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Friction Stir Spot Welding of Polycarbonate by a New Design Tool

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Microstructure, tensile properties and fracture energy of a friction stir spot welded polycarbonate (FSSW) were studied at varying rotational rates and dwelling times. The problem of common FSSW welding is the remaining of characteristic keyhole. This can act as a concentration place in mechanical tests. To order solve this problem authors took advantage of innovation for designing the welding tool. The results show that in constant dwell time, strength increases until 800 rpm and then decreases. In constant rotational speed (400, 800) the strength increases by increasing in dwell time but in 1600 rpm the best result was achieved in 10 Sec dwell time. Fractures energy which was exploit from stress-strain curve were in good agreement with strength of welds.

Keywords: Friction stir spot welding, Polycarbonate, Tensile strength, Tool without pin, characteristics keyhole

1 Introduction

Tomas et al in the early nineties for joining soft metals, as aluminum alloys such as those of series 2XXX and 7XXX, which are generally considered unweldable or difficult to weld developed a welding technic which named friction stir welding (FSW) [1]. This welding process also successfully used for joining magnesium [2], titanium [3] and copper alloys [4], steels [5] and thermoplastics [6]. Friction stir spot welding (FSSW) is a sub of the FSW process which being exclusively used for discontinuous lap joining and contains only plunge, stir and retraction step. Low energy consumption and not using any filler material led to low cost production by this method.
Hancock firstly applied FSSW as a method to welding aluminum sheets and claims a 99% reduction in electricity costs compared to conventional resistance welding [7]. High thermal conductivity of metals makes them a suitable case for FSW because softening near the pin and diffusion layer plays an important role during joining. In fact, thermoplastic materials are poor in thermal conductivity and do not show an efficient diffusion layer because of their macromolecular structure. In order to find the applicability of friction stir welding in polymeric material Kiss and Czigany done a close study under practical condition by using tensile test, DSC, optical and scanning electron microscope in (2007).

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They proved FSW technology can be applied as a method for joining seams but the optimization of technology parameters and the tool geometry still need more improvement [8].
So to continue their way, a lots of researchers investigated the joining of polymers by Friction Stir Spot Welding (FSSW) method. These works have concentrated on the joining of polymethyl methacrylate [9] (PMMA), polypropylene (PP) [6, 10, 11], high density polyethylene (HDPE) [12, 13] and dissimilar joining of PMMA to Acrylonitrile-butadiene-styrene (ABS) [14].
FSSW process starts with rotational of the tool with a specific rotational speed and plunging rate into the weld area. The plunging phase continues until the shoulder of the tool reach the surface of the upper workpiece. When the tool reaches the desired depth, the plunge motion ends and the stirring phase starts [15]. Unlike the FSW in FSSW there is no tool translation and it stands in one spot during dwelling time. Heat is generated from friction between tool and workpiece in this phase and, thus, the material adjacent to the tool is heated and softened. The softened upper and lower workpiece materials mix together in the stirring phase.
The shoulder of the tool creates a compressional stress on the softened material and prevents leakage of material out of the welding joint. When a predetermined bonding is obtained, the process stops and the tool is retracted from the workpieces [16]. Based on the microstructure observations the resulting weld has a characteristic keyhole in the middle of the joint as shown in Figure (1) [14, 17-18]. From cross section of welded area, two general concept can be identified. The first is (X) which is related to thickness of nugget and also an index of the weld bond area .The weld bond area increases with the nugget thickness. The second is the thickness of the upper sheet under the shoulder indentation (y).
The size of these two mentioned points determine the strength of a friction stir spot welding joints. Increase in nugget area lead to increase in strength [19-20]. There are numerous papers concerning about the friction stir spot welding parameters which affect the joint geometry and the weld strength [21-22]. These properties are depend on the tool geometry [23] and welding parameters (tool rotational speed [24], tool plunge depth [9] and dwell time [25]. In order to obtain desired properties of welded workpieces, controlling of these parameters which have direct effect in properties are necessary.
Dashatan investigated the effect of tool rotational speed on the weld strength. He claimed the lowest strength was obtained at the 280 rpm when small friction heat was produced and therefore a small weld bond area and a very low strength were obtained. Increasing rotational speed increases the maximum strength until 710 rpm speed and exceeded the 710 rpm the strength decreased because of the residual stresses. After fracture he observed two types of fractures, cross nugget failure that has low weld strength and pull nugget failure that has a high weld strength. In this paper strength shows a linear dependence, while increasing dwelling time cause the weld nugget thicker and then increase the weld strength [14]. Bilici and Yukler used 6 different pin geometry in FSSW process in order to analyses the effect of pin profile on weld strength. They tested square, triangular, threaded cylindrical, straight cylindrical, tapered cylindrical and hexagonal pin geometries. According to the pin geometry, tapered cylindrical shows the best and straight cylindrical shows the poorest weld strength. They claimed that the tapered pin has a higher welding force. A high welding force creates a high friction heat in the vicinity of the pin and causes high material temperature in the welding zone and a thicker nugget gained [26]. In spite of a large number of study on FSSW process it is still relatively low and most of them have been developed very narrow range of technics. In some works [23, 26] effect of pin profile are investigated. As Bilici alleged that weld strength is strongly depend on tool geometry which effects the nugget thickness [26]. As a same time Badarinarayan asserted pin profile is most important factor in static strength of friction stir spot welded joint [19]. So it seems more study on tool geometry in order to optimization of properties is necessary. In this study the effect of welding parameters, rotation speed and dwelling time, are studied.

