABSTRACT

Development of effective welding methods for thermoplastics is still in high demand. The new friction stir welding method will be applied here on high density polyethylene (HDPE) plates to provide the designer with reliable design data relevant to room temperature practical applications because welded joints can act as a failure initiation point. This may be a result of factors such as poor welding parameters and presence of weld defects. The combination effect of travel and rotational speeds of the welding tool is investigated. Tensile, impact and fatigue tests are applied on the HDPE welded joints in order to evaluate their loadability. The tool rotational speed, travel speed and tilt angle beside tool pin length are proved determined to be important in the joint formation quality and its mechanical properties. Optimum welding parameters of 930 rpm rotation speed at 25mm/min travel speed are determined in tensile, impact and fatigue testing. An optimum value of about 90% joint efficiency is achieved in tensile test, compared to the base material. In impact and fatigue tests, brittle failure due to presence of incomplete root penetration defect, takes place like a crack starter. Maximum impact strength of about 20 KJ/m^2 and fatigue life of 710 cycles are recorded and found to be too low compared to the base material. The final results indicate that friction stir welding of HDPE thermoplastics may be a valid alternative to the conventional joining techniques after elimination of the weld root defect.

KEYWORDS: - Friction stir welding, High density polyethylene, Tensile, impact and fatigue testing

1. INTRODUCTION

Modern thermoplastic materials such as polyethylene are used in an expanding range of engineering applications due to their stronger joints, high stress-to-weight ratio, flexibility, resistant to weather, abrasion and to chemicals. High Density Polyethylene (HDPE) belongs to thermoplastic polymers with the general formula CH_2 and low molecular weight. It has a good chemical resistance against almost all acids and bases, detergents and hot water. HDPE has good insulation properties and is easy to weld. The permeability of HDPE to water and inorganic bases is very low. HDPE is brittle and breaks at low strain without neck development. Nowadays, the majority of water pipes installed around the world are made from HDPE. Fabrication of larger and complex parts usually requires alternative joining technologies other than conventional welding processes [1-3].

Friction stir welding (FSW) is a new solid state welding technique. It is a patented process with a very simple basic concept in which a non-consumable rotating tool with pin and shoulder is plunged into edges of the mating plates. The pin traverses along the line of joint and the shoulder touch the plates' surface. Due to friction, the tool softens the edges and stirs them from a side to the other.

[1] *Professor, Production Engineering and Mechanical Design Department, Faculty of Engineering, Port Said University, Port Said, Egypt, E-mail: Ebtisam1953@yahoo.com*
[2] *Teacher, Mechanical Department, Faculty of Engineering, Suez Canal University, Ismailia, Egypt, E-mail:*
abubakr31869@yahoo.com
[3] *Mechanical Department, Faculty of Engineering, Suez Canal University, Ismailia, Egypt, E-mail:*

Localized heating softens mating material around the pin and the combination of the pin rotation and translation results in producing the welded joint [4]. FSW began to be applied on aluminium and magnesium alloys [5-17]. Recently, some researchers have studied application of FSW to thermoplastics [18-23]. In present work, the authors aim to investigate loadability of HDPE plates welded using the FSW process under combination of rotating and travel speeds. Evaluation of welded joints includes tensile, impact and fatigue tests.

2. EXPREMENTAL WORK

2.1. Material

High density polyethylene plate (HDPE) of 0.95 gm/cm^3 and 4 mm thickness is used. The plate is cut into rectangular samples of 200 mm length by 100 mm width. Typical mechanical properties of the as received HDPE are listed in Table 1.

Table 1: Characteristics of HDPE

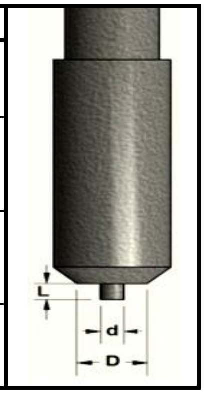
Fatigue life (cycle)	Impact strength (kJ/m^2)	Tensile strength (MPa)	Yield strength (MPa)
No failure up to 10^4	130	22	20.5

2.2. Tool geometry and dimensions

Preliminary experiments are carried out during the present investigation for proper choice of both pin shape and tilt angle. A thread and a smooth cylindrical pin are investigated. The welding tool of a smooth cylindrical pin shown in Table 2 indicated higher tensile values and is chosen and used in all welding experiments. Tool tilt angle also is investigated at angles 0° and 1°.

