Investigating friction spin welding of thermoplastics in shear joint configuration

Tarun Bindal¹ · Ravindra K. Saxena¹ · Sunil Pandey²

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Abstract

The welding of thermoplastic pipes under a shear joint configuration using friction spin welding is investigated. The shear joint configuration consists of two cylindrical and concentric polypropylene plastic parts joined with each other at their interfacing cylindrical surfaces through frictional heat generation. The effects of welding pressure and rotational velocity on the joint overlap distance and joint strength between the parts of polypropylene plastic are evaluated. The study is of a specific application in making plastic pressure vessels and joining of pipes. The joint strength is tested by conducting the hydraulic pressure burst test. The burst test is conducted for welded specimens manufactured using different values of rotational velocity and welding pressure. It is observed that at the constant spin velocities, the welding pressure in the range 64.8 to 65.2 kPa produced better joint strength than the other values of welding pressure in the overall range 64–76 kPa. It is concluded that the suitable welding pressure range to manufacture polypropylene plastic pressure vessels in the shear joint configuration using friction spin welding is 64.5 to 65.2 kPa. Further, it is established that the user can control the joint overlap distance at 64.8 kPa welding pressure by selectively controlling the rotational velocity in the range of 700 to 2500 rpm.

Keywords Friction spin welding · Thermoplastics · Shear joint · Spin initiate distance · Joint overlap distance · Spin time · Welding pressure · Rotational velocity

1 Introduction

Thermoplastics are easy to shape material, which through the molding process can be easily converted into a wide range of shapes and sizes [1, 2]. Several methods are available to join the thermoplastics, viz. vibration method, implants, radio frequency, and heating method [3–5]. Because of these different variants of joining methods, anything conceivable can be constructed using thermoplastics [6–9]. The fusion of mating surfaces of thermoplastics due to heating and pressure is termed as welding. The welding of thermoplastics may utilize directly applied external heat or heat generated internally through various

means [4, 5]. Figure 1 illustrates the classification of multitudes of thermoplastic welding techniques due to heating.

Mechanical friction welding is categorized into four main categories, viz. friction stir welding, linear friction welding, friction spin welding, and ultrasonic welding. All these four processes rely on relative motion between two parts that are to be joined leading to the generation of frictional heat. The schematic of these mechanical friction welding processes is given in Fig. 2. The difference between these processes is in the configuration of relative motion between the parts, amplitude, and frequency. In the case of friction stir welding, the two parts to be joined are stationary with respect to each other, but a tool rotates

✉ Ravindra K. Saxena, rksaxena04@yahoo.com; Tarun Bindal, tbindal@aquadyne.in; Sunil Pandey, profsunilpandey@gmail.com |

¹Department of Mechanical Engineering, Sant Longowal Institute of Engineering & Technology Longowal, Sangrur 148106, India. ²School of Engineering, Jawaharlal Nehru University (JNU), New Delhi 110067, India.

Fig. 1 Classification of welding techniques for thermoplastics

on their interfacing portion resulting in friction heat generation, melting, and fusing of parts [10, 11]. In the case of linear friction welding, the two parts undergo frictional heat generation using the linear motion with respect to each other, but this process applies to mutually flat surfaces in contact [12, 13]. Ultrasonic welding has been widely used in joining plastic using longitudinal vibrations at a certain high frequency while holding the workpieces together under applied pressure between the horn and anvil; however, the aforesaid application of ultrasonic welding has been limited to only short-length parts due to difficulty of transference of longitudinal vibrations over a long distance. Therefore, to join short pipes torsional vibrations are employed from a circumferential direction using ultrasonic welding [14].

The joining of two thermoplastic parts in axis-symmetric fashion has fewer options to choose from like external heating process followed by pressed fusion of heated surfaces and friction spin welding.

In the case of friction spin welding, the two parts to be joined undergo frictional heat generation due to rotational motion with respect to each other [15]. The two plastic parts to be joined using friction spin welding are gripped in a rotatable fixture and corresponding mating stationary fixture, respectively, as depicted in Fig. 3. The rotary fixture rotates the part and presses the rotating part on to the stationary part. The temperature of the material at the interface is increased due to generated heat from frictional work. Eventually, the material at the interface melts and becomes semifluid under the increased temperature. Interface film and the melt flow out at the perimeters of the interface to form the weld

bead. Finally, the rotation is stopped, and the joined parts can cool and solidify under pressure conditions. Friction spin welding has emerged as a popular method of joining thermoplastic axisymmetric parts due to its fast speed and reliability [15–18].