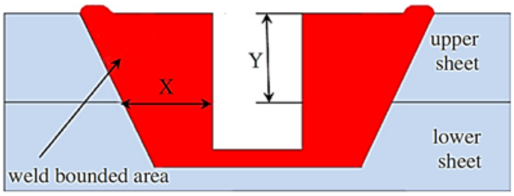

Figure 1 Schematic illustration of the weld zone of a friction stir spot welding joint [14].

It is worth to mention in this work pin profile is omitted and just shoulder used as a tool. So new innovation has been proposed to FSSW process.
By this innovation there is no any sign of keyhole in the welding zone and therefore weld strength can be increase because there is no local stress concentration during tensile test.

2 Experimental procedure

In order to carry out the FSSW, two polycarbonate plate, with 2 mm thickness, 140 length, 60 width were used. These plate over lapped by 40 mm in length and the two plate clamped by a vice so that they would not separate during welding procedure and then welded in over lapped area. At the end a spot weld joint was obtained in the middle of the specimen. All the welding were done in the room temperature by DecKel FP4M machine. The shoulder after each operation cooled to the room temperature for next operation. In order to investigate the effect of parameter process on weld strength, the tool rotation speed and dwell time were determined as welding parameters. Optimum ranges of plunge depth were determined after trial and error method and kept constant for all specimens. Because the plunge rate of the tool was determined to have a negligible effect on friction stir spot welding. This parameter was chosen to be constant during welding process. Welding parameters and their range for every test have been shown in Table (1) it should be mentioned that test range were based on the background study, experience of the authors and finally on pre-tests.
Figure (1) shows prospective of the tool used in the welding. The tool was machined from H13 in dimension of 16*60 mm. In order to reduce harmful effect of pin, new design has been utilized in this tool and pin is omitted. Mechanical properties of welded specimen were characterized by lap-shear test. Weld lap-shear specimen tested at constant 1 mm/Min cross head speed. The load and displacement were simultaneously recorded in Excel sheet during the test. From the curve obtained in the tensile test, fracture energy was also calculated.

