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The Effect of Electrode Geometry and Pre-heating Treatment on Resistance Spot Welding Strength

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HIGHLIGHTS

- The min. and max. improvement in tensile shear strength was (103–140)%.
- The min. and max. improvement in the torsional strength was (103-149)%.
- The preheating treatment of the lab joint leads to improving the tensile and torsional strengths of the weld joint.
- The preheating treatment showed an improvement range of (115-141)% in tensile shear strength and (124-171)% in torsional strength.

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ABSTRACT

Resistance spot welding (RSW) is one of the most significant and common metal joining methods used in industries. The present paper discusses the comparative performance of resistance spot welding electrodes of nontraditional design with the traditional one of 8 mm contact diameter in welding a 1.5 mm thick low carbon steel sheet used in automobile structural bodies and bridges. The modified electrode tip surface center was machined to have three different holes of 2, 3, and 4 mm depth and three different diameters of 2, 4, and 6 mm producing nine different hollow electrode dimensions. As well as the influence of pre-heating temperature on the mechanical properties of the weld joint was investigated by considering the other main parameters of welding time, current, and force are constant. The shear tensile test and torsion test examinations are carried out to investigate the mechanical properties. Also, to interrupt the results, a macrograph examination was conducted to determine the nugget size formation. The results show that the increase or decrease in the strength of the weld joint is greatly influenced by the proper selection of the modified electrode geometries. Also, the results indicated that the maximum improvement in shear tensile strength and torsional strength is about 140% and 150% compared to the traditional one. Furthermore, pre-heating processes helped decrease the contact resistance at the faying surfaces and improve the weld tensile strength and torsional strength to about 141% and 171% at 200°C. Moreover, improvement may be achieved by slightly increasing pre-heating temperatures

1. Introduction

Recently, resistance spot welding (RSW) has been the most variable welding technique used to join two or more sheet metals together in the manufacturing industry because of its, low-cost, lightweight, easy operation, and adaptable configuration of different types of materials [1]. Although, it is a quick welding technique that can be automated, and provides extremely high productivity [2]. The principle of (RSW), includes joining two or more pieces of sheet metal in specific locations where heating introduced by resistance to the flow of an electric current causes a small volume of metal to melt, and as soon as the volume of molten metal cools and begins to solidify at its edges immediately after the current is turned off. Weld nugget refers to the volume of metal from the workpieces that have performed heating, melting, fusion, and re-solidification [3]. Consequently, the spot-welding process can connect sheets with thicknesses of up to 3.2 mm, which is suitable for most applications because most commercial assemblies include sheets with thicknesses of less than 3 mm [4]. Resistance spot welding is extensively adopted to join various types of steel sheets used in the structural and automotive industry, such as advanced high-strength steels of various gauges Both mild steel and low carbon steel have good weldability and can be spot welded due to their low tensile strength [5, 6]. Moreover, there are still some challenges associated with welding thin and ultra-thin sheets, as the automobile panel of thin steel sheets (0.5 mm, 0.6 mm, and 0.7 mm) is frequently used [7]. Several parameters are determined the quality and characterization of the weld joint, such as welding current and welding time. When the welding current or interval is increased, the nugget size increases well, which can easily result in significant indentation, splashing, and other flaws [8]. Furthermore, in resistance spot welding, the electrode and thermal resistance of the workpiece has a significate effect on heat dispersion in the workpiece's environment. So the contact resistance between the bulk beside the contact resistance between the workpiece and