The friction spin welding process can join both amorphous and semicrystalline thermoplastics. The ABS, PVC, polymethyl methacrylate (PMMA) acrylic, polystyrene (PS), polycarbonate (PC), polysulfone (PS) are common amorphous thermoplastics. Polyethylene (PE), polypropylene (PP), polybutylene terephthalate (PBT), polyethylene terephthalate (PET), and polyetheretherketone (PEEK) are common semicrystalline thermoplastics. The ABS, PVC, polypropylene, polyethylene, and glass-filled nylon can easily be joined through the friction spin welding process. The slippery plastics, such as Delrin or ultra-high molecular weight polyethylene can also be joined through this process after suitable adjustments. Joining of hard plastics such as polycarbonate or acetal by spin welding process requires a higher magnitude of torque to get the materials to melting point by frictional heat generation [16, 18]. Generally, the friction spin welding process is carried out in the vertical orientation. Takasu [19] has demonstrated the friction spin welding machine for welding of thermoplastics in a horizontal orientation for joining pipes in butt joint configuration. The friction spin welding is generally performed in butt joint configuration and does not speak of shear joint configuration [20, 21]. The schematic difference between butt joint and shear joint configuration for friction spin welding is shown in Fig. 4. It is found that there have been no studies with respect to shear joint configuration for friction spin welding of thermoplastics.

Fig. 2 Illustrations of different mechanical friction welding processes

Fig. 3 Schematic of friction spin welding process **Fig. 4** Friction spin welding configuration: **a** butt joint and **b** shear joint

It is anticipated that friction spin welding in shear joint configuration could offer numerous benefits in terms of aesthetics and strength and afford flexibility to innovators in their product designs. There is no experimental work in the shear joint configuration field with respect to the effects of welding pressure and rotational velocity on joint overlap distance and weld joint strength and other possible parameters that could be detrimental to a successful product. The present research is an important milestone in that direction to fulfill the aforesaid gap and to enhance understanding. The present research is of specific applications in fabricating small plastic pressure vessels and joining pipes.

Table 1 Typical properties of polypropylene (PP) (grade: 3120MA)

Properties	Test method	Values
Melt Flow Index (230 °C& 2.16 kg)	ASTM D 1238	12 g/10 min
Density @ 23 °C	ASTM D 1505	0.90 g/cm ³
Tensile strength	ASTM D 638	27.0 MPa

2 Experimentation

2.1 The material of the specimen

The polypropylene (PP) thermoplastic is widely used in industrial processing to manufacture pipes and small plastic pressure vessels. It is light in weight yet possesses high impact strength and reliable heat fusion welding. Therefore, it was selected for making a test joint specimen in this study. The polypropylene (PP) grade: 3120MA of IOCL, Panipat, Haryana, which is a natural colored high impact copolymer, is selected for molding of test joint specimen parts. The properties of the above material are given in Table 1.

2.2 Specimen preparation

The test joint specimen consists of two parts. The dimensions of both the parts of the specimen are given in Fig. 5. The plastic parts are produced using automatic plastic injection molding as it is a reliable and most widely used method to produce the PP plastic parts with

Fig. 5 Schematic and dimensions of the specimen

consistency and high surface finish. The mold inserts used for the plastic injection molding operation to manufacture the specimen are shown in Fig. 6. A preliminary study demonstrated that a small taper on adjoining surfaces will assist the joining process in comparison with the straight surfaces, and therefore, the small taper as indicated in Fig. 5 is provided on the mating surfaces of the rotating and stationary parts.

A study on the diametrical interference was performed to find the required taper on the mating PP parts. The diametrical interference of 0.5, 1.0, 1.5, and 2.0 mm on the plastics parts was investigated. It was found that the joint formation was easier to obtain in case of higher interference, but beyond 1.5 mm the parts were deformed for the given specimen thickness of the plastic parts. The dimensions of the specimen standard were also preliminarily tested before the fixation of the standard for the strength of joints, and the same was found to be suitable for study. The total diametrical interference of about 1.5 ± 0.2 mm was selected for study as the same was found most suitable.

A special precision machined mold inserts with grinding surface finish (Grit No. 200) (surface roughness $0.4 \mu\text{m Ra}$) were manufactured for specimen preparation. These special-purpose mold inserts were fitted inside the mold base housing to produce the designated PP plastic parts through the plastic injection molding machine. The plastic injection molding machine from Ferromatik Milacron of 150-ton clamping pressure capacity was employed. The process parameters used to manufacture the specimen are given in Table 2. The molded plastic parts are degreased by water and kept for drying for a day at the room temperature of 25°C before investigation.