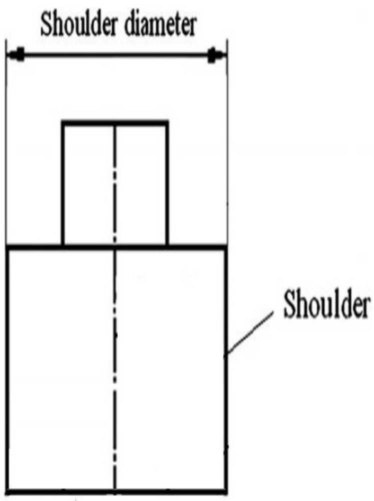

Figure 2 FSSW tool profile

Table 1 Welding parameter and their range

Rotational speed(rpm)	Dwell time(sec)	Plunge rate
400-600-1600	10-20-30	Constant

In order to characterize the main features of the welds, macrostructure examinations are conducted on the as-welded and mechanically tested specimens.

3 Results and discussion

Cross section of joint is like which has been shown in Figure (3). (W) is welding depth and (d) is diameter of stir zone. These two parameters is related to rotational speed and dwelling time. Figure (4) shows the appearance of the test specimen after the friction stir spot welding.
As shown in the figure, the joining is completed without any deformation of the upper or lower sheet. As shown in Figure (4), the shape of the tool is remained on the joint on the side into which the tool is pushed and the base metal that is pushed out by the tool forms a ring of excess metal around the weld.

As it can be seen from Table (2) in constant dwell time more heating is produced with increasing the rotational speed and then weld depth increase. To compare the result of strength and welding area parameters (diameter and weld depth), from Table (2) and Table (3) it can be found that the strength is not linear dependent to weld depth or diameter of stir area. So it can be concluded that it depends on both dwell time and diameter of weld.
Figure (5) is present the observation from fractured sample (Top view of upper sheet) of friction stir spot welding and the effect of rotational speed on strength and fracture energy has been shown in Figure (6). During lap-shear tensile tests, two macrostructure fracture modes were observed. In this paper most of the fracture modes are upper sheet failure. This class of failure shows high strength of welded samples.
Wherever only in 400 rpm, 10 second dwell time boundary failure is observed. This fracture mode happens when a low amount of friction heat is produced during the welding process; therefore, a small weld bond area and a very low weld strength are obtained in the sample as it can be seen from Figure (6a) and Figure (7a).

