Fatigue Life Prediction of Spot Welded Joints: A Review

Vipin Wagare

Abstract Resistance spot welding (RSW) is a major sheet metal joining process. It is widely used in many industries, such as the automotive, aircraft and spacecraft industries. Resistance spot welding (RSW) is dominant joining method which is very complicated process including close interaction of electrical, thermal, mechanical, and metallurgical phenomena. In the present automobile sector, vehicle contains about 4000–5000 spot welded joints, which has been subjected to continuous variable type loading condition. The life and structural integrity of this spot welded joints depends on many parameters. This is a review work that looks into the fatigue behavior of spot welded tensile lap shear specimen under cyclic loading condition. The main objective is to study the effects of different processes, designs, material parameters on the fatigue behavior of spot welded joints. The design parameters of spot welded lap specimens like distance between spot, number of spots as well as process parameters like nugget diameter weld time, electric current, etc., are varied and the effects on the structural integrity and fatigue behavior of spot weld joints have been observed.

Keywords Fatigue life · Fatigue damage · Strain life criterion
Cycles to crack initiation

1 Introduction

Spot welding is one among the oldest welding processes. It is a kind of resistance welding that could be a methodology of welding two or a lot of metal sheets along while not victimizing any filler material by applying pressure and heat to the world to be welded. Resistance spot welding could be a widely used connection method for fabricating sheet assemblies like vehicles, truck cabins, rail vehicles and residential applications as a result of its blessings in welding efficiency and quality for

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automation. As an example, a contemporary automotive body assembly wants 8000–10,000 spots of welding.

So it is required to look at the weight reduction of car and improve the fuel economy as well as to reduce exhaust emission gases by the use of lightweight materials like aluminum alloys. Aluminum alloys have applications in designed vehicles, trunks and doors.

The objective of this study is to review the knowledge about the influencing design, process and fatigue parameters on the fatigue life of spot welded specimen, and numerical techniques for fatigue life calculation and to discuss the future trends in spot welding to improve its joint strength and life.

Sohn [1] proposed the best method to determine fatigue design criteria for spot welded joint specimen of specific geometry details and materials. The method has been verified by the theory of Weibull probability distribution since fatigue strength of the spot weld affects structural rigidity and durability of the spot welded structures; safety and structural integrity of the structure are determined by fatigue strength of spot welded joint.

Therefore, correct stress analysis and systematical fatigue strength analysis of spot welded joint area unit important to work out its long fatigue design criterion. However, it is terribly troublesome to workout the fatigue design criterion with the particular structure directly. Thus, when estimating fatigue strength with simulated specimen satisfying the structural characteristic of the particular structures, the fatigue design criterion is mostly determined and applied to fatigue design of the spot welded structures.

Rahman [2] conducted the parametric studies of design parameter of spot weld on fatigue life of joint. It has been predicted as position of the weakest weld nugget during variable amplitude loading condition.

Ahmet [3] has investigated the fatigue lives of spot welded lap shear specimen which is made of low carbon steel under variable amplitude load condition. Experimental fatigue testing has been carried out for two types of resistance welding, i.e., manual type and automated type. The virtual testing simulation work has been carried out using commercial CAE tool and parametric study performed on fatigue lives of spot weld joint using coffin monsoon, morrows means stress models.

Gean [4] has conducted static and fatigue experimental testing of 1.2-mm aluminum alloy. Extensive work has been done, and investigated nuggets porosity, surface indentation, nugget size have no major effect on fatigue life of spot weld joint.

Spot welding is widely used sheet metal joining method in automobile sector because of its speed of welding, spot precision, efficiency and cost reductions. The spot welding process is used to join sheet materials using copper electrode and apply pressure with electrical current through the worksheet. In these steps during the current flow, the parts locally get heated and the material volume in-between the electrodes is yielded and squeezed and then it melts, destroying the interface between the worksheets. When the electric current supply has been switched off, the "nugget" of molten materials is formed. The material is with having high electrical resistivity and low thermal conductivity than the electrode used is suitable to choose such as steel because it making welding relatively easy. For another material such as aluminum, its electrical resistance and thermal conduction is nearer to that of copper; however, the melting point for this material is less than copper, so creating a weld is feasible (Kalpakjian et al.). In the spot welding, some of its parameters need to be thought about. These parameters can have an effect on the standard of the spot welds and its strength. The right combination of the spot welding parameter can manufacture a robust connection kind of joint. Spot welding parameters include:

(1) Electrode force
(2) Diameter of the electrode contact surface
(3) Squeeze time
(4) Weld time
(5) Hold time
(6) Weld current

The fatigue strength of the joint during this method depends on the quantity and size of spot welded structure of the welds. The diameters for spot weld vary from 3 to 12.5 mm (Milleer 2004). To analyze the strength of spot welds in terms of the specimen pure mathematics, attachment parameter, attachment schedule, base metal strength, checking speed and testing configuration, the tensile test methodology can also be used to analyze the strength of the spot weld.