2.3 Burst test setup

The welded joint specimen can be tested for strength through several available tests, viz. internal hydraulic

pressure test, tensile test, peel test, bend test, creep test, and fatigue test, etc. Given the application of such a product the best means of testing the strength of such a pressure vessel is by subjecting it to an internal hydraulic pressure test [22]. This internal hydraulic pressure test is termed as “*Burst Test*” for investigating the weld joint strength. The test is conducted by supplying the pressurized water to the spin-welded specimen at one of its ports through a pressure booster pump with maximum pressure boosting capacity of 1965 ~ 1980 kPa. The setup for the “burst test” is designed for pressure testing up to 1965 kPa given the design and usage requirement of the manufactured parts. The other ports of the welded specimen are connected using a push-fit elbow whose other end is closed by a sealant potting. The pressure dial gauge is connected in parallel to give a pressure reading. A pressure release valve is also connected in parallel to control the applied hydraulic pressure to the welded specimen.

The test is conducted by opening the water supply, switching-on the booster pump motor, keeping the pressure valve open initially, and gradually closing it, thereby increasing the pressure inside the welded specimen. In this manner, the pressure in the specimen is increased to the maximum possible pressure generation capacity of the pump (at present the designed pressure is 1965 kPa). The applied hydraulic pressure is maintained at the designed pressure for 10 s, and thereafter, the pressure is reduced to normal atmospheric pressure. The increase in the hydraulic pressure is monitored through a pressure dial gauge.

The joint behavior under the increasing pressure is video recorded to record the maximum pressure withstood by the specimen, and the value of pressure is recorded in case of joint failure as detailed. It was observed that the specimen inflates under the increasing pressure as depicted in Fig. 5. Many times, it was observed that the specimen showed leakage, or it burst, i.e., separation of the specimen into two pieces, under the increasing hydraulic pressure; all such specimen is termed as "fail." In the case

Fig. 6 Mold insert parts and molded test joint specimen parts

Table 2 Molding process parameters

S. No	Description of parameter	Value/units
1	Average temperature of screw barrel	180 °C
2	Injection pressure	75 bar
3	Injection speed	30 cm ³ /s
4	Cooling time	45 s

of no-failure, this inflation vanishes after the removal of hydraulic pressure, as it was elastic inflation. If the specimen can sustain the applied hydraulic pressure during the time, i.e., it does not leak or burst, the specimen is characterized as “pass” else it is termed to “fail” the burst test.

A term is defined called as “bursting pressure,” i.e., the value of hydraulic pressure at the point of burst (separation of the specimen into pieces) or leakage of liquid under pressure from the welded specimen. Further, a very low value of bursting pressure means that there is a leakage

of liquid under pressure and higher values of bursting pressure mean that the specimen “burst,” i.e., separates into pieces. The schematic diagram of the test apparatus and behavior of the specimen under hydraulic pressure is depicted in Fig. 7.

3 Friction spin welding machine

The welding of plastic parts is a difficult process. The friction spin welding of plastics in the shear joint configuration is required to be explored. In the present work, to perform the friction spin welding in shear joint configuration, a special-purpose friction spin welding machine apparatus is designed and fabricated. The three-dimensional model of the developed “friction spin welding machine” is shown in Fig. 8. The design of this machine was submitted for design registration and is granted the registration by the Indian Patent Office vide registration no. 314315–001 [23].

The machine uses a servo rotary actuator for rotation of the rotary part and a pneumatic linear actuator to provide the axial thrust to the rotary parts for insertion onto the stationary parts. This axial thrust provided to the rotating part is applied in the form of pressure to the spindle of the rotating fixture and termed as “welding pressure.” The stationary part of the specimen is mounted upon the stationary fixture, and the rotary part of the specimen is mounted upon the rotary spindle of the machine apparatus [24].

The control software for this machine is programmed to impart such functionality that when the welding process is initiated the rotary part on the rotary fixture approaches the stationary part. The rotary part while approaching the stationary part starts rotating with a preset rotational velocity at the predefined preset position. This preset position is termed as “spin initiate distance” which is defined as a specified distance from touch down to the stationary fixture at which the rotary part starts rotating. The schematic to demonstrate the “spin initiate distance” is shown

Fig. 7 Schematic diagram of the burst test setup

Fig. 8 Schematic of friction spin welding machine: (1A, 1B): specimen parts; (2) rotary fixture; (3) spindle; (4) linear carriage; (5) servo rotary actuator; (6) pneumatic linear actuator; (7) column; (8) bed; (9) operator console; (10) stationary fixed fixture; (11) pneumatic clamp mechanism; (12) control panel and HMI; (13) FRL unit

in Fig. 9. The aforesaid rotation of the rotary part is preset for a period defined as “spin time” which is controllable to the accuracy. The period is preset to ensure the attainment of the preset rotation from “zero” rotation to the rotary fixture. These are important control parameters for performing welding in a shear joint configuration.