Table 2: Welding Tool shape and dimensions

Parameters		Dimensions
Pin length	L (mm)	3.8
Pin diameter	d (mm)	4
shoulder diameter	D (mm)	16
Tool ratio	D/d	4



Preliminary experiments results, as shown in fig.1, indicate that tool tilt angle of 1° is better than atilt angle 0°. A tilt angle of 1° is used in all experiments. This is in good agreement with previous results [24-26].

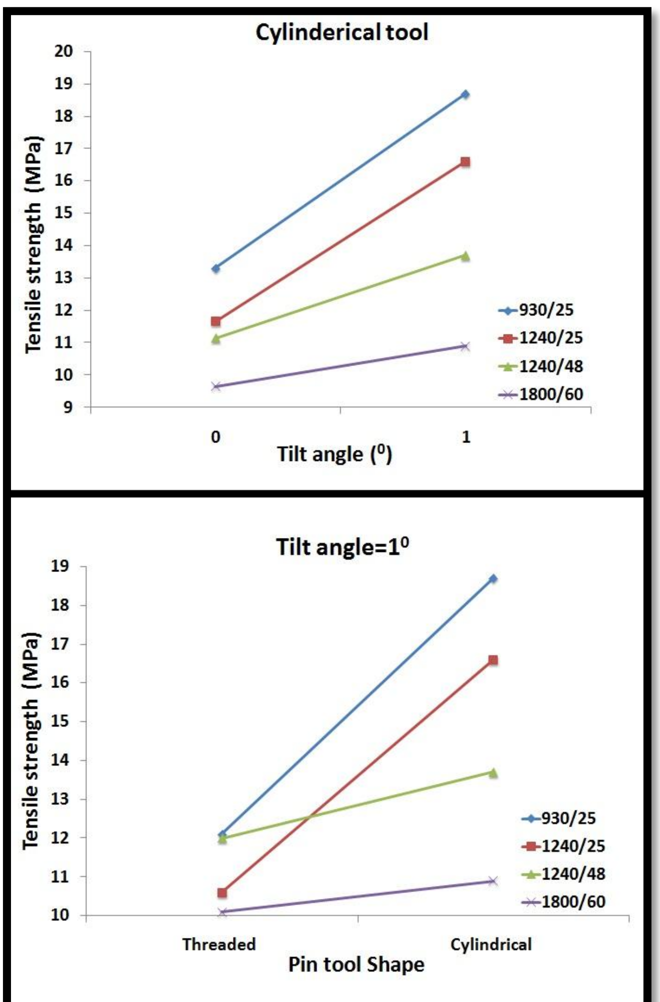


Fig. 1: Tilt angle and pin tool shape versus tensile strength

2.3. Friction stir welded process

FSW is performed on HDPE samples by a mill using the cylindrical smooth tool. A minor modification is made to the mill in preparation for FSW experiments. The modification is to replace the mill's vice with a rigid fixture used before [27] and shown in Fig. 2. This fixture provides a stiff backing against which the tool could apply forging pressure and securely hold the HDPE plates together during the welding process.

Fig. 2: Rigid fixture

Fig. 3: Friction stir welding operation

After clamping the test plates in the fixture in a butt joint configuration, the rotating tool pin is inserted into the butt line. Tap plates are used to start and finish welds on them, to ensure homogenous weld lines. The welding tool is driven downward until tool shoulder face contacts the surface of test plates, then the tool is traversed along the joint line until weld is completed. The welding operation is presented in Fig. 3. Welding parameters' levels are selected to represent a wide range of possibilities and performance for rotation speed (580, 930, 1240 and 1800 rpm) and travel speed (14, 25, 39 and 48 mm/min) at the predetermined pin tilt angle 1°.