2 Models for Fatigue Life Assessment

Different fatigue life prediction techniques have been suggested in the literature. They are classified on the basis of strain- and stress-based approaches in general.

- *Stress-Based Approaches*

These are the earliest, but the most widely used approaches. They are based on the assumption that the range of values for stress controls the fatigue behavior of a component. They involve empirical relations between uniaxial fully reversed stress and fatigue life (*S-N* curves), which are obtained through the standard rotating bending testing. However, mechanical components are usually subject to stresses oscillating about an average stress level. For these cases, a number of models were proposed [5–9, 20–25]:

$$\frac{S_a}{S_f} + \frac{S_m}{S_{ut}} = 1 \text{ (Modified Goodman, England-1899)}$$

$$\frac{S_a}{S_f} + \frac{S_m}{\sigma_f} = 1 \text{ (Morrow, USA-1960s)}$$

where S_a is the alternating stress, S_m is the mean stress, S_f is the fully reversed fatigue strength of the specimen, S_{ut} is the ultimate tensile strength. There is a controversy on how the equivalent stress should be calculated. Use of the maximum principal stress

$$S_{ea} = \sigma_{a1}$$

maximum shear stress

$$S_{ea} = \sigma_{a1} - \sigma_{a3}$$

or von Mises stress

$$S_{ea} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{a1} - \sigma_{a2})^2 + (\sigma_{a1} - \sigma_{a3})^2 + (\sigma_{a2} - \sigma_{a2})^2}$$

was suggested as representative of equivalent alternating stress, S_{ea}. Here, σ_{a1}, σ_{a2} and σ_{a3} are principal alternating nominal stresses with $\sigma_{a1} > \sigma_{a2} > \sigma_{a3}$. For equivalent mean stress, σ_{em}, similar suggestions were made [26]. For example, use of von Mises stress

$$S_{em} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{m1} - \sigma_{m2})^2 + (\sigma_{m1} - \sigma_{m3})^2 + (\sigma_{m2} - \sigma_{m2})^2}$$

or sum of the normal mean stresses

$$S_{em} = \sigma_{m1} + \sigma_{m2} + \sigma_{m3} = \sigma_{mx} + \sigma_{my} + \sigma_{mz}$$

was suggested as representative of equivalent mean stress, S_{em} [26]. Equivalent stress approaches are extensions of the yield criteria to fatigue.

- *Strain-Based Approaches*

According to these models, the range of values for strain controls fatigue life. They also take into account the effect of plastic strain. They are therefore especially suitable for cases where plastic effects dominate fatigue behavior. Although most engineering structures are designed such that the nominal stresses stay elastic, stress concentrations typically cause plastic strains to develop within the locality of notches, e.g., spot welds in our case. Fatigue cracks usually nucleate due to plastic straining at the notches. The total strain amplitude is resolved into elastic and plastic strain elements, all of that was shown to be correlative with fatigue life in an exceedingly linear fashion victimization log-log scale for many metals [7].

One method, referred to as “Morrow’s mean stress method,” can be written as [10, 24, 26],

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f' - \sigma_m}{E}(2N_f)^b + \varepsilon'(2N_f)^c$$

where σ_f' is the fatigue strength coefficient, ε_f' is the fatigue ductility coefficient, b and c are exponents determined by experiments, and σ_m is the mean stress.

In the case of multiaxial stress and strain state, equivalent alternating strain is calculated [7, 9, 21] using either maximum principal strain

$$\varepsilon_{qa} = \varepsilon_{a1}$$

or maximum shear strain

$$\varepsilon_{qa} = \frac{\varepsilon_{a1} - \varepsilon_{a3}}{1 + v}$$

or octahedral shear strain

$$\varepsilon_{qa} = \frac{\sqrt{(\varepsilon_{a1} - \varepsilon_{a2})^2 + (\varepsilon_{a2} - \varepsilon_{a3})^2 + (\varepsilon_{a3} - \varepsilon_{a1})^2}}{\sqrt{2}(1 + v)}$$

where $\varepsilon_{a1}, \varepsilon_{a2}$ and ε_{a3} are principal alternating strains with $\varepsilon_{a1} > \varepsilon_{a2} > \varepsilon_{a3}$.