4 Results

4.1 Friction spin welding of a specimen in shear configuration

The specimen is joined in a shear configuration using a friction spin welding machine. During the friction spin welding operation, the rotary part is brought near to the stationary part of the specimen under the specified value of “welding pressure.” The rotation of the rotary fixture is initiated at the “spin initiate distance.” The rotation is set for the duration of “spin time.” The rotary part continues to move toward the stationary part while rotating, and within the spin time, the parts encounter each other under the specified welding pressure. The stationary part begins to insert inside the rotary part causing the generation of frictional heat and plasticization.

The motor (rotary actuator) selected for providing the rotation to the rotary fixture has a maximum torque exertion capacity of 6.36 N-m. Under extreme circumstances, it can exert 300% of the maximum capacity instantaneously but not continuously, and once the torque limit is breached the motion of the motor comes to halt. This value of maximum torque is an assumed value for machine design as per the design and usage requirement of the manufactured parts. The rotation of the rotating part is stopped after the completion of the weld provided or at the limiting value of the torque, i.e., 6.36 N-m. The future scope of work on the advancement of the friction spin welding machine may include the updated machine with enhanced motor power with higher torque capacity and testing thereon for ascertaining the effect on the weld joint and performance of the produced parts. After the completion of the friction spin welding operation, the rotary part comes to halt. Thereafter, the spin-welded specimen can cool down for 5 s before the fixture holding the rotary part is detached and the spin-welded specimen is removed from the machine. The final spin-welded specimen produced using friction spin welding is shown in Fig. 10.

The distance traversed by the rotary part over the stationary part of the component is called “joint overlap distance.” The measurement of “joint overlap distance” is a challenging task after the completion of the friction spin welding operation. During the spin welding operation, the rotary part can slide over the stationary part at the taper portions provided on both the parts at the interface. The remaining exposed length in the stationary part of the test specimen after the spin welding operation is measured to deduce the value for “joint overlap distance” [25]. The schematic for the identification

Fig. 9 Schematic of the specimen before and after friction spin welding

Fig. 10 friction spin-welded specimen

and the measurement of “joint overlap distance” in the welded component is shown in Fig. 9.

4.2 Observations for welding pressure

A set of preliminary tests was conducted to determine the parameters for testing. The initial tests were conducted at welding pressure of 103 kPa, with a *spin initiate distance*

of 9.0 mm. The constant welding pressure of 103 kPa is applied to the rotating spindle to bring the rotating part in contact with the stationary part. These preliminary specimens burst/failed at low hydraulic pressures of 200–275 kPa. It was found that sufficient rotational momentum was not achieved prior to touchdown resulting in premature termination of rotation before the generation of sufficient frictional heat. Therefore, sufficient melting of the joint interface did not take place to fuse the two parts. During the investigation, it was observed that the joint strength for such welded parts is attributable to the elastic deformation due to the insertion of one cylindrical part into another part under applied welding pressure. The investigation at 55 kPa of welding pressure demonstrated the difficulty in the fabrication of joint and premature termination of rotation for the rotating parts before proper insertion over the stationary part. The joint failed under sufficiently low values of hydraulic pressure

Table 3 Preliminary observations from the trial run

S. No	Welding pressure, kPa	Rotational velocity, rpm	Observation	
			Sample-I	Sample-II
1	55.0	1300	Fail	Fail
2	64.8	1300	Pass	Pass
3	66.2	1300	Pass	Pass
4	90.0	1300	Fail	Fail
5	130.0	1300	Fail	Fail

(150 ~ 200 kPa). The observations for the preliminary test are presented in Table 3. Because of the aforesaid preliminary investigations, it is found that the welding pressure in the range 62 kPa to 75.8 kPa will be suitable for obtaining the required joint strength. Therefore, the selected range of welding pressures for the subsequent detailed study is from 64 to 75.8 kPa.

4.3 Observations for spin time and spin initiate distance

Next, a study was performed to find the optimum values of *spin time* and *spin initiate distance*. The study was performed at a welding pressure of 64.8 kPa and a rotational velocity of 1300 rpm. The performance is evaluated for joint overlap distance and bursting pressure. Based on the earlier observations, the study was performed for *spin time* from 1.0 s to 1.2 s and *spin initiate distance* from 9 to 19 mm.

