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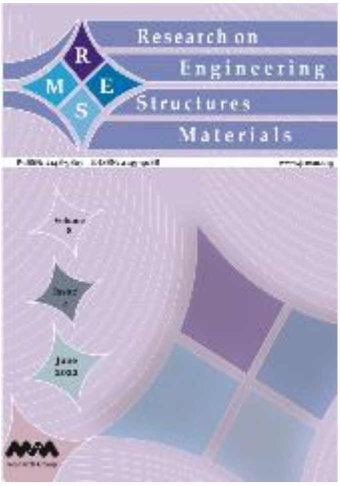

A Review of fatigue behaviour of resistance spot welds

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Technical Note

A Review of fatigue behaviour of resistance spot welds

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Abstract

Resistance spot welding (RSW) is a solid-state joining process in which sheet metal parts are joined by applying pressure and heat to the faying surfaces. Spot weld failure can cause severe mishap of any mechanical assemblies and can lead to severe damage. Therefore, robust design of spot welds for proper operation is essential. The cyclic stresses occurring on the spot welds in most of the applications result in fatigue failure of welds and decrease their performance efficiency and fatigue strength. This leads to failure of components at very low loads. Thus, it is essential to design the spot welds for fatigue loading conditions for all structures. This study presents the effects of critical factors affecting the fatigue performance of spot welds. The focus is on parameters, namely, sheet thickness, residual stresses, material properties and nugget size of spot welds.

1. Introduction

Resistance spot welding (RSW) is a widely used joining process in automobiles, aerospace, trucks, furniture, nuclear industries etc. to weld sheet metal components [1,2]. Particularly, 90% of the automobile parts are assembled by resistance spot welding process [3]. Spot welding is done in the automotive industry to transfer structural loads during crash. Around 4000 spot welds are performed in a vehicle for higher safety during a crash [4]. The spot-welding process involves thermal, mechanical and electrical interactions along the faying surfaces. Therefore, it is a complicated process and requires many design parameters like weld current, weld time, weld pressure etc. to be considered [5]. This process is also called thermo-mechanical-electrical coupled process. The ease of automation and robotization is the key feature of RSW process.

RSW is a solid-state joining process where the sheet metal parts are joined by heating at the faying surfaces. The resistance to current at the contact surfaces increases the heat and temperature rises. The metal surfaces begin to melt and localized nuggets are formed at the contact between two surfaces. Pressure is also applied on the copper electrodes to ensure proper contact between the surfaces. The current is then stopped and the pressure continues to be acting on the surfaces, which ensures cooling and solidification of the metal s. Spot weld failure can cause severe mishap of any mechanical assembly and can lead to severe damage. Therefore, robust design of spot welds for proper operation is essential.

There is a need to first understand the reasons as to complexity of spot welds and its factors for failure. There are three different zones formed at the weld nuggets, which have different microstructures. The fusion zone (FZ) shows cast structure with columnar grains. It determines the geometry of weld nugget and hence the strength of the spot weld. The heat-affected zone (HAZ), does not melt but undergoes microstructural deviations during

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heating. This zone can also affect the quality of spot welds. Base metal (BM) does not undergo any microstructural changes [6–8]. It is required to analyze the sensitization and strain hardening characteristics of all three zones for predicting the failure modes of spot welds. The failure analysis thus becomes more complicated. The failure also depends on the weld geometry and stress acting at the weld [9–12]. The difference in the strength of the zones causes strain concentration at the least strength zone and thus, to understand the mechanism of nugget failure, the strain properties of all zones should be studied [13]. The application of pressure on the electrode leads to the formation of an indent on the nuggets, which causes stress concentration at the weld. This causes reduction in the load-bearing capacity of the spot weld. This failure mode should also be considered during the design process [14].