3. TESTING PROGRAM

After welding, 3 standard test specimens at the same conditions for tensile, charpy-impact, and cantilever reciprocating bending fatigue tests are extracted perpendicular to weld centreline of the welded test coupons. Cutting plan of these test specimens is illustrated in Fig. 4.

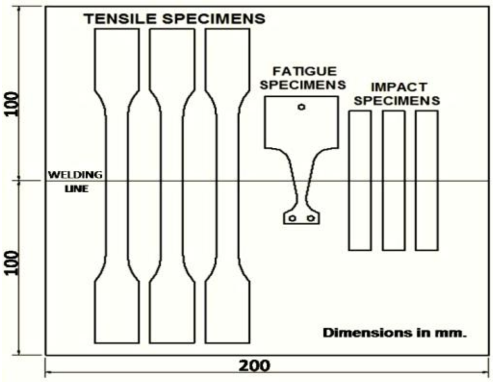


Fig. 4: Cutting plan of test specimens

3.1. Tensile test

Tensile tests are conducted to determine are ultimate tensile strength of the HDPE joints welded at the predetermined welding parameters. The standard (ISO 3167) smooth tensile specimen [28] is shown in Fig. 5. Tensile tests are carried out at room temperature at a cross head speeds of 20 mm/min. Mean value of three specimens in each condition are used for evaluation.

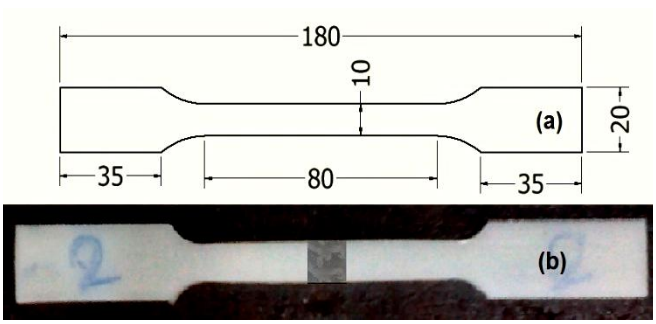


Fig. 5: Tensile specimen
(a) Standard in (mm) (b) Extracted from welded joint

3.2. Impact testing

Charpy impact tests are carried out using the JB-5 pendulum impact testing machine shown in Fig .6 at room temperature to simulate the intended used environment. The standard unnotched specimen is broken by the impact of a heavy pendulum hammer falling through a fixed distance to strike the specimen at a fixed velocity.

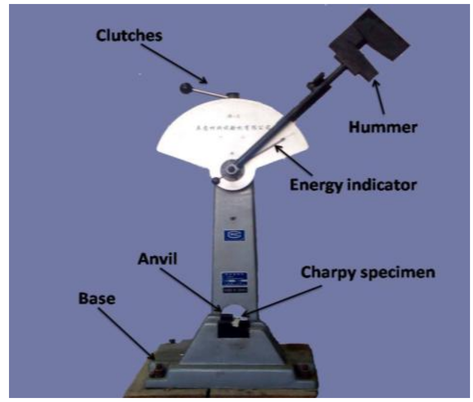
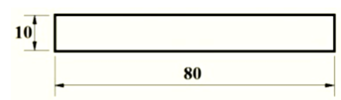


Fig. 6: Impact-testing machine

Unnotched test specimens shown in Table 3 are used in present work. The specimen is supported as a simple beam at (62 mm) by two anvils and the swinging pendulum strikes behind the edgewise side of test specimen according to the standard specification [29].

Table 3: Impact test specimens

Standard	Impact specimen (mm)	Direction of impact
ISO 179/1eU		(edgewise), e = 4

Impact strength measures the energy absorbed by high strain rate fracture divided by cross section area. Mean value of three specimens in each condition are used for evaluation.

3.3. Fatigue testing

Fatigue tests are conducted on the reciprocal fatigue bending machine shown in Fig. 7 at a loading repetition speed of (34 cycles /min) and room temperature.