A total of 18 experiments were performed with different values of spin time and spin initiate distance at welding pressure of 64.8 kPa and rotational velocity at 1300 rpm. The observations are given in Table 4, and 5 with the recorded values of the joint overlap distance and bursting pressures, respectively. The weld parts

which were able to bear the designed hydraulic pressure of 1965 kPa are found to clear the test and termed as “pass.” It was observed that few of the test specimens showed the leakage under applied hydraulic pressure and others burst, i.e., showed the separation into two pieces. Both types of cases are categorized as “fail.” The processes were video recorded for observation and analysis. It is observed that the maximum joint overlap distance is obtained with 9 mm spin initiate distance, and with the increase in spin initiate distance to 19 mm, the values of joint overlap distance decrease continuously (about 20%–35% decrease). However, the aforesaid range of variation of joint overlap distance decreases with an increase in spin time with a narrower range (25.0–20.0 mm) observed for the spin time of 1.2 s, whereas the aforesaid range of joint overlap distance was around 15% larger for a spin time of 1.0 s. It is again found that the spin time of 1.0 s and 1.2 s has produced joint overlap distances of 24.8 and 25.0 mm, respectively, with a 9 mm spin initiate distance. It is further observed that such test specimens have cleared the burst test and are termed as “pass.” In view of these observations, the *spin time* of 1.0 s and *spin initiate distance* of 9 mm is selected for further investigation.

Next, the friction spin welding operation for joining the plastic parts in a shear configuration was performed for various combinations of a range of welding pressures from around 64 to 75.8 kPa and a range of velocities from 700 to 2500 rpm. A total of 64 experiments were performed. The processes were video recorded for observation and analysis. The welded specimen was visually inspected, and the joint overlap distance was measured. No visual defect was observed on the welded specimen. Later, the weld specimen was subjected to a burst test for ascertaining the “pass” specimen. Subsequently, the fracture surface of the burst test specimen was analyzed.

Table 4 Measured values of joint overlap distance (mm)

		Spin initiate distance, (mm)					
		9	11	13	15	17	19
Spin time, (s)	1.0	24.8	18.5	18.0	17.5	17.0	16.0
	1.1	22.5	22.3	21.8	20.5	19.3	17.5
	1.2	25.0	23.5	23.0	22.0	22.0	20.0

Table 5 Measured values of bursting pressure (kPa)

		Spin initiate distance, (mm)					
		9	11	13	15	17	19
Spin time, (s)	1.0	1965	1965	1965	1690	1207	515
	1.1	1965	1965	1965	1965	1965	1690
	1.2	1965	1965	1965	1965	1965	1965

4.4 Observations for joint overlap distance

A study for joining the plastic parts in a shear configuration is performed at different rotational velocities and the welding pressure. A set of 64 experiments at different rotational velocities and welding pressure combinations are performed. To account for the variability or repeatability in the process, each of the experimental run is carried out twice. The weld parts are tested for “joint overlap distance.” The schematic of the joint overlap distance after the welding operation is presented in Fig. 9. The observations for joint overlap distance with respect to rotational velocity and the welding pressure are given in Table 6.

4.5 Observations for bursting pressure

The weld parts are subjected to a hydraulic pressure test for evaluating the performance of the joint produced using friction spin welding. The details of the test setup are presented in Sect. 2. The recorded values of the bursting pressure for the aforesaid two sets of 64 experimental runs are presented in Table 7. The test pieces with a larger value of joint overlap distance should generally be able to bear the higher value of the hydraulic pressure, but it was not observed in all the cases given the data presented in

Table 7. The weld parts which were able to bear the maximum designed hydraulic pressure of 1965 kPa are found to clear the “burst test” and termed as “pass.” It was observed that few of the test pieces showed the leakage under applied hydraulic pressure and others burst, i.e., showed the separation into two pieces. Both cases are categorized as “fail.” The test pieces which failed before the maximum designed hydraulic pressure of 1965 kPa are found to be not suitable for further use. It is found from Table 7 that several test pieces were able to clear the burst test to the maximum designed hydraulic pressure of 1965 kPa and are termed as “pass.” But there were many which failed, i.e., either showed leakage or burst under the increasing hydraulic pressure termed as “fail.”