Vehicle parts experience several vibrations due to rough roads, different driving conditions and road accidents. This causes fatigue loading on the spot welded parts and hence can cause fatigue failure of the spot welds [15–18]. The cyclic loading occurring on the vehicle reduces the performance efficiency of the spot welds and the tensile strength decreases considerably with the formation of fatigue crack. This leads to failure of the vehicle part at very low loads. Thus, it is essential to design the spot welds for fatigue loading conditions for all applications [19]. This critical review presents an understanding of the factors that affect the fatigue performance of spot welds. The focus is placed on parameters like sheet thickness, material properties and nugget size of spot welds.

2. Fatigue Failure Modes for Resistance Spot Welds

Resistance spot welds can fail due to many factors such as mechanical properties of the base material, welding time, welding force, sheet thickness, weld diameter. Interfacial (IF) mode, plug failure and pull-out failure (PF) are the three modes of spot welds failure. Crack propagation in IF mode is through FZ and it has a very high effect on the crashworthiness of the vehicle. In the PF mode, the weld nugget delaminates from one or more sheets and crack propagates from the base metal or heat affected zone. This depends on the sheet material and the geometry of the weld nuggets. Both these failure modes largely affect the energy absorption capacity and load-bearing capacity of spot welds. Due to higher energy absorption in the PF mode, spot welds are preferably designed considering the welding parameters for PF mode [20–23]. Fig. 1 shows the three modes of spot weld fatigue fracture. The PF mode in fatigue is divided into three stages: first, the initiation of fatigue crack, second, crack propagation through sheet thickness and third, crack propagation through sheet width [24]. A detail review of the effects of material properties, sheet thickness and nugget size on the fatigue behavior of spot welds is discussed in this paper.

3. Fatigue Performance of Resistance Spot Welds

3.1 Effect of Nugget Size

A study on the effect of different nugget diameters on the fatigue life of spot welds was done by [26]. Spot welding was performed to join two sheets of galvanized steel and austenitic stainless steel. The welding current was varied to get three different nugget diameters of 4 mm, 5 mm and 6 mm. Fatigue tests were performed on the specimens to get the S-N curve. The tests revealed similar fatigue life for all nugget diameters showing a little higher fatigue life for 6-mm nugget diameter.

(a) (b) (c)

Fig. 1 Fatigue failure modes (a) Pull out failure (b) plug failure (c) Interfacial failure [25]

Banerjee et al. [27] considered two specimens P1 and P2 with different RSW current and weld time parameters. Nuggets formed for P1 samples showed diameter of 5.4 mm and P2 samples predicted diameter of 4.42 mm. The samples were tested for fatigue failure at load range of 7.3 to 6.2 kN. The results predicted that even at larger loads, P1 samples exhibit higher fatigue life as compared to P2. Samples of P2 specimen showed interfacial failure mode and P1 samples showed pull-out failure mode.

Kato et al. [28] performed spot welding on three different material steel sheets of varying tensile strength. The welding parameters were controlled to get two different weld diameters of 5 mm and 3.8 mm. Spot welds with lower nugget diameters showed lower fatigue strength. For 5-mm nugget size, the fatigue strength was almost similar for all the three materials. This is due to dominant fatigue crack propagation life. For nugget size of 3.8 mm, the materials with higher tensile strength showed lower fatigue life.

Heewon Cho et al.[25] studied the fatigue and fracture behavior of Transformation Induced Plasticity Steel (TRIP) steels spot welds using two different electrodes of diameters 8mm and 10 mm. The electrodes with larger diameters gave larger nugget size. The fatigue tests showed that the fatigue life is more for larger nugget size. Fatigue fracture showed pull out, HAZ and plug fracture modes. For both the nugget sizes, the crack initiation occurred at the interface of HAZ region. In pull out fracture mode, the crack propagation occurred around the nugget whereas in the HAZ fracture mode, the crack propagated through the thickness of the sheets. However, the plug fracture occurs having characteristics of both HAZ and pull-out fracture. Fig. 2 shows the S-N curve for fatigue fracture of spot welds of TRIP steels for different electrode diameter.

