A method for prediction of S-N curve of spot-welded joints based on numerical simulation

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Abstract
Currently, ΔF-N curves are often used to predict the fatigue lives of spot-welded joints, but the method for obtaining these ΔF-N curves is time-consuming, laborious, and non-universal. Tensile-shear fatigue tests were performed to obtain the fatigue lives and the corresponding normalized S-N curves of spot-welded joints. Subsequently, the force acting at the spot-welded joints was obtained by extracting the force and moment of the beam element in the shell-element-based finite element model, and the equivalent structural stress at the spot-welded joint was obtained based on the equivalent structural stress method. Finally, the S-N curves of the spot-welded joints were fitted using the least-squares method. A comparison of the S-N curves of the spot-welded joints with those of different materials revealed that the material type had a significant influence on the S-N curve. To avoid this influence, a method for predicting the S-N curve of the spot-welded joints was proposed based on the relationship between the ratio of the tensile strength and that of the fatigue limit of each material. This research provides guidance for predicting the fatigue life of spot-welded joints in engineering applications.

Keywords: Spot-welded joints; Simulation; Numerical simulation; Finite element methods (FEM); S-N curve; Prediction method; Equivalent structural stress

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1. Introduction
Spot-welded structures are widely used in modern industrial production owing to their advantages of light weight, stable performance, and high automated production efficiency. This is an important connection mode in the mechanical manufacturing process [1]. Spot welding is mainly used in the fields of automobile manufacturing, rail-vehicle manufacturing, aerospace, and ship building, especially in automobile bodies and stainless-steel bodies of rail vehicles. According to statistics, a stainless-steel body of rail vehicles usually has up to 50000 spot-welded joints, and an automotive body has approximately 4000-6000 spot-welded joints [2].

As the spot-welding nugget is located between two relatively close plates and fatigue cracks often appear on the inner side of the plate, it becomes difficult to monitor the crack length and depth and perform non-destructive inspection [3-6]. Spot-welding fatigue-assessment methods mainly include the load-life, nominal stress, hot-spot stress, local, notch stress, fracture mechanics, and equivalent structural stress methods. At present, the load-life method specified in the standards ISO 14324-2003 [7], NF A89-571-2004 [8], JIS Z3138-1989 [9], KS B 0528-2001 [10], and GB/T 15111-1994 [11] are still used to predict the fatigue life of spot-welded joints. Howev-
er, the $\Delta F-N$ (load-amplitude-life) curves corresponding to different types of spot-welded joints in these standards are limited, and it is impossible to establish $\Delta F-N$ curves for individual spot-welding structures; furthermore, the load-life method is an approximate estimation method [12]. Therefore, the limitations of the load-life method are evident. In addition, other spot-welding fatigue assessment methods have limitations, such as high sensitivity to finite element meshes and a small application range, while the equivalent structural stress method has been widely used owing to its insensitivity to meshes.

Current spot-welding fatigue-life prediction methods based on equivalent structural stress include the Radaj [13], Rupp [14], Sheppard [15], Kang [16], and Dong methods [17]. In the early stages of fatigue research of spot-welded joints, Radaj [13] derived the formula for the maximum equivalent structural stress at the edge of a weld nugget. Based on the Roark stress-strain formula, Rupp [14] predicted the fatigue lives of spot-welded joints using the structural stress and verified the accuracy of the structural stress via tests. Sheppard [15] calculated the equivalent structural stress using the spot-welding finite element model and evaluated the fatigue lives of spot-welded joints according to the relationship between the structural stress and fatigue life. Kang [16] substituted the stress components in the von Mises equation with the local structural stresses in the vicinity of the spot weld and used the forces and moments that were determined via finite element analysis to calculate the structural stresses at the edges of the weld nugget in each sheet. Through a finite element simulation, Dong [17] transformed the nodal forces and moments at the edge of the spot-welding nugget into the linear membrane stress and bending stress and proposed a structural-stress calculation method that was insensitive to meshes. Subsequently, Yan [18] combined the Dong and Rupp methods and proposed a new fatigue characteristic parameter and simplified structural stress of the spot welding. Subsequently, the author determined the correlations of the spot-welding fatigue characteristic parameters of the Rupp, Kang, Dong, and Sheppard structure stresses on the fatigue performance of single and double spot welding [19]. Wu [20] used the classical, nonlinear generalized reduced-gradient algorithm to propose a process for optimizing the empirical parameter terms in the Rupp structural stress formula. The optimized Rupp structural-stress formula can effectively correlate the fatigue lives of spot-welded joints of various geometric sizes.