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the electrode represented the total electrical resistance that affects the welding properties [9]. Based on the Joule law, the use of electrodes as the contact tip workpiece and joining unit during resistance spot welding has a significant impact on the wear behavior and contracting which is affected by electrode force [10]. Also, the performance of the (RSW) process is influenced by a variety of spot weld electrode geometry, especially, the shape and size of the electrode tip, which has an important factor in (RSW) processes [11]. Related to the importance of the function of the size, shape, and material of the electrodes and the force applied by the electrodes, several researchers deal with the effect of electrode tip geometry on the mechanical properties and appearance of the weld joint. For example, Dren et al. [12] developed a modified electrode with an 8 mm face diameter and 4 mm hole diameter at the center filled with ceramic to weld 0.7 mm and 1mm steel sheets metal of an automobile panel. Their result demonstrated that the indentation of the annular nugget decreased significantly. Furthermore, they concluded that by adjusting the geometry of the annular electrode, the size of the annular nugget can be controlled and the strength of the nugget could be improved by forming a large nugget area. Correspondingly, Watmon et al. [11] investigated the effect of welding current, time, and force on weld quality using modified electrodes with a center hole of 4 mm depth and 2.5 mm diameter at the electrode tip and filled with kaolin ceramics and a resistant mixture of cement and explored that, the weld strength and weld nugget size of the recent electrode were higher compared with a solid electrode; furthermore, the analyzed static data established that welding time has a significant effect on weld quality. Similarly, Watanabe et al. [13] investigated the influence of a concave electrode with a 6 mm diameter and a 2 mm hole at the tip center with a 4 mm depth. The concaved geometry of the electrode suppressed the initiated expulsion at a high current and prevented the electrode degradation, and produced a large nugget diameter that improved the cross-tensile test to about 1.5% compared to the conventional electrode. Deng et al. [14] investigated how electrode topography affects weld quality. For comparison, three different kinds of electrode surface designs were explored; “a textured electrode and a multi-ring domed electrode with two ring heights H1 and H2”. They found that there was no statistically significant relationship between the electrode face design and the average peak load or nugget diameter, and all fracture modes were interfacial. However, their electrodes have a considerable impact on resistance heat production and electrode cooling effects that caused welds with variable morphology, microstructure, and mechanical properties. Li et al. [15] systematically studied the influence of truncated electrode cone angle on electrode wear and weld nugget characteristics using experimental and physical finite element methods. As a result, the low cone angle produced small weld nuggets and consumed more electrodes, but, improved the electrode cooling ability and significantly reduced the electrode tip temperature, while, needing a high current to adjust the heat wasted by the cooling process. Moreover, Zhang et al. [16] investigated the influence of 18 mm×5 mm rectangular terminated electrodes on the shape and dimension of the (RSW) process under the effect of different currents, pressure, and welding time. The results showed that the nuggets are generally elliptical such that the long and the short axis dimension have a particular percentage. Chan et al. [17] investigated the impact of four distinct electrode shapes and electrode cup geometries on nugget formation. The form of the electrodes affects the growth and ultimate shape of the weld nugget according to SORPAS resistance spot welding finite element studies. Although the Para CapTM electrode was determined to have the widest useful current range between the minimum weld size and nominal weld size. On the other hand, pre-heating is a thermal treating technique that may considerably improve the mechanical properties of the resistance spot welding based on predetermined heating temperature. In different conditions, the specifics and modes of pre-heating may vary, but typically, the main objective is to prepare the metal before welding and, affect the cooling habits after welding so that shrinkage stresses will be lowered (compared to welding without pre-heating), a slower rate of cooling [18]. Thus, Lane et al. [19] looked into the findings of the influence of pre-heating and post-heating on the resistance spot weldability of (1.3 mm) hot-dipping galvanized steel sheets utilizing high-speed cinematography. They showed that the pre-heating current resulted in a slower and more uniform production of weld nuggets. Nithin et al. [20] suggested four group conditions as weld, with pre-heating, water quenching, and pre-heating then quenched, then investigated and compared the effect of these treatment processes on tensile strength and quality of spot welding. They obtained that pre-heating current and water quenched can improve mechanical properties. Saleem et al.[21] used the finite element method (COMSOL software) and experimental work to study the effect of induction pre-heating of aluminum before welding to decrease the power needed for welding. As the overall result observed that heating the sheet to 200 ^{o}C can reduce the current required to about 22%.

The present work aims to investigate experimentally the effect of regulating the current density and heat distribution in the spot welding process of low carbon steel sheets on the mechanical strength properties using a modified design of hollow electrodes over a range of different combinations of hollow diameter and depth. As well as the influence of the pre-heating technique on the spot welding quality is investigated and the effects of pre-heating temperatures on welding strength are studied. The study is carried out under the conditions of constant welding current, welding force, and welding time to explore the influence of the modifications adopted in the present work.

2. Experimental Work

2.1 Materials and Methods

Low carbon structural steel of 1.5 mm thickness was selected as a sheet material in the present work. The mechanical properties of the steel sheet are evaluated using the United Universal SHFM-600KN tensile testing machine and the result is shown in Table 1.

Table 1: Mechanical properties of low carbon steel sheet

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Elastic modulus (GPa)
310	385.36	34.24	200

Furthermore, the chemical composition of the sheet metal specimen was examined using the Foundry Master Xpert Oxford machine, and the specimen's chemical composition is given below in Table 2.

Table 2: Chemical compositions of low-carbon steel sheet

% C	% Si	% Mn	% P	% S	% Cr	% Mo	% Ni	% Cu	% V
0.0516	0.0121	0.557	0.0162	0.0140	0.0409	0.0010	0.050	0.0925	0.0040

The specimens used in the present work were prepared according to (AWS C1 .1M/C1 .1:201 9) standard with the dimensions of (150 mm x 30 mm x 1.5 mm). Fixing the specimens in the spot welding process is essential for getting an accurate result. For this reason, an incremental fixture was designed and fabricated to guide (fix) the samples and keep the specimen from being distorted by the effects of applying the force and current and consequently ensure that the tensile shear tests are performed axially. The fixture is made of aluminum of grade 6061 and provided with a polyamide conical component to fit the electrode without interrupting the electrical current. The fixture is designed to be useful for welding samples of both shear and torsion tests, as shown in Figure 1.

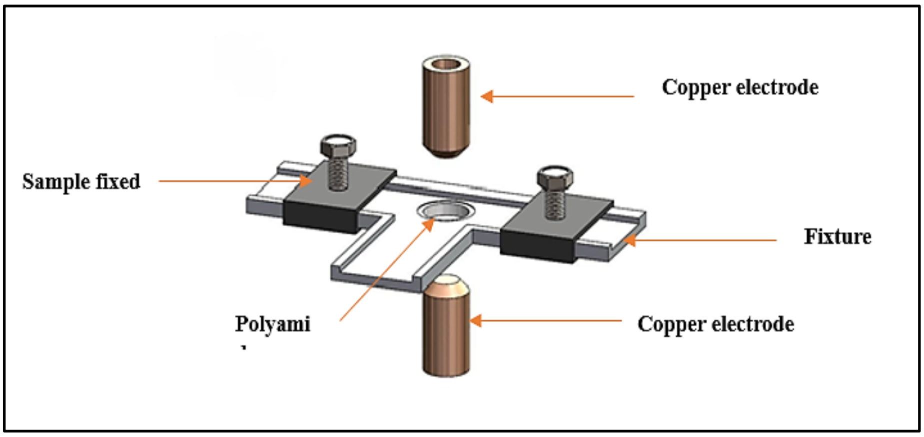

Figure 1: Fixture for guiding spot welding sheet

The experimental work was performed using two electrode conditions, traditional-traditional, and traditional-modified hollow electrodes. Both electrodes have the same specification, such as all were truncated electrode shapes made from copper rods of 16 mm diameter and 45° conical edge with 8 mm face tip diameter according to (AWS C1 .1M/C1 .1:201 9) standard.