4.6 Joint fracture surface morphology of failed specimen

The fractured parts of the welded joint specimen which burst, i.e., showed the separation into two pieces during burst tests was visually inspected for the joint characterization. In all the cases of failure, the weld joint failed at the joint interface and the welded parts separated under hydraulic pressure depicting a weaker joint than the base material. It may be noted that some joints showed the

Table 6 Observations for joint overlap distance (mm)

		Rotational velocity, (rpm)							
		700	900	1100	1300	1500	1800	2200	2500
Welding pressure, (kPa)	64.1	21.60, 22.00	21.00, 21.40	14.02, 14.38	16.30, 16.90	14.41, 14.79	14.42, 14.98	14.60, 14.80	15.17, 15.63
	64.5	16.08, 16.12	23.15, 23.25	24.82, 24.98	27.25, 27.55	27.49, 27.51	27.61, 27.79	27.22, 27.38	27.78, 27.82
	64.8	22.39, 22.41	23.24, 23.36	24.03, 24.17	24.78, 24.82	27.15, 27.25	28.18, 28.22	28.66, 28.74	28.68, 28.72
	65.2	22.28, 22.32	23.43, 23.57	26.12, 26.28	26.73, 26.87	27.22, 27.38	27.41, 27.59	27.65, 27.75	26.76, 26.84
	65.5	23.97, 24.03	22.90, 23.10	24.98, 25.02	23.97, 24.03	24.99, 25.01	24.98, 25.02	25.29, 25.31	25.97, 26.03
	66.2	22.78, 22.82	23.31, 23.49	23.80, 24.20	23.8, 24.00	23.42, 23.58	23.42, 23.58	23.83, 24.17	23.81, 23.99
	69.0	33.56, 33.64	29.03, 29.17	24.38, 24.62	24.40, 24.60	23.85, 24.15	23.88, 24.12	23.88, 24.12	23.9, 24.1
	75.8	33.78, 33.82	33.78, 33.82	33.76, 33.84	33.79, 33.81	33.77, 33.83	33.70, 33.90	33.75, 33.85	33.77, 33.83

Table 7 Observations for bursting pressure (kPa)

		Rotational velocity, (rpm)							
		700	900	1100	1300	1500	1800	2200	2500
Welding pressure, (kPa)	64.1	840, 884	1965, 1965	132, 212	1965, 1965	852, 872	1329, 1429	1965, 1965	1965, 1965
	64.5	842, 882	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965
	64.8	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965
	65.2	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965
	65.5	838, 886	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965
	66.2	840, 884	1429, 1467	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965	1965, 1965
	69.0	246, 306	1676, 1772	810, 844	242, 310	1075, 1131	389, 439	600, 640	1408, 1488
	75.8	255, 297	271, 281	264, 288	239, 313	264, 288	268, 284	242, 310	244, 308

leakage, and later these joints burst under the increasing hydraulic pressure, whereas few others burst without showing any leakage. The surface morphology of such burst joints can be analyzed. It was observed that during welding the circumferential plasticized bands were formed at the weld interface, i.e., the exterior surface

of the stationary part and interior surface of the rotary part. The aforesaid exterior surface morphologies of the fractured stationary parts which failed under the low, medium, and high value of hydraulic pressure values during the burst test are shown in Figs. 11, 12 and 13, respectively.

Fig. 11 Single non-continuous narrow plasticized band (welding pressure 65.5 kPa, 700 rpm, joint failed @ 862 kPa bursting pressure) (for better visualization of the figure, please refer to online version)

Fig. 12 Two plasticized bands, one continuous and other non-continuous (welding pressure 69 kPa, 2500 rpm, joint failed @ 1448 kPa bursting pressure) (for better visualization of the figure, please refer to online version)

Fig. 13 Two continuous plasticized bands (welding pressure 69 kPa, 900 rpm, joint failed @ 1724 kPa bursting pressure) (for better visualization of the figure, please refer to online-version)

4.7 Observations on the cross section for the spin-welded joint

The joints are characterized as “pass,” i.e., which survived the designed pressure of 1965 kPa. The joint was segmented using a rotary saw for studying the longitudinal cross section of the weld region. Figure 14 shows the methodology to extract the joint segment and the magnified view of the interface. It was observed that there is no identifiable separation line on the longitudinal cross section to differentiate one wall from the other. It can be deduced through these observations that substantial plasticization has occurred during the spin welding due to frictional heat generation at the interface and which has completely penetrated/fused two walls. It is easily understood here that the provided interference between two mating cylindrical surfaces of the specimen caused the frictional heat generation during rotation and penetration under controlled low pressure.