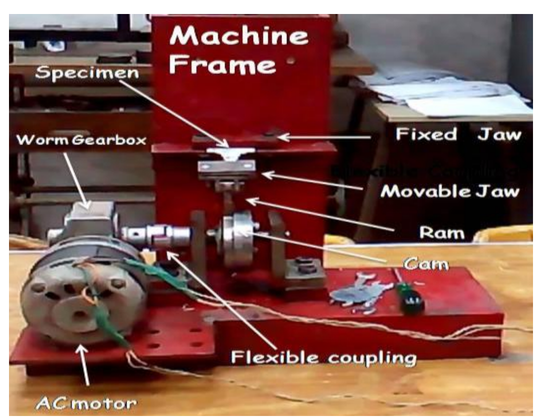


Fig. 7: Reciprocating fatigue bending testing machine

The reversed applied stress (σ_r) = 15.65 MPa, which provided by the constant beam deflection (δ) = 15mm is shown in Fig. 8. The standard cantilever fatigue taper specimen design shown in Fig. 9 (ASTM D671 Type B) used in present investigation, allows a constant stress along the specimen surface.

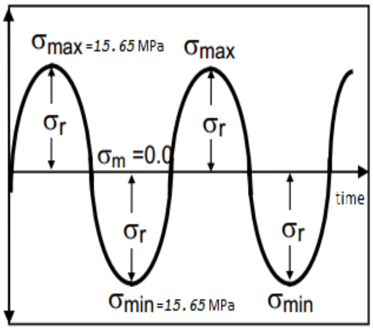


Fig. 8: Reversed applied stress

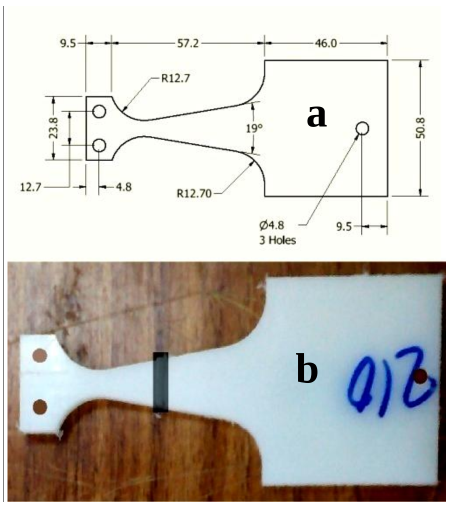


Fig. 9: Fatigue specimen [30]
(a) Standard in (mm) (b) Extracted from welded joint

Calculation of constant stress (σ_r), applied during the fatigue testing on standard cantilever flat taper plate specimen is described in equation (1) and in Fig .10, as a function of plate thickness (t) and beam deflection (δ):

$$\sigma_r = \frac{\delta t E}{L^2} \qquad (1)$$

where:
Young's modulus (E) of HDPE = 1 GPa
Specimen thickness (t) = 4 mm
Length of tapered cantilever (L) = 61.9 mm
Beam deflection (δ) = 15 mm

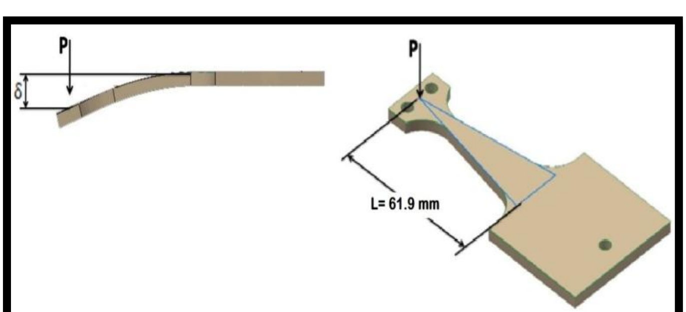


Fig. 10: Design of fatigue taper cantilever specimen [31]

4. RESULTS AND DISCUSSION

Table 4 summarizes mechanical properties results of all tests at the applied welding parameters. Tensile testing expressed as tensile strength and joint efficiency, charpy impact testing as impact strength, while reciprocating bending fatigue as number of cycles to failure.