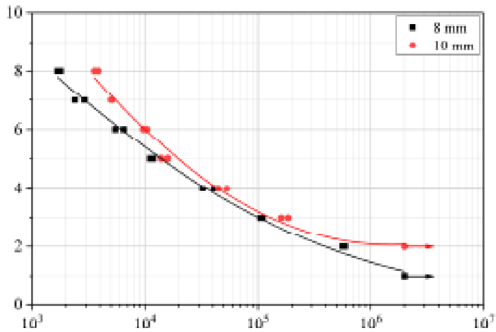


Fig. 2 S-N curve for fatigue fracture of spot welds of TRIP steels for different electrode diameter [25]

A recent study 29] investigated the fatigue life of two sheets of interstitial free steel and high strength niobium micro alloyed steel joined by resistance spot welds. Welding was performed with welding current of 7 kA and 9 kA and an electrode force of 2 kN. The nugget size formed varied due to the different welding currents. Fatigue strength for smaller nugget diameters was found to be high than the larger nugget diameters. This was due to the presence of compressive residual stress in the HAZ and higher micro hardness. The fatigue crack was intergranular, which initiated from interface of HAZ and interstitial free steel side base material.

A study of Akbulut [30] also predicted the influence of nugget size and sheet thickness on the fatigue life of spot welds. Tensile shear specimens of high strength low carbon steel sheets were used for the analysis. Strain-based approach using Coffin Mansion and Morrows mean stress equation was modeled for the specimen analysis. The results show that fatigue life is higher for higher thicknesses because of large elastic and plastic strains. Also, for fatigue life was more for specimens with larger nugget diameter.

Farrahi et al. [31] simulated a finite element model to determine the fatigue damage characteristics of a spotweld on a vehicle body. The results from the FEA model and experimental results were similar. The results showed that the spot welds with small diameters failed in larger number. Approximately 125 spot welds of diameter 2 mm failed due to fatigue. Likewise, spot welds of diameter 4 mm, 6 mm and 8 mm failed in lesser numbers. The comparatively lesser number of spotwelds with 8 mm in diameter failed in fatigue. This can be because the nugget size affects the stiffness of spot welds and thus, the stress concentration at the weld. Thus, the nugget size should be carefully designed to avoid the fatigue failure. Fig. 3 explains the overview of effect of nugget size on fatigue life.

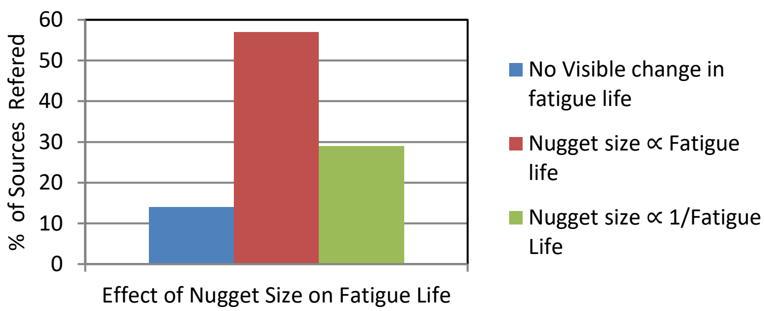


Fig. 3 Overview of effect of nugget size on fatigue life.

3.2 Effects of Sheet Parameters (Geometry/Material)

Bae and Sohn[32] discusses the effect of residual stress, thickness, width and joining the angle of sheet on fatigue life of spot-welds. Fatigue testing was performed for the tensile mode at frequency of 25Hz and stress ratio 0. Variation in fatigue life for different thicknesses is not much significant. However, for smaller loads, the fatigue life increases with an increase in thickness as higher thickness will have higher bending rigidity. Fatigue life decreases as the joint angle increases. However, the effect of sheet width on fatigue life is unpredictable. To consider the effect of residual stress, goodman equation was used to describe a fatigue life equation. It was observed that the there is a significant decrease in fatigue life considering the residual stress at the weld nuggets. Thus, it is essential to consider the residual stress while predicting the fatigue life.