The upper electrode is a traditional one, as shown in Figure 2, while the lower one is a non-traditional hollow tip electrode that is equipped with a hole or cavity at the center of the electrode's top surface with a diameter of (D) and a total depth of (d), as shown in Figure (3-a).

In the present study, to carry out the experimental work over a wide range of modified electrodes nine hollow electrodes were used as shown in Figure (3-b).

Figure 2: Traditional electrode

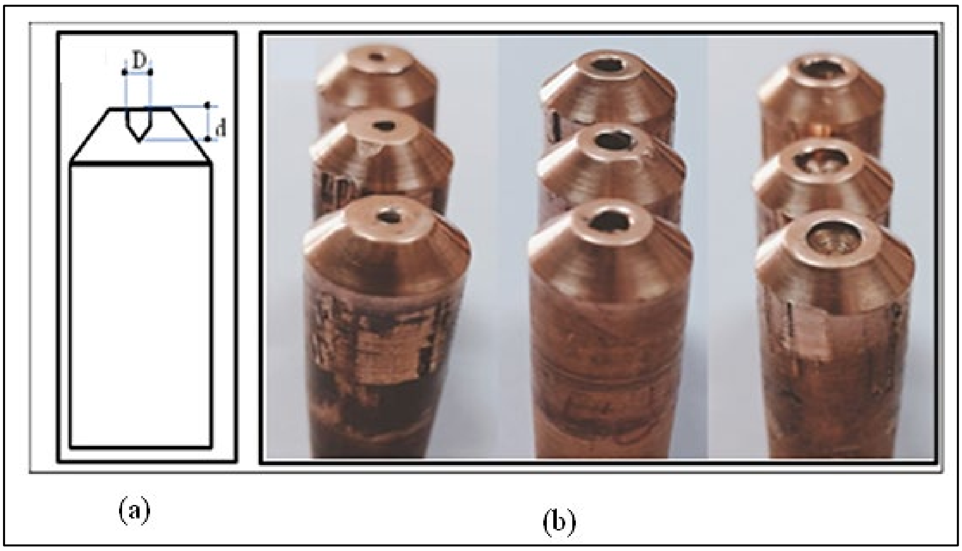

Figure 3: (a) Hollow electrode details (b) Sets of the hollow electrode

The dimensions of the nine hollow electrodes used in the present experimental work are presented in Table 3.

(RSW) was performed using a resistance spot welding machine of an electronic variable resistor firing control of 50 kVA AC with a linear descent air-operated arm. In (RSW), it is important to select proper welding conditions to control welding quality, and they are mainly related to the type of sheet metal, thickness, and tensile strength. However, the welding conditions were selected according to standard (AWS C1.1M/C1.1:201 9) and welding currents were selected according to the peel test result that demonstrated 8 kA achieving an expectable nugget size. In general, welding current, welding time, and welding pressure are kept constant as shown in Table 4. And noted that each cycle corresponds to (0.0192 sec).

Table 3: Hollow electrode details

Level Condition	1	2	3	4	5	6	7	8	9
Hole diameter (D) (mm)	6	6	6	4	4	4	2	2	2
Hole depth (d) (mm)	2	3	4	2	3	4	2	3	4

Table 4: Spot welding input conditions

Welding current (kA)	Welding force (kN)	Squeeze time (cycles)	Welding time (cycles)	Holding time (cycles)
8	5	70	13	30

2.2 Pre-heating treatment

Pre-heating is the process used to enhance the temperature of the parent metal before welding to improve welding quality and decrease the probability of crack production in the welding zone. A Theco laboratory oven was used in the present work to preheat the specimen before welding and a digital reading screen equipped with a thermocouple was inserted with the specimens for monitoring the temperature of the specimen while it is heated up. The specimens are preheated for different temperatures of 100°C 150°C, and 200°C. Moreover, each sample was heated to a temperature of 5°C greater than the required pre-heating temperature to compensate for the heat losses due to the setup time of preprocessing welding conditions. In addition, each specimen holds at each pre-heating temperature for about 20 minutes to satisfy the temperature uniformity requirements.

2.3 Tensile and torsion tests

United Universal Testing Machine SHFM-600 kN tensile test machine was used to measure the weld joint strength under shear and torsion loads with a crosshead speed of 20 mm/min to assess the strength and the amount of force required to break the welded joint. The shear tensile test and torsion test samples were prepared and joined as depicted in Figure 4. (a) and 4.(b) respectively.

2.4 Macrographic Examination

A macrograph test for the spot weld joint was performed to measure the spot weld nugget size and to explore the effect of the modified electrode on the nugget size formation mechanism. Preparation of the macrographic test has been performed according to the metallographic standard that involves cross-sectioning of the weld zone at the center line and mounting it in a small die containing acrylic curing mixed with epoxy hardener to carry out easily the sample preparation requirements. The prepared surface was ground by using a single disc grinding machine with grinding paper of 120,400, 600, and 2000 for 10 minutes at 400 rpm speed, then, the ground samples were washed with acetone and water. The grinding process is followed by the polishing process of specimens with Al_2O_3 of 0.03 µm size using a fine cloth disc for about 10 minutes, then samples are washed and dried with warm air. After that, the etching of the polished surface has been carried out by swapping the surface with (25% HNO_3 and 75% ethanol) for 20 seconds, then, washed with water and alcohol, and dried with warm air. To identify the characteristics of the spot weld zone (base metal, HAZ zone, and fusion zone), a micrograph test of the prepared samples was carried out by using an optical magnifier of 4X, and a digital vernier was used to carry out the measurement process of the nugget size, as shown in Figure 5.