Table 4: Summery of mechanical testing results

Rotating speed (rpm)	Travel speed (mm/min)	Tensile strength (Mpa)	% Joint efficiency (strength of joint / strength of base material)	Impact strength (kJ/m^2)	No. of cycles
580	14	11	50	11.84	460
	25	16	73	16.38	608
	39	14	64	15.72	527
	48	12	54.5	12.35	116
930	14	13	59	14.13	402
	25	19	89.5	19.5	710
	39	17	77	17.36	664
	48	14	64	14.83	510
1240	14	9	41	10.24	42
	25	17	77	16.6	618
	39	15	68	15.8	575
	48	13	59	13.67	279
1800	14	4	18	7.5	13
	25	10	45.5	11.03	82
	39	9.5	43	10.78	72
	48	9	41	10.44	61

4.1. Tensile testing

Tensile strength is the main characteristic property considered in the present investigation at static tension loading. Testing results described quantitatively success of FSW and influence of each welding parameter on the tensile strength of welded joints.

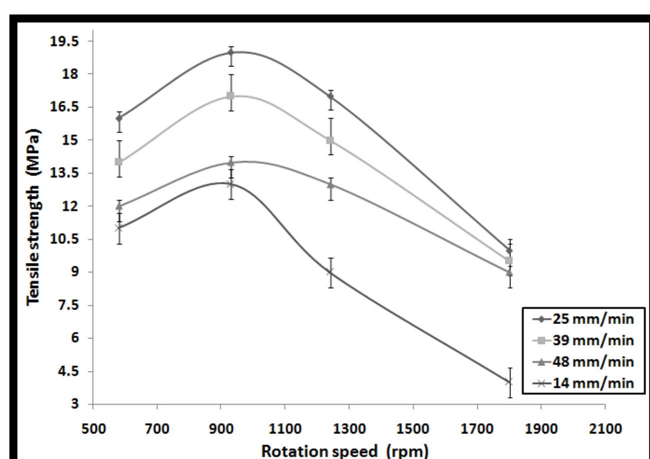


Fig. 11: Effect of rotation speed on tensile strength at different travel speeds

Fig. 11 shows that both rotation speed and welding speed play dominant role in FSW process. It can be realized that when the rotational speed increases from 580 to 930 rpm, the tensile strength and joint efficiency increase; however, further increases in the rotational speed resulted in a decrease in the tensile strength and joint efficiency. One of the key factors in the FSW of polyethylene sheets is the generation of enough heat to soften the polymer. The machine's rotational speed is the parameter that determines the level of heat generation. At low rotational speeds, insufficient heat is created and thus the polymer does not soften enough to mix and make a strong weld at interfaces of the butt joint. At very high rotational speeds, the flow of softened polymer is excessive and thus, instead of being mixed and squeezed into sides of the weld seam, the softened polymer is ejected from butt joint as seen in Fig. 12. A moderate rotational speed of 930 rpm seems to be a good compromise between generating enough heat and excessive flow of softened polymer.

Fig. 12: High rotation speed caused ejection of polymer

Also, decreasing travel speed generally results in increasing tensile strength for all rotation speeds. An increase in travel speed from 25 to 39 and 48 mm/min causes the tensile strength to decrease, but the welding speed 14 mm/min has lowest tensile strength because of the large deformations expected in the polymer that result in a weak weld zone. At high travel speed of 48 mm/min, the process has insufficient time to heat up the polymer to bring about flow of softened material. It is also observed that at high travel speeds, the rotating tool removes polymer from side to side instead of joining it, and the process resembles milling rather than welding. Shape of weld seam under the tool shoulder is affected by reducing the travel speed and is shown in Fig. 13. Maximum strength and joint efficiency approximated to 19 MPa and 89.5 % respectively, are recorded using rotation speed of 930 rpm at a travel speed of 25 mm/min. This seams is good agreement with pervious work [26]. Minimum strength and joint efficiency approximated to 4 MPa and 18 %, respectively, are recorded using rotation speed 1800 rpm at a travel speed of 14 mm/min. A travel speed of 25 mm/min is an appropriate travel speed for the welding process.