Vural et al. [26] performed fatigue tests on spot welds used to join two similar sheets of austenitic stainless steel and dissimilar sheets of galvanized steel and austenitic stainless steel. Fatigue test results reveal that the spot welds on similar sheets have higher endurance strength than that of dissimilar sheets. This is due to the different expansion properties of different materials. The nugget formed is not symmetrical in the case of dissimilar sheets and thus the fatigue life is lower. Xin Long and Khanna [33] also predicts the fatigue strength of different high strength steel materials. The author mentions that there was no significant change in the fatigue strength of different material spot welds. Fatigue strength depends on loading conditions on spot weld and stress concentration at the weld nugget.

Research shows that with an increase in sheet thickness, the fatigue life decreases. The author modeled the Paris law for determining the effect of sheet thickness on fatigue life of spot weld [34]. In a work of Rahman [35] ,the author considered two specimens of sheet thickness of 1.2 and 0.2 mm for fatigue testing of spot welds. The sheet with 1.2-mm thickness showed larger fatigue life than the other sheet.

Xue, et al. [36] performed fatigue tests to find out the fatigue strength of spot welded dissimilar sheets. AA5754 sheet and high-strength low-alloy (HSLA) steel sheet were welded together with spot welds. The fatigue tests revealed that the fatigue strength of such dissimilar configuration was more than AA5754 welded to itself. Finite element simulation was conducted which enhanced that the larger notch root angle at the weld nugget gives a higher fatigue life as the maximum principal strain is reduced effectively. Fig. 4 explains the overview of effect of sheet material on fatigue life.

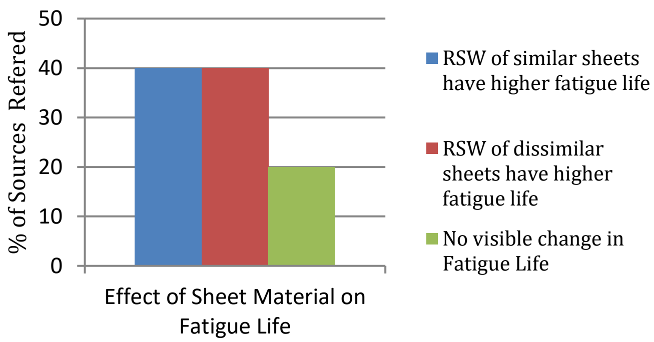
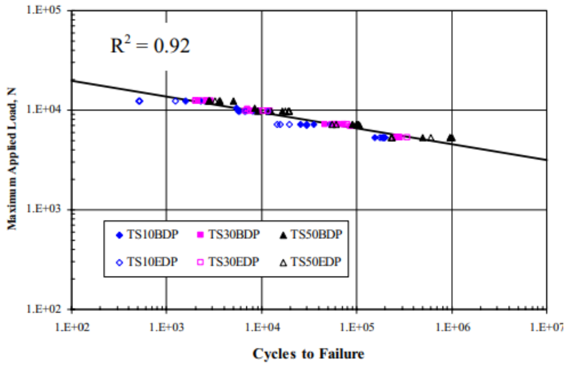


Fig. 4 Overview of effect of sheet material on fatigue life

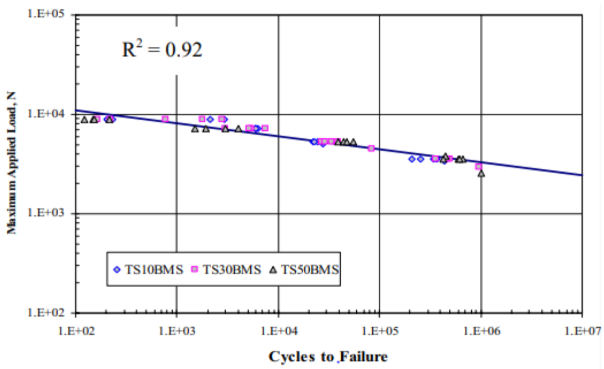
3.3 Effects of RSW Parameters

Kang et al. [37] studied the fatigue performance of three sheets of dual phase 600 and mild steel welded separately. Two shapes of electrode tip B nose and E-nose were used for welding. Fatigue tests at a frequency of 10 Hz and stress ratio of 0.01 were performed for both the specimens. Tests were also performed for different indentation levels. The results show that the shape of the electrode tip did not affect the fatigue life of DP600 steel spot welds. Also, fatigue life was not significantly affected by the different indentation levels for both the materials. Dual phase 600 material showed larger fatigue life than mild steel. Fig. 5 shows number of cycles to failure for DP600 and mild steel.