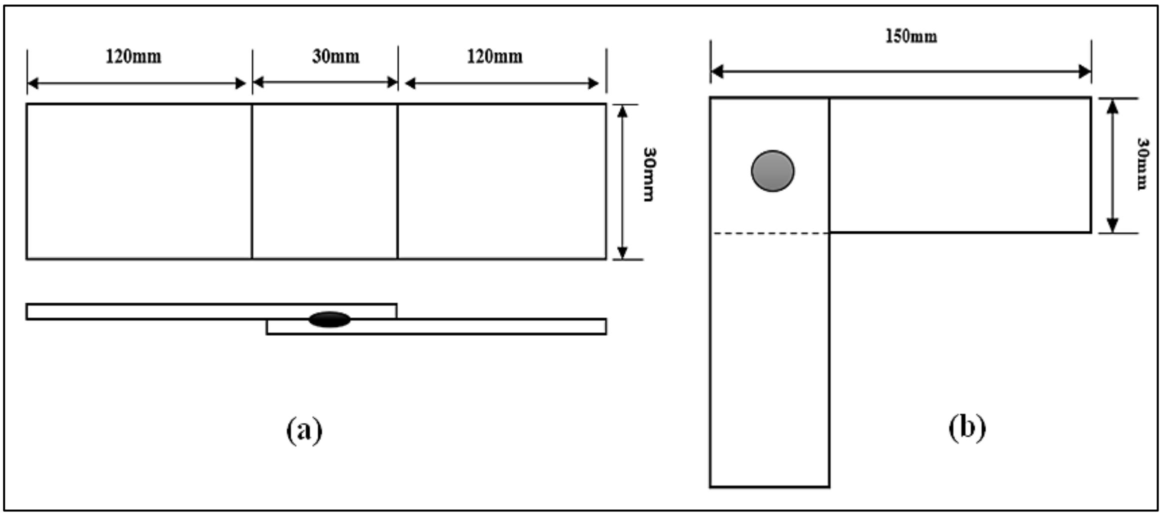

Figure 4: Specimens arrangement for welding in (a) tensile test, (b) torsion test

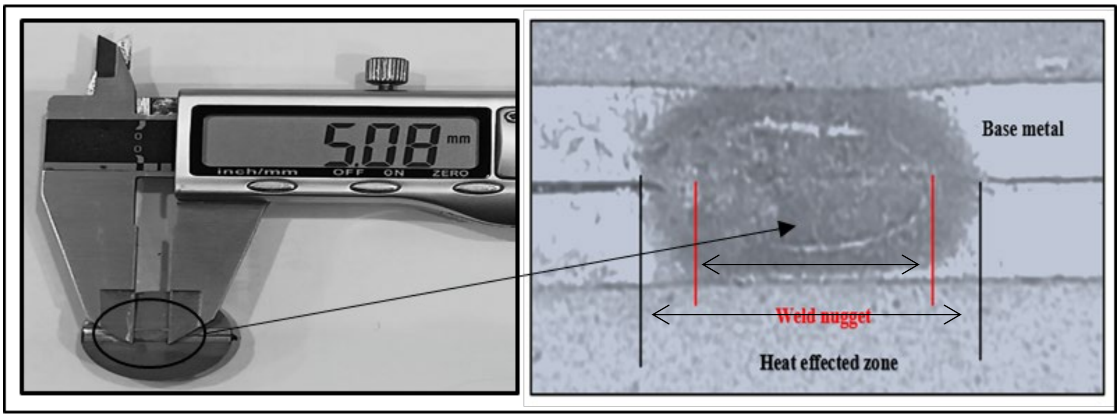

Figure 5: Macrograph test for spot weld nugget identification and size measurement

3. Results and Discussion

3.1 Effect of Hollow Electrode Dimensions on Spot Welding Strength

This section explains how the hollow electrode's diameter and depth affect the tensile shear strength and torsional strength. Generally, the results indicated that using different hollow electrode hole dimensions can be effectively changed the strength properties in the joining of low carbon steel sheet by resistance spot welding process, especially under constant welding conditions, which reflects the fact that the strength may be controlled and improved by using the modified electrode shape or geometry. Consequently, Figure 6 and Figure 7 show the variation of the spot weld strength with the hollow electrode hole depth at different hole diameters. The results show that the variation in the hole depth caused a variation in welding strength at the same hole diameter, while, at the same time, the strength may be greatly affected by changing the hole diameter. Alternatively, the vice versa is also satisfied as shown in Figure 8 and Figure 9. For instance, at a hole depth of 2 mm and a diameter of 4 mm, the results show that the shear tensile strength and the torsion strength are 252 MPa and 83.7 MPa respectively, but, with decreasing the hole diameter to 2 mm the results show a percentage increase in tensile shear strength and torsion strength of 36.3% and 23.9% respectively. While increasing the hole diameter to 6mm the results show a percentage decrease in tensile shear strength of 7% while showing a percentage increase in torsional strength of 8.4% compared with that at 4 mm hole diameter. Respectively, it is evident that there is a critical magnitude for the hole diameter and hole depth at which a transition or change in the spot welding strength is noticed, thus, the hollow electrode hole dimensions should be chosen carefully to obtain better improvement in the quality of the resistance spot welds; and avoiding the conditions at which the problems of electrode adhesions and degradations may be occurred [22].