The aforementioned studies have made significant contributions to the fatigue-life evaluation method, equivalent-structural-stress calculation method, finite element simulation method, fatigue characteristic parameters, and fatigue influence parameters of spot welding. However, there is insufficient research on the normalized-spot-welding $S-N$ curve. Different from the above studies, in this study, the quasi-static failure loads of spot-welded joints of different materials were obtained by carrying out quasi-static tensile tests. Based on the quasi-static failure loads, the load levels of tensile-shear fatigue tests were determined, and the fatigue lives of the spot-welded joints were obtained via tensile-shear fatigue tests. The equivalent structural stresses of the spot-welded joints were obtained based on the Rupp equivalent structural stress method, and the $S-N$ curves of the spot-welded joints were fitted based on the least-squares method. Finally, based on the influence of the material on the $S-N$ curve, a method for predicting the $S-N$ curve of spot-welded joints was proposed, which provides a useful reference for engineering applications.

2. Materials, methods, and experimental testing

In this study, tensile-shear fatigue tests were performed on spot-welded specimens to study the fatigue lives of spot-welded joints. Because the process of welding the stainless-steel body of rail vehicles often comprises the use of spot-welded joints, the SUS301L stainless steel commonly used in the stainless-steel body was selected as the specimen material. To avoid eccentricity in the fatigue test process of the plate welding specimens of various thicknesses, the upper and lower auxiliary plates were welded onto the plate to ensure that the spot-welded joint was stressed uniformly. The parameters of the spot-welded specimens are listed in Table 1, and the structural diagram is presented in Fig. 1.
A method for prediction of S-N curve of spot-welded joints based on numerical simulation

**Table 1** Parameters of spot-welded specimens

<table>
<thead>
<tr>
<th>Type</th>
<th>Upper plate</th>
<th>Lower plate</th>
<th>Weld nugget diameter (mm)</th>
<th>Load ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material</td>
<td>Thickness (mm)</td>
<td>Material</td>
<td>Thickness (mm)</td>
</tr>
<tr>
<td>A1</td>
<td>SUS301L_1/8H</td>
<td>1.5</td>
<td>SUS301L_1/8H</td>
<td>2</td>
</tr>
<tr>
<td>A2</td>
<td>SUS301L_1/8H</td>
<td>2</td>
<td>SUS301L_1/8H</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>SUS301L_1/16H</td>
<td>1.5</td>
<td>SUS301L_1/16H</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>SUS301L_1/4H</td>
<td>2</td>
<td>SUS301L_1/4H</td>
<td>2</td>
</tr>
</tbody>
</table>

Note: Type-A1 and Type-A2 comprise the same material, and only their sizes are different. Type-A is the name used to indicate Type-A1 and Type-A2.

Table 1 The structural diagram of spot-welded specimens

**Table 2** Quasi-static tensile test results of spot-welded specimens

<table>
<thead>
<tr>
<th>Specimen serial number</th>
<th>Failure load F (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type-A1</td>
</tr>
<tr>
<td>1</td>
<td>20.66</td>
</tr>
<tr>
<td>2</td>
<td>21.01</td>
</tr>
<tr>
<td>3</td>
<td>20.50</td>
</tr>
<tr>
<td>4</td>
<td>23.31</td>
</tr>
<tr>
<td>5</td>
<td>22.26</td>
</tr>
<tr>
<td>Average failure load F</td>
<td>21.548</td>
</tr>
</tbody>
</table>

First, the specimens presented in Fig. 1 were installed on a hydraulic universal testing machine (WE-30) for the quasi-static tensile test to determine the failure load of the spot-welded specimens. The test results are listed in Table 2.

Based on the average failure load $F$ in Table 2, the tensile-shear fatigue tests were then performed under four sets of load levels (multiples of $F$) on a PLG-20C high-frequency tension-and-compression fatigue-testing machine for each spot-welded specimen. The group and the ladder test methods were used, the load form was an equal-amplitude sinusoidal curve, and the load ratio was 0.1 ($F_{min}/F_{max}$). The loading frequency gradually decreased with the crack propagation in the specimens, and the frequency range was 50-1000 Hz. While considering the fatigue fracture of the spot-welded specimens as the failure criterion, the fatigue lives of the spot-welded specimens were obtained, as shown in Table 3.
The \( \Delta F-N \) curves of the spot-welded specimens were obtained according to the test loads and tensile-shear fatigue lives of the specimens, as shown in Fig. 2. It can be observed that the overall dispersion of the data points was relatively high, and the correlations between the \( \Delta F-N \) curves for each material were weak. It was found that the correlation between the load amplitude \( \Delta F \) and fatigue life \( N \) of the spot-welded joint was weak, and the \( \Delta F-N \) curves fitted appropriately only for the spot-welded joints of the same material. When predicting the fatigue lives of the spot-welded joints of different materials, fatigue tests were performed for each structure. This is time-consuming and laborious. Furthermore, the selection process also becomes cumbersome when too many curves are considered. Therefore, it is of greater engineering significance to plot the normalized \( S-N \) curves of spot-welded joints suitable for different steels and different weld sizes.