Pal [38] predicted the fatigue behavior of spotwelds used to join sheets of martensitic steels. The welding conditions were varied by changing the welding current, weld time and weld force. Thus, for every specimen, the nugget diameters obtained were different. All the specimens showed similar fatigue characteristics at lower loads, but showed significant variation at higher loads. At the higher loads, interfacial fracture is observed, which propagates through the weld metal. However, the crack fails to propagate through the weld for lower loads. At the lower loads, plug and hole fracture mode is observed. There is transition in fracture mode at 50% loading of the yield stress.



(a)



(b)

Fig. 5 (a) No. of cycles to failure for DP600, (b) No. of cycles to failure for mild steel [37]

Duan et al. [39] predicted the fatigue life of spot welds used in tensile shear and cross tension specimens of steel. It was seen that the fatigue limit of the tensile shear specimen was more that than that of the cross-tension specimens. Fatigue cracks for both the specimens were initiated in the HAZ region at the notch tip and also at the interface boundaries of the two sheets. The fatigue crack propagation was through the thickness and then into the width of the sheet before the final fracture for tensile shear specimen. However, the crack propagation for cross tension specimen was completely through the thickness only before the final fracture.

Duan et al. [40] compared the fatigue life of spot weld on two materials high strength steel and mild steel. The high strength steel sheet had a thickness of 1.8 mm and M190 steel had a thickness of 1.2 mm. Fatigue strength was more for high strength steel spot welds due to thicker sheets and proper nugget formed which follows the standard nugget size rule. The crack initiated at the edges of the sheet or at the interface of two sheets and propagated through the HAZ region.

Rao et al. [41] considered two dissimilar sheet stackups of wrought aluminium and interfacial steels and two similar sheets of wrought aluminium. These materials were spot welded in two configurations first, tensile shear and second coach peel. For the tensile shear configuration, the fatigue life of dissimilar stackup was higher than similar aluminium stackup and for coach peel configuration there was not much difference in the fatigue life of spot welds for both the combinations of materials. The dissimilar materials stackups showed better performance due to larger weld nuggets formed. For both configurations of tensile shear and coach peel, the crack growth was seen from the aluminium sheet.

Ordoñez et al. [42] studied the resistance of spot welds used to join dual phase steels by fatigue tests. It was found that due to the stress concentration at the weld nugget at the fusion zone, the fatigue life of weld decreases. Fatigue failure was initiated at the sheet interface. Compressive residual stresses on spot weld increases its fatigue life. A work of Fujimoto et al. [42] also increased the compressive residual stresses in spot weld lap joints of high strength steel sheets by shot blasting process. The work reported that with the compressive residual stress, the fatigue life of spot weld is improved.