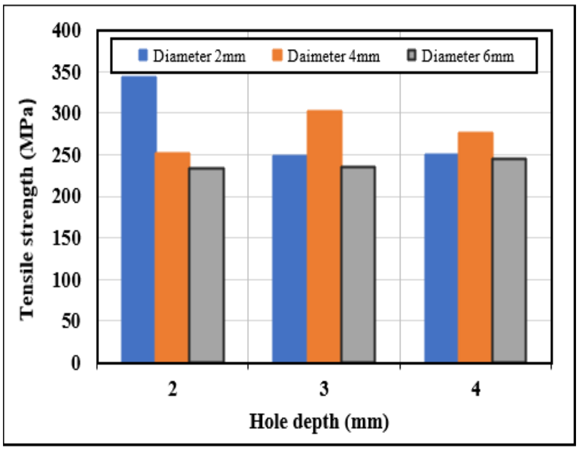

Figure 6: Variation of the spot welding tensile shear strength with the hole depth

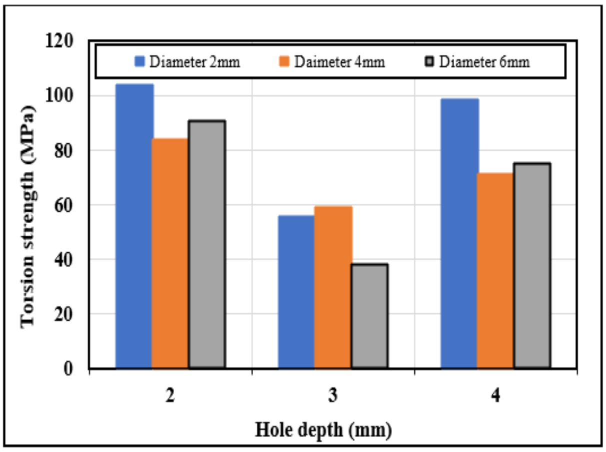

Figure 7: Variation of the spot welding torsional strength with the hole depth

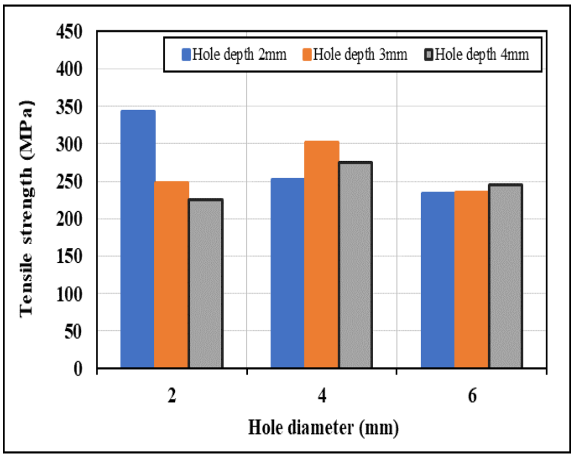

Figure 8: Variation of the spot welding tensile shear strength with the hollow electrode hole diameter

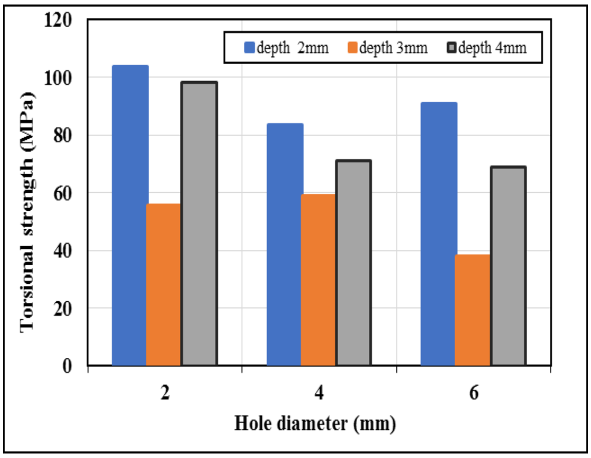

Figure 9: Variation of the spot welding torsional strength with the hollow electrode hole diameter

To understand well the effect of a hole or cavity in the top surface of the hollow electrode on the spot welding quality; a percentage change in the tensile shear strength is presented in Figure 10. The tensile shear strength percentage change (Δ) may be defined as the percentage ratio of the modified electrode (hollow electrode /traditional) strength to that of the as-received one (traditional/traditional) electrodes. In general, it can be seen that there is a good improvement in the tensile shear strength of spot welding and these results can be interrupted by the nugget size measurements provided by the macrograph test, as shown in Figure 11. For example, the hollow electrode geometry D2d2 shows a nugget size of 6.84 mm compared with 5.08 mm for the traditional electrode which increases the shear tensile strength by the amount of 140%, while, the electrode geometry D4d2 provides a nugget size of 6.36 mm which shows an increase in the tensile shear strength of 103% compared with that of the traditional strength. Consequently, the enhancement mechanism in the strength of spot welds experienced by applying the hollow electrode geometry may be attributed due to the: firstly, the presents of the hole at the top face of the electrode provide an improvement in the weldability conditions by allowing the molten metal between the upper and lower sheets to move towards the electrode cavity which forms a pathway for the melted metal to expand into, as indicated by all results of macrograph test. While, in traditional electrodes, the molten metal expands toward the edges of the joined surfaces until the hydrostatic pressure in the melt surpasses the pressure from the electrodes. As well as the hollow electrode tends to raise the current limit and produces substantially larger nugget sizes by allowing the molten metal to expand into the electrode's hole instead of fading to the sides and improving the weldability properties [23]. Secondly, the hollow electrode geometry produces relatively more heat by changing the contact resistance and current density distribution compared with the conventional electrode [24]. which in turn, leads to an increase in the nugget size and improves the strength of the spot welds. Alternatively, the results also show a decrease in the spot welds strength with more increase in hollow electrode hole diameter, despite the large size and indentation experienced by the nugget size measurement, as seen, in Figure 11 for specimen D6d2 (7.62 mm) in comparison with D2d2 (6.88 mm). This result may seem to be due to the fact that with a large hole diameter the contact resistance of the hollow electrode increases which in turn causes a reduction in current density. Thus, based on Joule law the heat generated was minimized, and mainly at the annular of the electrode surface, poor weldability condition prevails, which in turn leads to minimizing welding quality and decreasing the spot welding strength.