One more equation derived by Smith, Watson, and Topper (often called "SWT parameter") is given by [6, 20, 21],

$$\sigma_{max}\varepsilon_a E = \left(\sigma_f'\right)^2 (2N_f)^{2b} + \sigma_f'\varepsilon_f' E (2N_f)^{b+c}$$

In addition to these equations, there are two more universal relations which are used in fatigue life calculations proposed in the literature based on the experimental data. These relations are "Muralidharan and Manson" and "Brinell hardness" equations written as the following.

$$\frac{\Delta\varepsilon}{2} = \varepsilon_a = 0.623\left(\frac{S_{ut}}{E}\right)^{0.832}(2N_f)^{-0.09} + 0.0196(\varepsilon_f)^{0.155}\left(\frac{S_{ut}}{E}\right)^{-0.53}(2N_f)^{-0.56}.$$

3 Design and Process Parameters

3.1 Specimen Thickness and Nugget Diameter

Figure 1 shows the result of the sheet thickness and spot diameter on the fatigue lifetime of the spot weld structure. Spot weld diameter of 2.5–8.5 mm and sheet thickness for one and a couple of zero. From 2 to 1.2 mm are thought of during this study, the spot weld diameter and therefore the thickness of the sheet metals

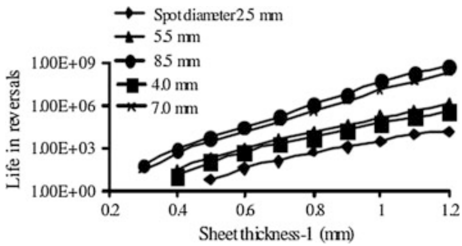


Fig. 1 Effect of the sheet thickness

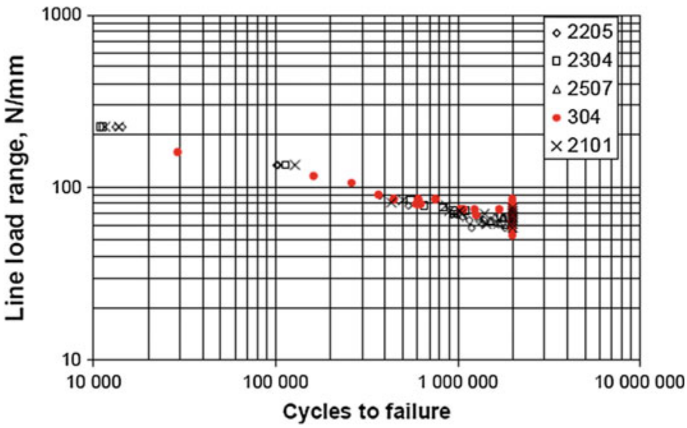


Fig. 2 Effect of the sheet thickness

influences the fatigue lifetime of the structure. It is discovered that the fatigue lifetime of the structure will increase with the increase in the spot weld diameter and thickness of the sheet. Increase in shear strength may be stopped with the increase in sheet thickness. Less thickness sheet probably failed in pull-out-type failure mode during testing. It is observed that there is gradual increase in strength after the thickness of sheet is increased. Because of more thickness, more surface contact area is formed in-between the weld and specimen. The strength of spot weld joint increases as the diameter of nugget significantly increase in strength of spot weld joint. It occurs because more nugget diameter contains more volume of metal which is nothing but more surfaces in joint so more shear strength obtained. In graph smooth linear curve has been obtained from experiment. So, we can say that by the increase in nugget diameter we can also increase the shear strength of spot weld joint (Fig. 2).