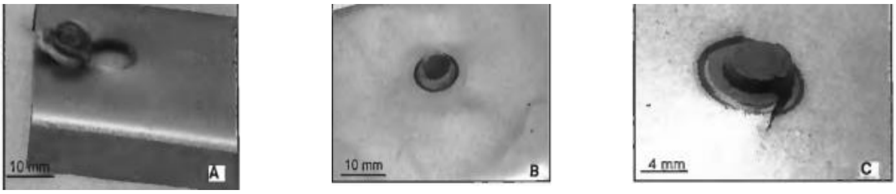
Kang et al. [44] also considered the spot weld joining of aluminium and steel sheets. Three specimens were considered, Al-Al weld, Al-steel weld with positive electrode polarity and Al-steel weld with negative electrode polarity. The fatigue analysis was performed to understand the effect of nugget diameter, notch angle and polarity on the fatigue life of spot welds. The research predicted that the nuggets with negative polarity show the largest fatigue life than the nuggets with positive polarity. Also, the Al-Al sheet nuggets showed the least fatigue life. The results were more significant for tensile shear specimens than for the coach peel specimens. Al-Al sheets, had a lesser nugget size of 6.2 mm whereas the Al-Steel sheets had nugget diameter of 8.5 mm approximately. This also shows that the sheets with larger nugget diameters have larger fatigue life as it would take larger energy to fail. Another consideration showed that, as the notch root angle decreased, the tensile stresses increased. This also affects the fatigue life of spot welds. The spot welds with negative polarity have notch root angle of 33 degrees whereas, the welds with positive polarity had a notch root angle of 11 degrees. Thus, owing to increase in the tensile stresses, spot welds with lesser notch root angle failed at had lesser fatigue life.

4. Fatigue Failure Characteristics

There is a lot of research where results on fatigue life of spot welds is studied. However, study on the fatigue crack initiation and propagation is very difficult as fatigue cracks occur at a very critical area of spot weld at the sheet interface. This area undergoes several microstructural changes and hence it is very difficult to understand the fatigue mechanism from the point of fracture mechanics. Also, fatigue cracks are not easily visible unless the specimen fails through the thickness. As direct observation was not possible, scientist used instruments to study the crack nucleation and propagation after fatigue loading on spot welds [45].

Hassanifard et al. [46] reported that there is higher stress concentration at the circumference of nugget and hence the crack initiation takes place from such areas. Lanciotti and Polese [45] described the fatigue crack initiation and propagation in spot welded stainless steel. The author mentioned that the crack initiation takes place at a distance of 0.93 mm from the spot weld nugget. The crack initiation took place for 10% of fatigue life. Another research [47] considered the use of half cut tensile shear specimens to study the fatigue fracture mechanism in spot weld. Steel sheets of hot rolled high strength galvanized alloy were spot welded and tested. The spot welds developed crack of depth 0.25mm at 50% of its fatigue life. The crack was measured after the crack initiated and until the early propagation phase. A study was also done to report the effect of fatigue crack on stiffness of spot welds. The experimental results showed that the stiffness is not affected until a large crack is formed [48].

Pouranvari and Marashi [4] reported that there are various different crack propagation modes for spot welds within low cycle and high cycle region. They mentioned that within the low cycle region, the crack propagates through the base material while within the high cycle region; the crack propagates through the HAZ region. (Xu et al.) [16] found that the kinked angle for the fatigue crack was 80 º. (Newman and Dowling) [49] also formulated an equation to calculate J integral and stress intensity factor and reported that the kinked angle for fatigue crack was 75º. The crack propagation can be predicted by calculating the stress concentration at the weld nugget area and the crack growth angle. The tensile shear and cross tension configurations can have plug type and interfacial fracture mode [50]. Fig. 6 (a), (b) shows the plug type fracture mode for tensile shear and cross tension specimen. Fig. 6 (c) shows the interfacial fracture mode for cross tension specimen.



(a) (b) (c)