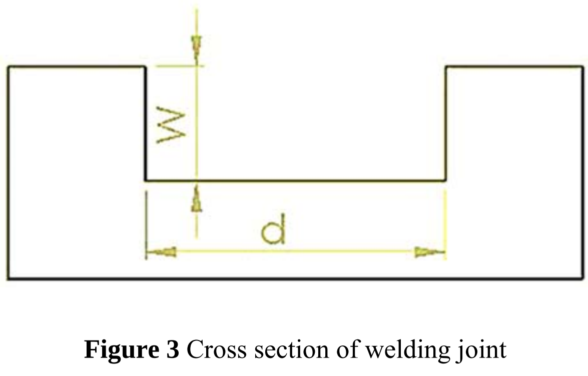

Figure 3 Cross section of welding joint

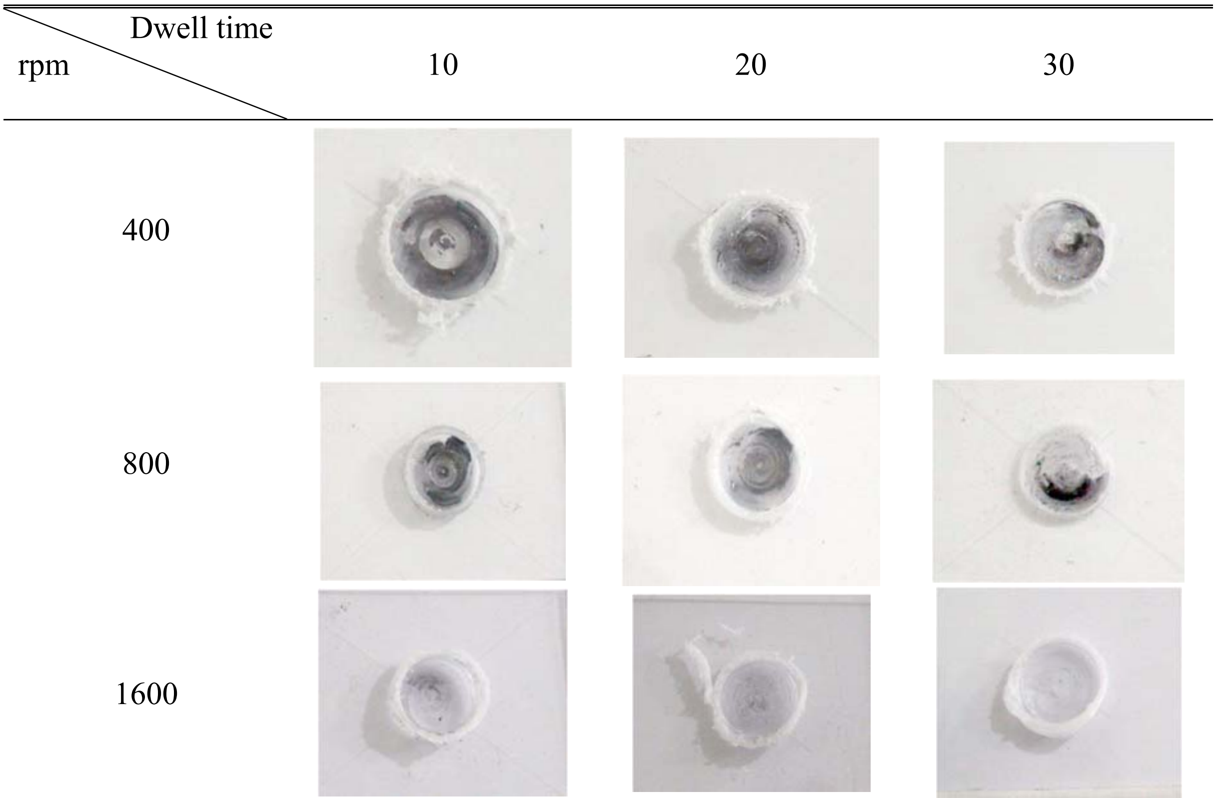

Figure 4 Appearance of a friction stir spot welding

Table 2 Weld depth as a function of welding parameters in mm

Dwell time / rpm	10	20	30
400	3.05	3.07	3.17
800	2.65	2.88	2.84
1600	3.62	2.73	2.85

Table 3 Diameter of a weld area as a function of welding parameters in mm

Dwell time / rpm	10	20	30
400	15.37	19.42	16.36
800	15.73	15.85	16.16
1600	16.34	15.84	16.50

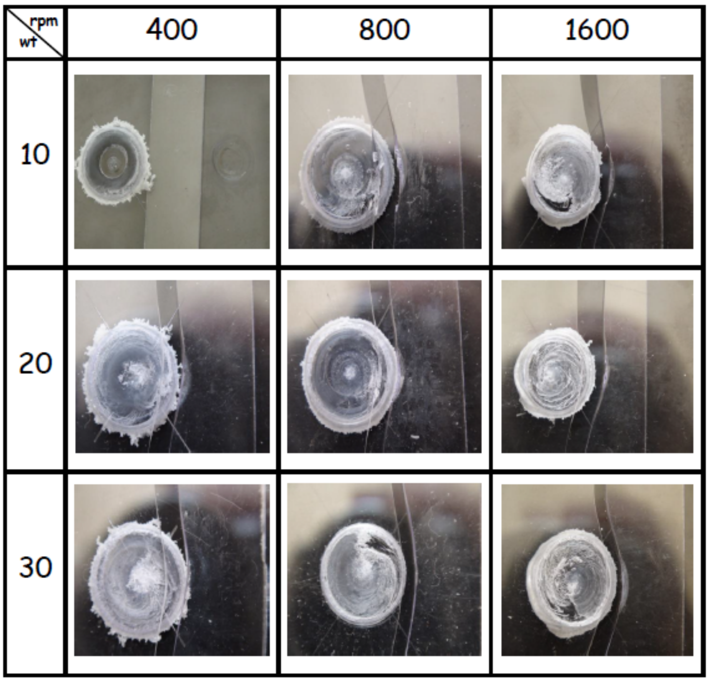

Figure 5 Macrosection of fractured Welded joint in different rpm and dwell time.