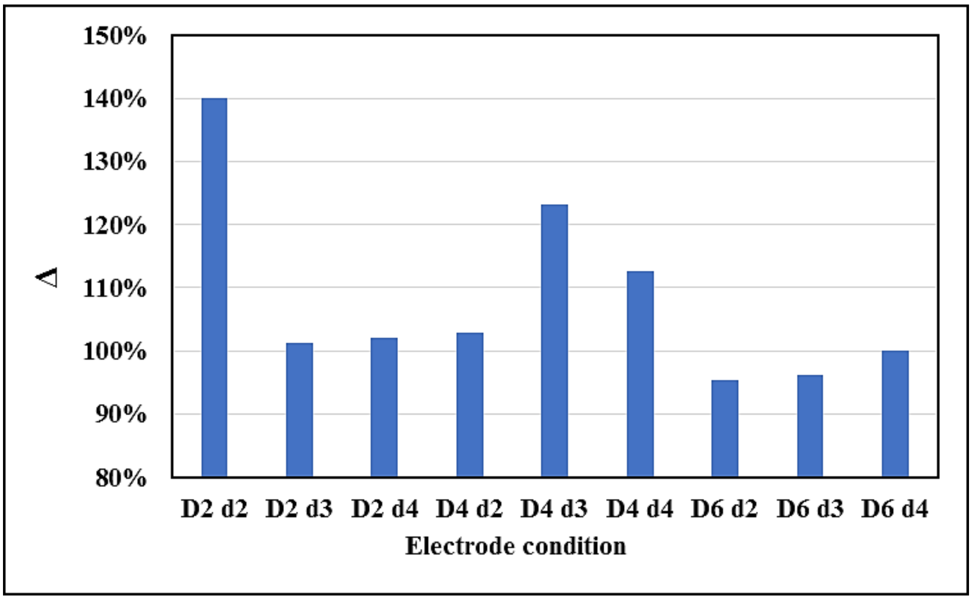

Figure 10: Percentage change in tensile shear strength with hollow electrode conditions