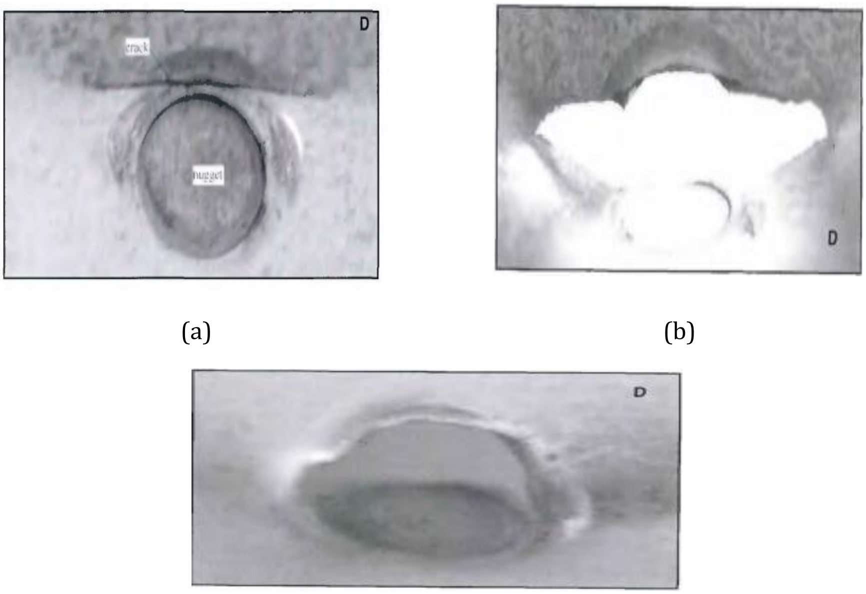
Fig. 6 (a) Plug type fracture mode for tensile shear (b) For cross tension specimen. (c) Interfacial fracture mode for cross tension specimen [50]

Ma et al. [51] reported that the fatigue fracture initiates in the HAZ region showing plastic deformation at higher load levels. The crack initiates at the nugget area, penetrate through the thickness of sheet and propagate through the base metal along the normal to the load at lower load levels. Also, for intermediate load levels, the fractures initiate at the nugget area and propagate along the circumference, and fractures takes place in the base metal. The natural frequency of spot welds significantly changes after the fatigue life reaches more than 50% of the total fatigue life. At 95% of life, the cracks were visible on the surfaces of the joint [52]. First fatigue crack was seen at approximately 50% of total fatigue life of spot welds.

Cooper and Smith [53] tried observing the fatigue crack length of spot welded mild steel sheets. The authors used tensile shear specimens for the test. The potential drop method was used to estimate the crack length. The principal fatigue mechanism was macro crack propagation in the spot welds and the cracks propagation rate was constant throughout the thickness. A work of Swellam et al. [54] also predicted the fatigue crack mechanism in high strength steel spot welds and galvanized steel spot welds. Nucleation of cracks was the major fatigue mechanism for galvanized steel while crack propagation through thickness was that for high strength steel.

A work of Wang and Barkey [55] reported three different fatigue failure modes. In mode A, the crack initiates away from the spot weld nugget, propagates through the base metal and the crack growth was in a straight line. In the mode B, the crack initiation was at the HAZ region and propagated around the spot weld nugget and finally through the base sheet until fracture to partially break the weld at the nugget edge and partially at the base sheets.

Nugget is rotated before fracture. There is no nugget rotation in mode A. In the mode C, the crack is seen to propagate around the spot weld nugget and fracture is seen when half of the nugget is peeled out of the sheet. The nuggets rotated by about 90 ° before final fracture. Mode A occurs at high cycle tests and mode C occurs at low cycle tests. Mode B occurs between the two. Most cracks propagated in mode C and very few cracks propagated in mode A. For all modes, crack initiated at approximately 50% of the total fatigue life. Fig. 7 shows failure of spot welds due to fatigue in mode A, B, C.



(a) (b)

(c)

Fig. 7 Fatigue failure of spot welds in modes A, B, C [55]

The fatigue fracture mode of spot welds with positive polarity was observed to be interfacial mode. The weld with negative polarity failed with pull-out fracture mode. The specimen with a smaller notch root angle of 11 degrees exhibited a large shear stress at the notch tip and hence the fatigue crack growth was interfacial. Whereas, specimens with a larger notch root angle of 33 degrees, did not show much stress concentration at the notch tip and hence exhibited a pull-out fracture mode at the weld [44].

Mukhopadhyay et al. [56] studied the fatigue failure of DP600 resistance spot welded steels of thickness 1.4 mm .High cycle fatigue tests were conducted for tensile shear configuration at 3.8kN electrode force. The fatigue crack initiated at the HAZ and propagate through the thickness of sheets till complete fracture. The fatigue failure occurred due to stress concentration at the sheets interference and due to strength of DP600 steel.