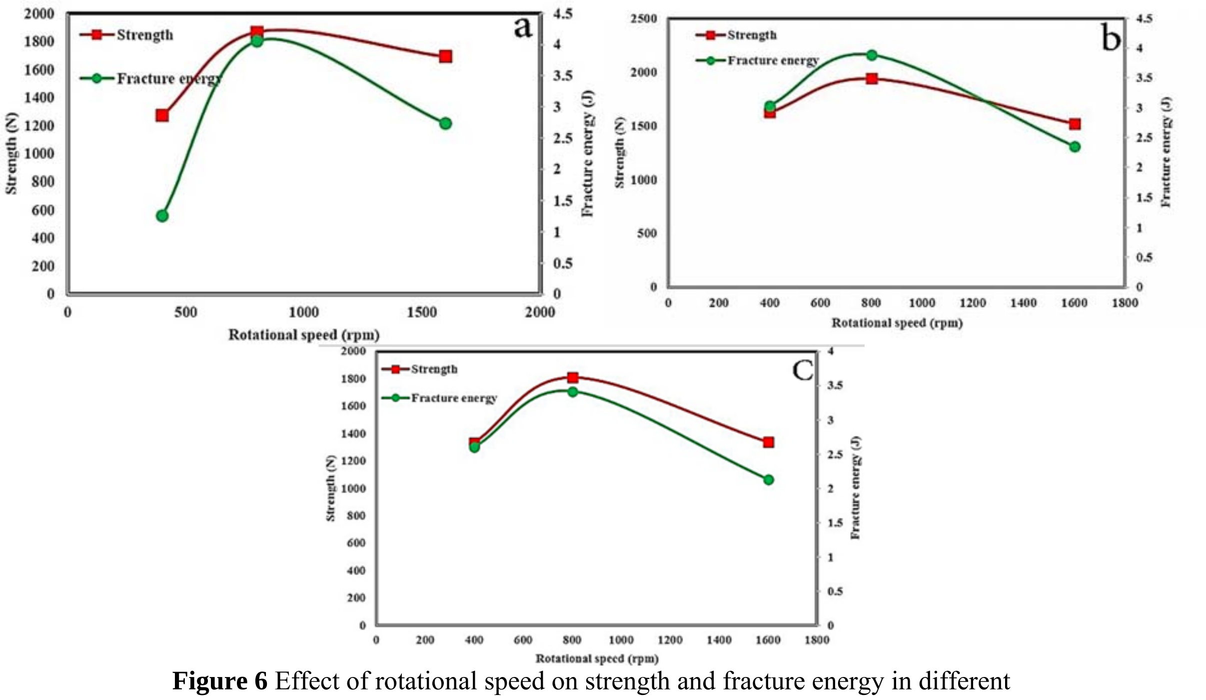

Figure 6 Effect of rotational speed on strength and fracture energy in different constant dwell time (a) 10 sec, (b), 20 sec, (c) 30 sec

Figure (6a) is related to 10 second, (b) is related to 20 Second and (c) is related to 30 second dwelling time. As these figures show, tensile strength increases with increasing rotational speed, especially when 800 (rpm) is applied. Beyond this level result shows strength decrease. It may be explained high rotational speed supply more friction and then more heating is produced. When a molten thermoplastic material is heated to a high temperature a decrease in the molecular weight of the material occurs [27] and then decreasing in the mechanical properties of thermoplastic occurs [28].