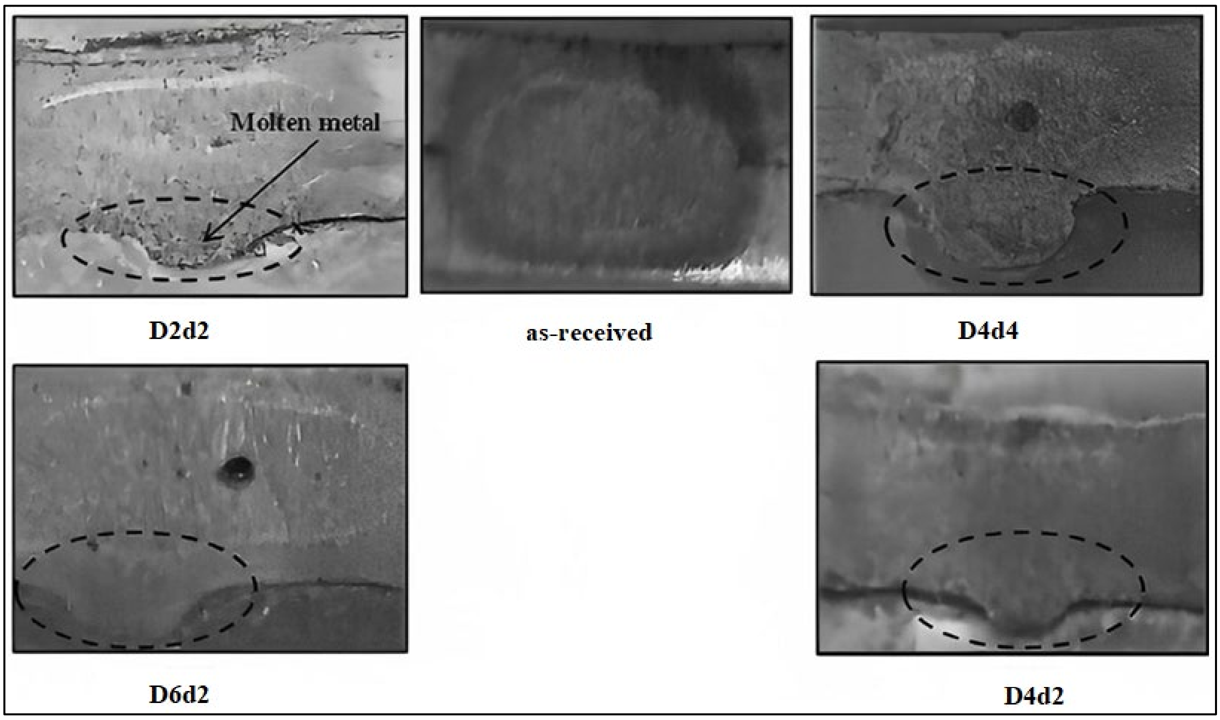

Figure 11: Nugget geometry-cross sectional view

3.2 Effect of Pre-heating Temperature on Spot Welding Strength

The influence of pre-heating temperatures on the tensile shear strength and torsion strength was investigated. In general, the pre-heating temperatures are selected to be below the considerable melting temperature of the sheet/sheet interface using the traditional electrode. The variations of the spot welds' strength with the pre-heating temperatures are shown in Figure 12 and Figure 13 respectively. As can be seen, pre-heating of the lap sheet metal joint before welding has a significate effect on improved mechanical properties. Such that, increases in pre-heating temperatures from 100ºC to 150ºC and 200ºC, experienced an improvement in tensile shear strength to about 115%, 131.4%, and 141% and about 124%, 154%, and 171% for torsional strength respectively, compared to that without pre-heating treatments. These results may be attributed to that: pre-heating the metal before welding offered a decrease in the contact resistance at the faying surfaces between the electrode/sheet, and helped slightly in the solidification of molten metal at the welding zone and a dramatic reduction in spatters at faying zone can be achieved. Moreover, the weld quality is improved under the concept that no defects, such as porosity or cracks were presented during the nugget's formation [25], which leads to an increase in the heating energy and produces a larger nugget size which leads to improving the shear tensile strength and torsion strength of the spot welds. Finally, these results were proved by the nugget size measurements at the above-mentioned pre-heating temperatures, which show nugget sizes of 6.36 mm, 6.82 mm, and 7.0 mm respectively, compared with the nugget size of weld joint without pre-heating that is measured 5.08mm. which reflects the improvement in the spot weld quality under the same welding conditions.

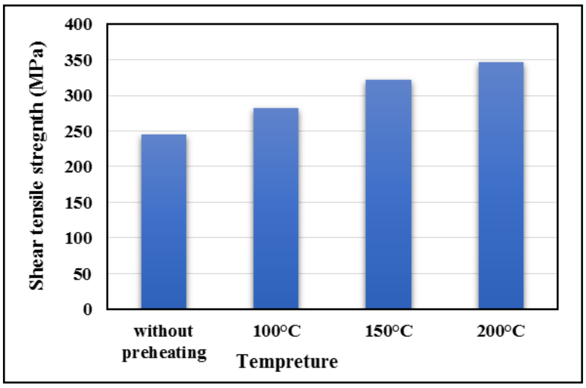

Figure 12: Effect of pre-heating temperature on shear tensile strength

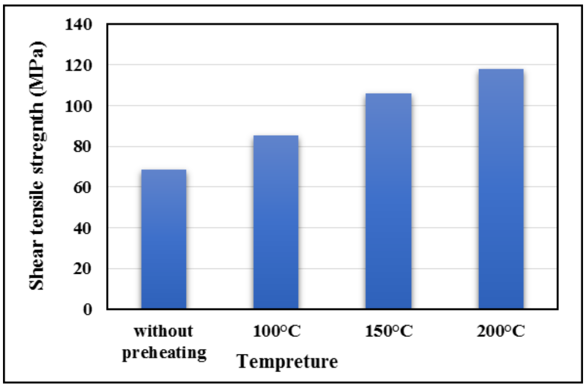

Figure 13: Effect of pre-heating temperature on Torsional strength

4. Conclusion

In this study, the influence of electrode geometry and pre-heating temperature on spot weld strength was investigated experimentally and compared to the traditional electrode. Consequently, based on the obtained results, the following conclusions are drawn:

1) The application of hollow electrodes in the spot welding process is responsible for producing a significant influence on the strength of the weld joint.
2) The variation in the tensile and torsional strengths is greatly affected by the diameter and depth of the hollow electrode hole and their values must be selected carefully for better improvement.
3) The presence of the hole on the electrode top surface leads to producing different nugget indentation configurations depending on the hole of the hollow electrode geometry.
4) The minimum and maximum improvement in tensile shear strength are (103–140)% and (103-149)% in the torsional strength compared with the traditional one.
5) The preheating treatment of the lab joint leads to improving the tensile and torsional strengths of the weld joint.
6) Preheating treatment decreases the expulsion and spatters between contact sheets and enhances nugget growth.
7) The preheating treatment shows an improvement range of (115-141)% in tensile shear strength and (124-171)% in torsional strength at the selected temperature range.

Author contributions

All authors contributed equally to this work.

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Data availability statement

Not applicable.

Conflicts of interest

The authors of the current work do not have a conflict of interest.

References

[1] C. Summerville, P. Compston, M. Doolan, A comparison of resistance spot weld quality assessment techniques, Procedia Manuf., 29 (2019) 305-312. https://doi.org/10.1016/j.promfg.2019.02.142

[2] B. Feujofack Kemda, N. Barka, M. Jahazi, D. J. M. Osmani, and M. International, Multi-objective optimization of process parameters in resistance spot welding of A36 mild steel and hot dipped galvanized steel sheets using non-dominated sorting genetic algorithm, Met. Mater. Int., 28 (2022) 487-502. https://doi.org/10.1007/s12540-021-00986-9

[3] J. A. Khan, L. Xu, Y.-J. Chao, K. Broach, Numerical simulation of resistance spot welding process, Numer. Heat Transf. A: Appl., 37 (2000) 425-446. https://doi.org/10.1080/104077800274145

[4] A. Pandey, M. Khan, K. Moeed, Investigation of the effect of current on tensile strength and nugget diameter of spot welds made on AISI-1008 steel sheets, Int. J. Tech. Res. Appl., 1 (2013) 1-8.