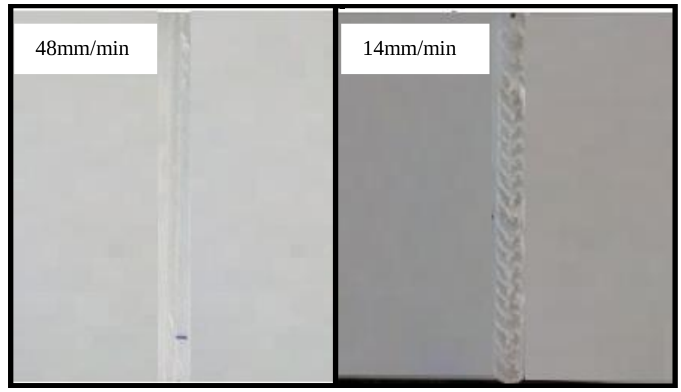


Fig. 13: Effect of travel speed on weld seam (constant rotation speed 1240 rpm)

4.2. Impact behaviour

Sudden loading responses of FSW joints at room temperature are examined and evaluated versus welding parameters involving rotation speed and travel speed as shown in Fig. 14. The total energy dissipated in the HDPE polymeric material up to failure is a measure of its impact strength. Impact strength increases with increasing the tool rotation speed from 580 to 930 rpm and decreases again with further increase in the tool rotation speed 930 to 1800 rpm. That is true for the investigated travel speeds.

Also, impact strength increases with decreasing the travel speed except for minimum travel speed of 14 mm/min. Maximum impact strength of 19.5 KJ/m^2 is recorded at a 25 mm/min travel speed while minimum value of 7.5 KJ/m^2 is recorded at a 14 mm/min travel speed.

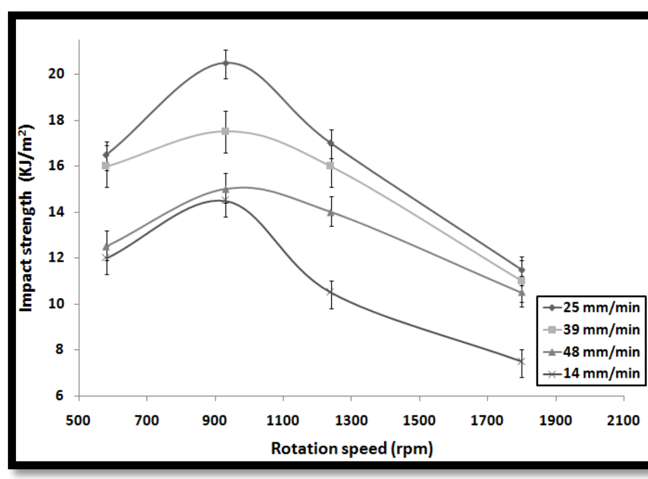


Fig. 14: Effect of rotation speed on impact strength at different travel speeds

The samples welded at the optimum welding parameters of 930 rpm and 25 mm/min exhibit impact strength three times higher than the samples which welded at worst parameters of 1800 rpm and 14 mm/min, although all samples failed in a brittle mode. Maximum impact strength of 19.5 kJ/m^2 is recorded at 930 rpm, lower than that recorded for the HDPE base material 130 kJ/m^2. Optimum FSW parameters are 930 rpm rotation speed and 25 mm/min travel speed, so room temperature impact energy is greatly affected by FSW parameters.

4.3. Fatigue life

HDPE base material records the specified 10^4 cycles without failure during fatigue testing. The specimens welded using FSW with parameters involve the predetermined rotation speeds and travel speeds fail at weld after sustaining the life cycles during fatigue loading shown in Fig. 15. As can be seen, the fatigue life increases with increasing tool rotation speed from 580 to 930 rpm, then decreases again to reach minimum life cycles at tool rotation speed of 1800 rpm. That seems true for all investigated travel speeds except for 14 mm/min.