But Strand mentioned that rotational speed generates more heat, so proper flow of the polymer in the stir zone is provided and then formation of defect is prevented and increasing the strength of the welds is observed [29]. Bilici claimed that lap-shear force of a FSSW joint is directly proportional to the stir zone thickness and the weld bond area. As long as the weld bond area increase, the strength increase [23]. According to Figure (1), (x) is represent the weld bond area, whatever the keyhole increase in diameter, weld bond area decrease, and as a result strength of joint would be declined. In this study, tool geometry consists only shoulder, therefore the characteristic keyhole was not observed.

As a result, increasing in strength would be expected. Fracture energy is one of the most important properties of any material for many design applications. Fracture energy is a quantitative way of expressing a material's resistance to brittle fracture. If a material has high fracture energy it will probably undergo ductile fracture. Brittle fracture is very characteristic of materials with low fracture energy. Fracture energy versus tool rotational speed in constant dwelling time has been shown in Figure (6a-c).

Fracture energy is in good agreement to joint strength and wherever strength joint increase, fracture energy is also increase. Figure (7) shows the effect of dwell time on strength and fracture energy. From Figure (7a-b) it is concluded that in 400 and 800 tool rotational speed there is an optimum value for strength. This is probably due to the effect of the dwell time on the weld zone area. When the dwell time is low, there is less time for heat to be conducted around the tool. When dwell time increase, the friction heat and therefor temperature produced in the vicinity of the tool increased [30] and as a result bigger weld zone area and significant improvement in strength is observed but in Figure (7c) the strength is decrease with increasing the dwelling time. It is presumed that 1600 rpm in 10 sec is high enough to stir weld bond area properly. Extreme dwelling time cause higher temperature in the weld area and higher inertial forces that reduce the strength of the joint is expected to happen.