4.8 Qualitative assessment of spin-welded joint interface

The joint interface for the “pass” specimen is investigated. The schematic to separate the joint at the weld interface is shown in Fig. 15. The segmented joint (Fig. 14) was held in a vice through one wall and attempted to disintegrate the joint interface as shown in Fig. 16. However, it became

apparent during these attempts that the walls are integrated through a dense plasticized layer and they cannot be separated without damaging the structure relevant for the study as shown in Fig. 17. The peeling efforts to separate the wall distorted the wall yet not yielding at the joint surface. It can be derived that the strength of the joint due to plasticization has exceeded the strength of the base material, and any effort to disintegrate the joints results in breakage of the joint walls of the mating surfaces.

5 Discussion

The results presented for joint overlap distance, bursting pressure, and the joint fracture surface morphology in the previous section are discussed in this section. The joint overlap distance of the test pieces is presented in Table 6. It is observed that at low welding pressure in the range of 64.1 kPa, the joint overlap distance decreases with the increase in rotational velocity (700 ~ 2500 rpm), whereas the joint overlap distance increases with the increase in the rotational velocity when the welding pressure is more than 64.1 kPa. The relative increase in joint overlap distance is around 76% more for 64.5 kPa, whereas the relative increase is in the range of around 5 ~ 28% with welding pressure in the range of 64.8 kPa to 66.2 kPa. Again, at the higher welding pressure range of 69 kPa, the value of joint overlap distance decreases with the increase in

Longitudinally segmented cross section surface of weld joint observed under 100x magnification

Fig. 14 Longitudinal cross section of the joint interface

Fig. 15 Schematic to disintegrate the joint at the weld interface

Fig. 16 Methodology to disintegrate the friction spin-welded joint interface

the rotational velocity. Further, at a higher welding pressure range of 75.8 kPa, there is an insignificant effect of the increase in rotational velocity on the joint overlap distance.

The increase in welding pressure with a constant value of rotational velocity is analyzed. It is found from Table 6 that the increase in joint overlap distance is in the range of 55% ~ 130% with the increase in welding pressure at the same rotational velocity. The relative increase of around 130% in joint overlap distance is observed with the rotational velocity of 1500 rpm. It was observed that lower values of welding pressure (~64.1 kPa) are producing a lower value of joint overlap distance at higher velocities, which is attributed to the plastic welding occurring at an early stage due to slow linear motion, and higher value of joint overlap distance is prohibited by the early solidification of weld bead in such scenario. The high welding pressure (~75.8 kPa) is causing to arrest of the rotation prematurely, and joint overlap distance is more in such cases (33.8 mm). It was observed during the welding process that at higher welding pressure, i.e., 75.8 kPa, the rotation of the rotating part was terminating due to higher welding pressure resulting in reaching the torque limit of 6.36 N-m. This premature termination of rotation is resulting in less frictional heat generation than required for plasticization and melt flow. Rather the onwards welding pressure which is the same as welding pressure (~75.8 kPa) was leading to elastic deformation. The joint strength obtained in such a case was due to the stress energy stored in the elastic

Fig. 17 Surface of the fractured joint interface

deformation, which is found to be inadequate to retain the parts together and therefore failing during the burst test. It is interesting to note from Table 6 that the welding pressure of around 64.8 kPa is giving an increasing joint overlap distance with a similar increase in the rotational velocity of the rotary part. It is because applied welding pressure has reached the optimum range which is allowing plastic welding on the larger surface area with an increase in rotational velocity, thereby giving the larger value of the joint overlap distance.

The investigation of the joint surface morphology gives insight into the characterization of weld joints and failure of the weld pieces under the burst test. The surface morphology of the failed weld pieces is given in Figs. 11, 12, and 13, respectively. It was observed that the weld surface has bands of plasticization for producing the weld joint. These weld bands are categorized as “single band non-continuously plasticized,” “two bands one continuously plasticized and another non-continuously plasticized,” and

“two bands both continuously plasticized,” respectively. The first two types of the band are found in the case of joints failing under lower hydraulic pressure. It is found that the “single band non-continuously plasticized” type has blindness/non-continuity as shown in Fig. 11. This non-continuity in the plasticized weld band may be due to insufficient frictional heat generation between two surfaces. The heat-deficient plasticized layer weakly intermingles with the walls of both specimen parts producing a weak fusion joint. The aforesaid weakness is responsible for the failure of the joint when the plasticized layer breaks away under pressure from one of the parts and causes leakage of the liquid through the non-continuity in the welded band. A similar non-continuity is found in two bands: one continuously plasticized and another non-continuously plasticized as in Fig. 12, where the joint strength is more than the case of a single plasticized weld band joint. The last one, i.e., Fig. 13, with “two band both continuously plasticized” is thickly layered and continuous.