[5] M. Pouranvari, S. Sobhani, F.Goodarzi, Resistance spot welding of MS1200 martensitic advanced high strength steel: microstructure-properties relationship, J. Manuf. Process., 31 (2018) 867-874. https://doi.org/10.1016/j.jmapro.2018.01.009

[6] K. Paveebunvipak, V. J. M. Uthaisangsuk, and Design, Microstructure based modeling of deformation and failure of spot-welded advanced high strength steels sheets, Mater. Des., 160 (2018) 731-751. https://doi.org/10.1016/j.matdes.2018.09.052

[7] Z. Ling, Y. Li, Z. Luo, Y. Feng, Z. J. M. Wang, and M. Processes, Resistance element welding of 6061 aluminum alloy to uncoated 22MnMoB boron steel, Mater. Manuf. Process., 31 (2016) 2174-2180. https://doi.org/10.1080/10426914.2016.1151044

[8] X. Zhang, F. Yao, Z. Ren, H. J. M. Yu, Effect of welding current on weld formation, microstructure, and mechanical properties in resistance spot welding of CR590T/340Y galvanized dual phase steel, Materials (Basel), 11 (2018) 2310. https://doi.org/10.3390/ma11112310

[9] R. Al-Sabur, M. Slobodyan, S. Chhalotre, and M. J. M. T. P. Verma, Contact resistance prediction of zirconium joints welded by small scale resistance spot welding using ANN and RSM models, Mater. Today: Proc., 47 (2021) 5907-5911. https://doi.org/10.1016/j.matpr.2021.04.431

[10] M. Hamedi , M. Atashparva, A review of electrical contact resistance modeling in resistance spot welding, Welding in the World, 61 (2017) 269-290. https://doi.org/10.1007/s40194-016-0419-4

[11] T. B. Watmon, C. Wandera, J. J. Apora, Characteristics of resistance spot welding using annular recess electrodes, J. Adv. Join. Proc., 2 (2020) 100035, 2020. https://doi.org/10.1016/j.jajp.2020.100035

[12] D. Ren, D. Zhao, C. Li, L. Liu, and K. J. J. o. M. P. Zhao, Resistance ceramic-filled annular welding of thin steel sheets, J. Manuf. Process., 45 (2019) 588-594. https://doi.org/10.1016/j.jmapro.2019.07.043

[13] G. Watanabe, T. Amago, Y. Ishii, H. Takao, T. Yasui, and M. Fukumoto, Improvement of cross-tension strength using concave electrode in resistance spot welding of high-strength steel sheets, AIP Conf. Proc., 1709,2016,020003. https://doi.org/10.1063/1.4941202

[14] L. Deng, Y. Li, B. Carlson, and D. J. W. J. Sigler, Effects of electrode surface topography on aluminum resistance spot welding, Weld. J., 97 (2018) 120-132. https://doi.org/10.29391/2018.97.011

[15] Y. Li, Z. Wei, Y. Li, Q. Shen, Z. J. Lin, M. Transfer, Effects of cone angle of truncated electrode on heat and mass transfer in resistance spot welding, Int. J. Heat Mass Transf., 65 (2013) 400-408. https://doi.org/10.1016/j.ijheatmasstransfer.2013.06.01

[16] X. Zhang, L. Wei, G. Xu, C. J. M. Wang, Connection Status Research of the Resistance Spot Welding Joint Based on a Rectangular Terminal Electrode, Metals, 9 (2019) 659. https://doi.org/10.3390/met9060659

[17] K. R. Chan, N. Scotchmer, J. C. Bohr, I. Khan, M. L. Kuntz, Y. J. S. X. S. Zhou, Effect of electrode geometry on resistance spot welding of AHSS, (2006) 7-4.

[18] S. Dutt, R. Saluja, Kh. Moeed, A Review on Effect of Preheating and/or Post Weld Heat Treatment (pwht) on Hardened steel, Int. J. Tech. Res. Appl., 1 (2019) 5-7.

[19] C.T. Lane, C.D. Sorensen, G.B .Hunter, S .Gedeon, T. W. Eagar, Cinematography of resistance spot welding of galvanized steel sheet, Weld. J., 66 (1987) 260s-265s.

[20] S. Nithin, C. J. Joseph, V. Remin Mathew, T. Saloop, Effect in Tensile Strength of Resistance Spot Welding of IS2062A Steel on Preheating and Water Quenching, Int. J. Res. Eng. Manag. Sci., 2 (2019) 286 - 288.

[21] J. Saleem, A. Majid, A. W. Malik, K. Bertilsson, An efficient method of spot welding Aluminium alloys with induction preheating, J. Electr. Syst., 12 (2016) 817-825.

[22] J. Jun, S. Rhee, Study on spatter reduction of resistance spot welding of SPRC440 using hemispherically concaved electrode, Sci. Technol. Weld. Join., 17 (2012) 333-337. https://doi.org/10.1179/1362171812Y.0000000012

[23] D. Kim, J. Yu, S. Rhee, Effect of a conically shaped hollow electrode on advanced high strength steel in three-sheet resistance spot welding, Int. J. Precis. Eng. Manuf., 17 (2016) 331-336. https://doi.org/10.1007/s12541-016-0041-9

[24] R. Al-Sabur, M. Slobodyan, S. Chhalotre, M. Verma ,Contact resistance prediction of zirconium joints welded by small scale resistance spot welding using ANN and RSM models, Mater. Today: Proc., 47 (2021) 5907-5911. https://doi.org/10.1016/j.matpr.2021.04.431

[25] M. Pouranvari, A. Abedi, P. Marashi, M. J. S. Goodarzi, Effect of expulsion on peak load and energy absorption of low carbon steel resistance spot welds, Sci. Technol. Weld. Join., 13 (2008) 39-43. https://doi.org/10.1179/174329307X249342