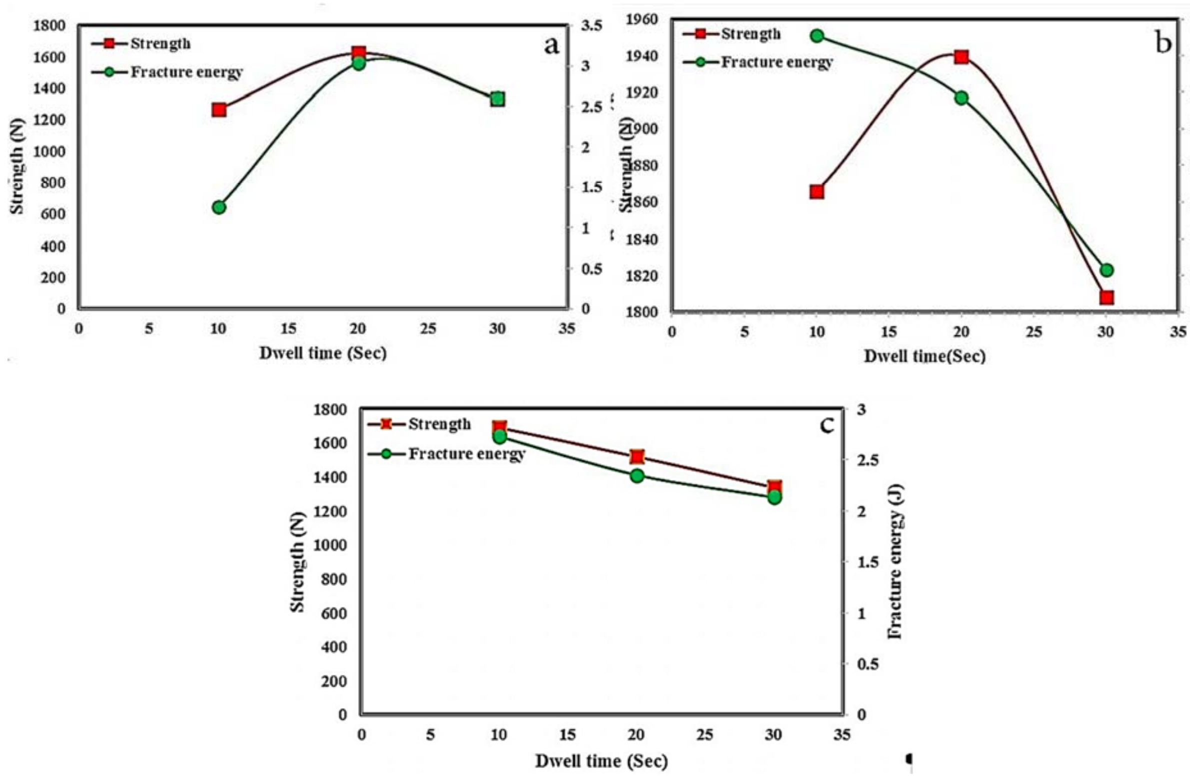

Figure 7 Effect of dwelling time on strength and fracture energy in different constant rotational speed (a) 400, (b), 800 sec, (c) 1600 sec

In Figure (7b), it can be seen that in 10 sec the strength is low but fracture energy is in its higher level. It phenomenon is due to that the fracture energy is area under curve (AUC) of strength and this dependence is not linear. In the final expression to consider strength of joints as it have shown in Figure (6) and Figure (7) it should be mention that in comparison to the same work done by Paoletti [31] who use tool with pin, our results show better strength.

4 Conclusion

Our study on polycarbonate plate showed that strength is not linear dependent to weld depth or diameter of stir area although more depth and diameter led to more stiff joint and eventually better strength results. Another important is that increasing dwell time led to more temperature and more agitation so porosity is observed in boundary between stir weld area and base metal. According to macro study of fracture surface, two macrostructure fracture modes were observed. Most of the fracture modes in this study are upper sheet failure. Eventually fracture energy which is area under curve (AUC) of strength calculated and conducted that its dependence to strength is not linear.

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چکیده

در پژوهش پیش رو، میکروساختار، خواص کششی و میزان انرژی شکست پلی کربنات جوش داده شده بوسیله همزن اصطکاکی نقطه‌ای در نرخ‌های چرخش مختلف و زمان جوشکاری‌های متفاوت مورد مطالعه قرار گرفته شده است. مشکلی عمومی که در تمامی جوشهای داده شده بوسیله روش همزن اصطکاکی نقطه‌ای به چشم می‌خورد باقی ماندن سوراخ کلیدی می‌باشد که از همین نقطه تمرکز تنش رخ می‌دهد و سبب کاهش میزان مقاومت مکانیکی مواد جوش داده شده در این نقاط می‌شود. بدین منظور برای حذف کردن این اثر، نویسندگان ازخلاقیت و ایده‌ای جدید در طراحی ابزار جوش بهره گرفتند و سبب نوآوری در روش FSSW شدند.

ابزار جوش مورد استفاده شده در این پژوهش به منظور اتصال ورقهای پلی کربنات بصورت بدون پین طراحی شد و بکار گرفته شد که در نتیجه سوراخ کلیدی مشخصه حذف گردید. ابزار مورد استفاده سبب ایجاد جریان مناسب در منطقه جوشکاری شده در نتیجه سبب افزایش میزان خواص مکانیکی شد. بعد از جوشکاری ماکروساختار جوش داده شده بوسیله میکروسکوپ نوری مطالعه قرار گرفته شد. نتایج نشان داد که در میزان زمان جوشکاری ثابت، خواص مکانیکی تا میزان سرعت چرخشی 800 rpm افزایش پیدا کرده و سپس کاهش پیدا می‌کند. در زمان چرخش ثابت (400، 800) میزان استحکام با افزایش زمان جوشکاری افزایش پیدا می‌کند در صورتی که در میزان 1600 rpm بهترین نتایج در زمان جوشکاری 10 ثانیه دیده شده است. میزان استحکام شکست که از منحنی تنش-کرنش بدست آمده با میزان استحکامات بدست آمده تناسب مناسبی داشته است.