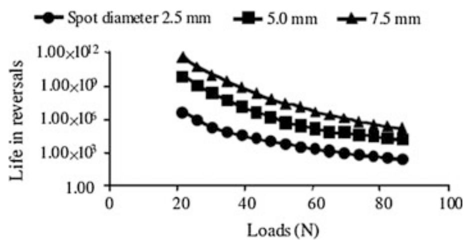
3.2 Effect of Material Strength

Linder and his colleagues [11–13] have studied the spot welded joint with explicit relevancy fatigue characteristic. A separate study by Marples [10] is additionally according during this section. Three completely different joint configurations (test specimen types) are studied as shown in Fig. 3. Nord [4] has tested spot and projection welded 1.5-mm temper-rolled AISI 301 employing a forty six-millimeter-wide sort 3 specimen. Yield and tensile strengths were 1072 and 1391 MPa severally. The amount of specimens tested for every series of spot welded joints was depleted for a calculation of confidence limits and however brought along as in Fig. 8; the fatigue strength at 2 * 106 cycles will be calculable to be 1.68 kN or 70 N/mm, forward a 24-mm pitch. The uncertainty is calculable as ± 10 N/mm. Lump size was 6.4 mm. For a smaller lump size, 5.3 mm, the fatigue strength is reduced; however, looking at series it was too tiny to make sure a big distinction. These results are almost like those of the medium-strength AISI 304 on top of the Ueda and Kawataka [12]-tested single row, multiple spot joints of 1.5-mm-thick AISI 301. The fatigue testing was done on a 120-mm-wide specimen with 35-mm overlap and 192-mm grip distance. Over the breadth, a pair of, 3, 4, 6 and 12 nuggets with 7 mm diameter were welded. This resulted in pitch distances of 60, 40, 30, 20 and 10 mm. The results are shown in Fig. 12. It has been shown many times that fatigue properties for joints in steel sheets with completely different parent material strengths are similar. This is often illustrated in Fig. 16 to be the case even for untainted steels. In this figure, the fatigue results for various untainted steels with yield strengths within 290 and 725 MPa are compared. For spherical clenched joints, there are indications that accumulated strength results in accumulated fatigue strength; however, at intervals a restricted vary since use of the clinching method set limitations on the clinch ability of thicker material.

3.3 Effects of the Loads

Figure 3 shows the consequences of the masses and confidence of survival on the fatigue life on the spot weld structure. From the obtained results, it is often seen from Fig. 11 that the fatigue life decreases linearly with the increase in hundreds;

Fig. 3 Effect of the sheet thickness



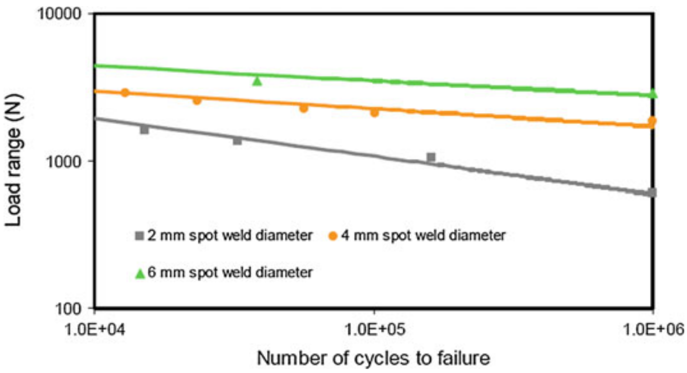


Fig. 4 Fatigue lives predicted using "Coffin and Manson's approach" for TS specimen [3]

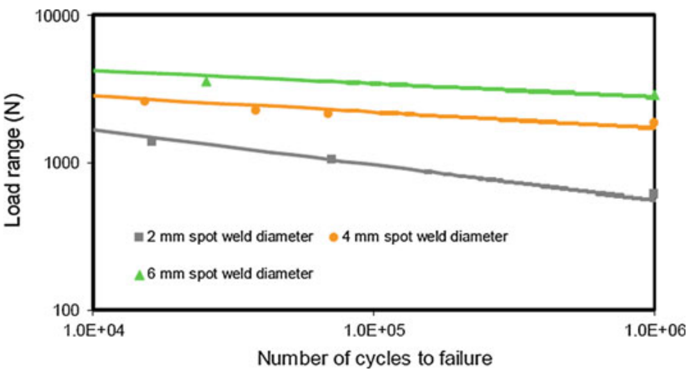


Fig. 5 Fatigue lives predicted using "Morrow's mean stress approach" for TS specimen [3]

however, the fatigue life increases with the increase in spot weld diameter. The obtained results from Fig. 12 clearly show that the fatigue life influences the arrogance of survival parameter that is predicated on the quality error of the *S*-*N* curves.

3.4 Distance Between Two Spot

It is observed that as the distance between two spots is increased the curve linearly increases and shear strength of weld is increased. In our experiment, distance between two spots varies from 9 to 13 mm. As the distance between spot weld joints increases, there is after certain limit a decrease in strength because bending action takes place and failure occurs. Above given distances are least it means if less distance then there will be overlapping of the nugget diameter which affect strength of weld and if more than upper then decrease In lap shear strength of spot weld joints.