This type of band is found in the case of joints that failed under very high hydraulic pressure.

It can be predicted that the test pieces which were able to sustain the maximum designed hydraulic pressure of 1965 kPa have broader bands of continuous and substantial plasticization in the joint interface. It can be deduced from Fig. 14 that the weld joint interface has thoroughly fused into a homogeneous structure. The earlier existing boundary distinction of the two walls is not visible. There is no visible non-continuity, porosity, or any other weld defect. Further, the qualitative observations in Sect. 3.8 demonstrate that any peeling efforts to separate the joint interface distorted the wall of the base materials yet not yielding at the joint surface. It can be derived that the strength of the joint due to plasticization has exceeded the strength of the base material, and any effort to disintegrate the joints results in breakage of the joint walls of the mating surfaces.

The study for the bursting pressure of the test pieces is given in Table 7. It was found that there were two modes of failure of the test pieces, viz. leakage of liquid under pressure and the burst, i.e., separation of the test pieces into two parts. The test pieces showed the leakage when the welded band formed was not continuous and had blind spots through which leakage was taking place (Fig. 11). It was again observed that the weld joints obtained at a lesser welding pressure than 64.8 kPa started bursting with such failure becoming a regular occurrence at 64.1 kPa. Further, it was observed that the weld joints obtained at greater welding pressure of 65.5 kPa or more and rotational velocity of 700 rpm started bursting with such failure becoming a regular occurrence at a higher welding pressure and rotational velocity combinations.

The high welding pressure (~ 75.8 kPa) is causing to arrest the rotation prematurely. This premature termination of rotation is resulting in less frictional heat generation than required for plasticization and melt flow. Therefore, all the welded specimens produced using different rotational velocity with a constant value of 75.8 kPa welding pressure failed at very low hydraulic pressure during the burst test. It was observed that the optimal range of welding pressure is 64.5 to 65.2 kPa. The welded process using the welding pressure in this range is completing the full tenure of the rotation of the rotary parts during the insertion of the rotating part on to the stationary part. It was resulting in sufficient frictional heat generation and melting of plastic material in the heat-affected zone which is cooling later during the onwards welding pressure phase. The joint strength obtained was due to the plastic melt flow in the interfacing surface and solidification. Further, it is observed from Tables 4 and 5 that the value of joint overlap distance is continuously increasing with the increase in rotational velocity for welding pressure

of 64.8 kPa. Given that, it can be stated from the above experimentation that the joint overlap distance is increasing without any compromise on the bursting pressure with the respective increase in the rotational velocity during the welding process for the case with a welding pressure of 64.8 kPa.

6 Conclusions

The friction spin welding is preferably used for the welding of axisymmetric parts. The present work is an important milestone to investigate the joining of axisymmetric parts in a shear joint configuration. The analysis of the performance of shear welded joint considering joint overlap distance and bursting pressure confirms the effectiveness of the process for the intended application.

It is concluded from the present investigation that in the case of a shear-type joint for any particular interference configuration and torque limitation (6.36 N-m in the present case), there is a very narrow range of suitable welding pressure (64.5 to 65.2 kPa in the present case) in which the rotation will take place effectively to produce a “sound” weld of high joint strength capacity, and therefore, the process needs to be optimized within that welding pressure range. Given the parameters used for the present work, the optimum value of the welding pressure is 64.8 kPa. It is further noted that at optimized welding pressure the joint overlap distance continuously increases by increasing the rotational velocity. Because of that, it can be concluded that the operator has control over the value of joint overlap distance by exercising the control on the rotational velocity at 64.8 kPa welding pressure and obtain a “sound” welded component with a controlled dimension. It is further noted that to control the joint overlap distance in shear joints the spin time, spin initiate distance, and rotational velocity play a very important role. It is established that at optimum welding pressure the joint strength increases by increasing rotational velocity, but further joint strength testing is required to generate data based on higher hydraulic pressures (greater than 1965 kPa). It can be concluded that the spin time of 1.0 s, spin initiate distance of 9 mm, rotational velocity in the range 700 to 2500 rpm, and welding pressure in the range of 64.5 to 65.2 kPa may be used to obtain the “sound” spin-welded joint for this material with the given dimensions. Thus, the aim of recognition of the range of process control parameters and their optimum values for higher joint strength in shear joint friction spin welding are achieved. The future scope of work in addition to the advancement of the spin welding machine may include the updated machine with enhanced motor power and torque capacity and testing

thereon for ascertaining the effect on the weld joint and performance of the produced parts.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest for the presented work.

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