Table 1. Summary of the effects of different welding factors on fatigue life of spot welds

	Factors	Effect on fatigue life of spot weld
[27], [28], [25], [30]	Nugget size	Larger nugget sizes exhibited a higher fatigue life.
[29]	Nugget size	Fatigue strength for smaller nugget diameters was found to be higher.
[31]	Nugget size	The spot welds with least diameter failed due to fatigue in large numbers
[26]	Sheet material Nugget size	Spot welds used for joining similar sheets have a higher fatigue limit than that of dissimilar sheets. Similar fatigue life for all nugget sizes.
[33]	Sheet material	Different materials do not significantly affect the fatigue strength of spot weld
[34]	Sheet Thickness	With an increase in sheet thickness, the fatigue life decreases
[32]	Sheet thickness Joint angle Residual Stress Sheet width	Fatigue life increases with an increase in thickness. Fatigue life decreases as the joint angle increases. A significant decrease in fatigue life considering the residual stress at the weld nuggets. The effect of sheet width on fatigue life is not predictable.
[35], [40]	Sheet Thickness	The increase in sheet thickness, the fatigue life increases
[36]	Sheet Material Notch root angle	Fatigue strength of such dissimilar configuration of AA5754 sheet and high-strength low-alloy (HSLA) steel was more . Larger notch root angle is beneficial to achieve longer fatigue life .
[37]	Electrode Tip Indentation levels Sheet material	The shape of the electrode tip did not affect the fatigue life of spot weld Not significantly affected by the different indentation levels for both the materials Dual phase 600 material showed larger fatigue life than mild steel.
[38]	Weld Current Weld Time	All the specimens showed similar fatigue characteristics at lower loads but showed a significant variation at higher loads
[39]	Tensile shear configuration Cross Tension configuration	Fatigue limit for tensile shear specimen was more that than the cross-tension specimen.
[42][43]	Compressive residual stress	Fatigue life improves with induced compressive residual stress in spot welds.
[41]	Sheet material	Fatigue life of dissimilar stackup was higher than similar aluminium stackup.
[44]	Nugget diameter Notch angle Polarity	Sheets with larger nugget diameters have larger fatigue life as it would take larger energy to fail As the notch root angle decrease, fatigue life decreases The nuggets with negative polarity showed largest fatigue life than the nuggets with positive polarity

5. Conclusion

Resistance spot welding is a solid-state joining process wherein sheet metal parts are joined by heating at the faying surfaces. It is a complex thermo-mechanical-electrical coupled process. Mechanical structures that undergo extensive vibrations can cause repetitive loading on the resistance spot welds that leads to fatigue failure. Spot welds have different regions of different microstructures and hence, they are very critical to study for its fatigue failure. It is thus important to consider fatigue parameters while designing the resistance spot welding process. This review presents the study of critical factors affecting the fatigue performance of spot welds. The focus is on RSW parameters and sheet parameters. RSW parameters include weld current, weld time, residual stresses polarity while sheet parameters include sheet materials, sheet thickness and nugget size.The findings of the review are as follows:

- It is observed that with an increase in sheet thickness and nugget size, the fatigue life of spot welds increases. This is due to a decrease in the stress concentration at the nugget area.
- Spot welds used for joining sheets of dissimilar material have lesser fatigue life due to the different thermal expansion coefficients of materials.
- Fatigue life improves with increase in compressive residual stresses at the spot nuggets.
- There is no effective change in fatigue strength with change in weld current or weld time.
- Fatigue cracks occur at the sheet interference and hence it is very difficult to study the fatigue crack characteristics.
- Spot Welds with positive polarity failed in an interfacial mode while welds with negative polarity failed with pull-out fracture mode.
- Crack propagation in IF mode is through the FZ. In the pull-out mode, the weld nugget delaminates from one or more sheets and crack propagates from the base metal or heat affected zone.
- Due to higher energy absorption in the pull-out mode, spot welds are preferably designed for this fracture mode.

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