3.5 Effect of Corrosive Field

The result of a corrosive (3% NaCl aqueous) setting on the fatigue properties of spot welded AISI 304 and duplex SAF 2304 chrome steel is reportable by Linder and Melander [14]. The study was created on four metric linear unit sheet material victimization specimens sort one at close temperature and 50 cps. In the fatigue testing, the run-out was set at 107 cycles, and therefore, the testing time was up to 60 h. Result of testing setting. Testing in aggressive third common salt setting reduces the fatigue strength of spot welded AISI 304 chrome steel joints at long lives by up to four-hundredth. Exposure of up to 2000 h before testing failed to have more effect on the fatigue strength. Though not tested a similar response is anticipated for tight joints and optical maser welded joints. Unblemished to galvanized steel joints have not been tested in aggressive environments; however, area unit is expected to be terribly sensitive owing to galvanic corrosion. Connection ways. Spot welded and projection welded joints show similar fatigue strengths. Within the thickness from 0.8 to 1.5 metric linear unit spot attachment, optical maser attachment and adhesive bonding have similar fatigues strength, 70 N/mm. Dry setting adhesive bonding and combination of spot attachment and adhesives have potential to present very high fatigue strengths compared with spot attachment. The result of adhesives is larger for thicker materials. At around one metric linear unit, thickness spot attachment and rectangular clinches offer similar fatigue strengths, generally 1.2 kN per lump or clinch. Spherical clinches offer some double this fatigue strength.

3.6 Numerical Modeling

In the FE model, a 3D 10-node tetrahedral solid part, SOLID92, was used for the bottom metal [3]. This part has physical property, stress stiffening, massive deflection and huge strain capabilities. On the other hand, the nugget was sculptured employing a two-node beam part, BEAM188. Contact and target parts, Targe170 and Conta175, were created on the inner surfaces of the plates round the spots. The beam part, BEAM188, is predicated on Timoshenko beam theory. Shear deformation effects are thus enclosed that are particularly vital for brief beams. This part has six degrees of freedom at every node. As a result of the nugget experiencing low stresses, its material model was chosen as linearly elastic. In welding method, heat treatment does not have an effect on the mechanical properties of the fabric. Therefore, it is necessary to use identical material properties for the hunk and base metal. Hence during this study, base metal and spot weld hunk square measure modeled victimization identical material properties that young's modulus and poison's quantitative relation as 2.07E5 Mpa and 0.25, respectively [3]. First, the strain and strain values of the essential nodes of spot welded MTS and TS for various spot weld diameters were calculated employing a nonlinear finite component analysis (FEM). Once these calculations were done, it was clear that a stress concentration or singularity exists at the interception of the hunk boundary with the interface of joined sheets as a result of all von Misses stresses, tensile stresses, bending stresses, etc., having their most magnitudes close to the hunk boundary (that is the inner surfaces of flanged or center items of TS specimens on the peripheries of the spots). These stress distributions make a case for with success the development that why the fractures square measure usually initial created round the nugget for the spot welded joints. Peak tensile stress values on x, y and z directions were found at the inner edges of the spot welds, whereas peak compression stress values were found at the external edges of the spot welds. Thence, it may be aforesaid that the high tensile stresses along with the high tearing stresses square measured all settled at the perimeters of the spot welds within the spot welded joints and can cause bending of the lap zones of the specimens though this bending values in tensile shear specimens (TS) do not seem to be therefore essential. Using differing kinds of fatigue life prediction techniques, typical spot weld fatigue results for various pure mathematics and spot weld diameters are given through Figs. 4 and 5[3].

4 Conclusion

The fatigue life of the spot welded specimens depended most importantly on the kind of specimen, applied load amplitudes and off beam the spot weld diameter. The behavior of diameter of spot weld and sheet thicknesses are important parameters in stress distribution close to spot welds. The uninheritable results show that the spot diameter and thickness of the sheets greatly influence the fatigue lifetime of the spot welded structures. The results of the loading and geometric configuration on the fatigue lifetime of spot welded joints may be directly incorporated within the structural stress methodology. Equivalent stress approaches have been commonly used because of their simplicity, but their success in correlating multiracial fatigue data has been limited to a few materials and loading conditions. In addition, they should be used only for proportional loading conditions, in which the principal axes directions remain fixed during the loading cycle. It is familiar that the failure modes for tensile and changed tensile loading cases depended totally on the magnitude of the applied mean load and therefore the nugget diameter. It absolutely was determined that the amplitude of the applied load seems less of an impact on the ultimate failure mode, though this had a major result on the specimen fatigue life.

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