Maximum fatigue life of 710, 618, 608 and 82 cycles were recorded at travel speed of 25 mm/min with rotation speeds of 930, 1240, 580 and 1800 rpm, respectively, while minimum values of 82, 72, 61 and 13 cycles were recorded at rotation speed of 1800 rpm with the travel speeds 25, 39, 48 and 14 mm/min respectively. Optimum fatigue life of 710 cycles is recorded at a tool a rotation speed of 930 rpm and at a travel speed of 25 mm/min. So, room temperature fatigue life is greatly affected by FSW parameters. In the same time, all welded samples indicated low fatigue life compared to base material. The reasons may be related to the high stress amplitude applied during the fatigue testing (15.65 Mpa) (represented about 71% of the base material tensile strength) together with low frequency [32] during the reciprocal fatigue test.

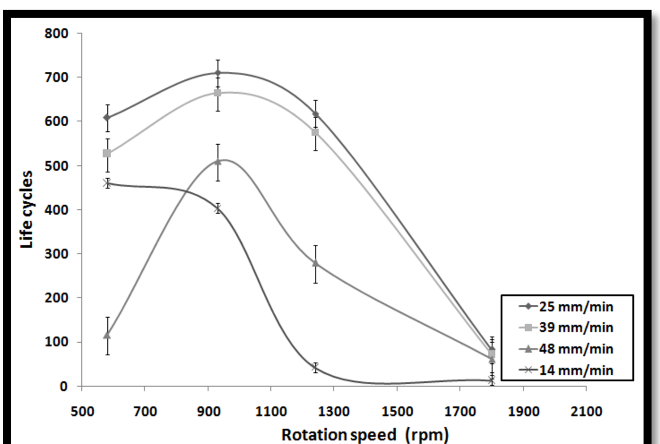


Fig. 15: Effect of rotation speed on fatigue life at different travel speeds

4.4 Effect of tool pin length on mechanical properties

Low results of impact and fatigue life is probably due to incomplete root penetration appeared after FSW as seen in Fig. 16. This causes a crack start during both impact and fatigue testing. Channel backing strip of a “U” shaped bottom is suggested to eliminate such a problem or using a double shoulder welding tool.

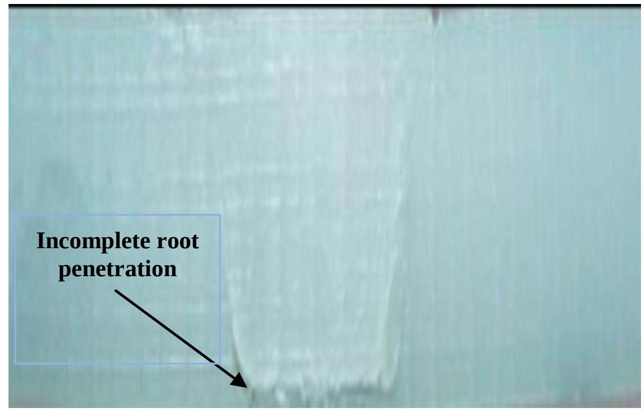


Fig. 16: Incomplete root penetration weld defect

5. CONCLUSIONS

In this research, high density polyethylene plates are joined using the solid state friction stir welding process. The effects of different process parameters including rotational speed, travel speed, pin shape and tilt angle are investigated and correlated to static, impact and dynamic mechanical properties. The main conclusions which can be drawn from this study are as follows:

1. The process parameters have significant effects on the weld mechanical properties.
2. Moderate rotational speed of 930 rpm and travel speed of 25 mm/min exhibit the highest quality of welded joints and highest mechanical properties in tensile, impact and fatigue testing.
3. Highest rotation speed created the lowest mechanical properties.
4. Too low or too high travel speed produced weakest welded joints.
5. Presence of incomplete root penetration defect at weld diminished impact and fatigue properties to a great extent compared to base metal, so a u-shaped channel strip packing must be used in the future to eliminate such problem or using a welding tool with double shoulder.
6. Friction stir welding of thermoplastics may be a valid alternative to the conventional joining techniques, if optimum welding parameters are used.

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