![Fig. 2 \( \Delta F-N \) curves](image-url)
3. Structural-stress calculation method

3.1 Structural-stress calculation model

To fit the S-N curve, it was necessary to obtain the structural stress (S) of the spot-welded joints. The spot-welding equivalent structural stress proposed by Rupp based on Roark’s stress-strain formula is widely used in the fatigue-strength evaluation of spot-welded joints; its equivalent structural stress calculation model is presented in Fig. 3.

![Fig. 3 Method for calculating equivalent-structural-stress of spot-welded joints](image)

The plate thickness of the spot-welded joint in this study satisfied the relation \( d > 3.5\sqrt{t} \) (\( d \) is the diameter of the weld nugget, \( t \) is the thickness of sheet). According to the structural-stress calculation model, the equivalent structural stress of a spot-welded joint was obtained, as shown in Eqs. 1 to 7, respectively [14].

\[
\sigma_{v1} = -\sigma_{\text{max}}(F_{x1})\cos\phi - \sigma_{\text{max}}(F_{y1})\sin\phi + \sigma_{\text{max}}(M_{x1})\sin\phi - \sigma_{\text{max}}(M_{y1})\cos\phi \quad (1)
\]

where

\[
\sigma_{\text{max}}(F_{x1}) = \frac{F_{x1}}{\pi t_1} \quad \text{(2)}
\]

\[
\sigma_{\text{max}}(F_{y1}) = \frac{F_{y1}}{\pi t_1} \quad \text{(3)}
\]

\[
\sigma_{\text{max}}(M_{x1}) = K_1\left(\frac{1.972M_{x1}}{dt_1^2}\right) \quad \text{(4)}
\]

\[
\sigma_{\text{max}}(M_{y1}) = K_1\left(\frac{1.972M_{y1}}{dt_1^2}\right) \quad \text{(5)}
\]

where \( t_1 \) is the thickness of sheet 1, \( K_1 = 0.6\sqrt{t} \) is an empirical correction factor, and \( \phi \) is the radial stress angle.

When the axial force on the weld nugget is a tensile force, it results in fatigue failure, and the influence of the axial force should be considered, that is, when \( F_{z1} > 0 \):

\[
\sigma(F_{z1}) = K_1\left(\frac{1.774F_{z1}}{t_1^2}\right) \quad (6)
\]

When the axial force on the weld nugget is the result of a pressure, fatigue does not occur. At this time, the effect of the axial force is ignored, that is, when \( F_{z1} \leq 0 \):

\[
\sigma(F_{z1}) = 0 \quad (7)
\]

3.2 Equivalent structural stress calculation

To obtain the force and moment at the spot welding, a finite element model of the spot-welded joint was established in the software HyperMesh, wherein the base metal was simulated as the shell element and the weld nugget was simulated as the CBAR element. The weld nugget center nodes of the upper-plate and lower-plate nuggets were connected using a CBAR element. The mesh size of the model was 2 mm, and the load and boundary conditions were consistent with...
those of the test. One end of the specimen was fully constrained, the other end was connected to the rbe2 rigid elements, and the specimen was unconstrained in the direction of the load. The time of finite element model simulation was 38 s, and the required storage space was 8.04 MB. The spot-welded shell-element-based finite element model is presented in Fig. 4. This finite element model can accurately simulate the actual stress of the spot welding and easily obtain the stress of the spot-welded structure [2, 19, 21].

![Spot-welded shell-element-based finite element model](image)

**Fig. 4** Spot-welded shell-element-based finite element model

In the finite element simulation, first, the maximum and minimum loading forces $F_{\text{max}}$ and $F_{\text{min}}$, respectively, of the different types of spot-welded specimens were applied to the finite element models. Then, the software NASTRAN was used to calculate the force and moment of the beam element nodes of the finite element models. Finally, the force and moment of the beam element nodes were introduced into Eqs. 1 to 7 to obtain the equivalent structural stresses of the spot-welded joints under tensile-shear loads. The calculation process is presented in Fig. 5 (A and B indicate the nodes at each end of the beam element).

![Equivalent structural stress calculation process](image)

**Fig. 5** Equivalent structural stress calculation process [22]
On considering the Type B specimen, with $F_{\text{max}} = 6.675$ kN, as an example, according to the calculation process shown in Fig. 5, the force and moment of the beam-element nodes in the model and the equivalent-structural-stress amplitude of the spot-welded joint were obtained, as shown in Table 4.

**Table 4** Force and moment of beam element nodes in the model and the equivalent-structural-stress amplitude of spot-welded joint

<table>
<thead>
<tr>
<th>Nodes</th>
<th>Force and moment</th>
<th>$F_{\text{max}} = 6675$ N</th>
<th>$F_{\text{min}} = 667.5$ N</th>
<th>$\sigma_{a, \text{max}}$, $\sigma_{b, \text{max}}$ (MPa)</th>
<th>$\sigma_{a, \text{min}}$, $\sigma_{b, \text{min}}$ (MPa)</th>
<th>$\Delta \sigma_{a}$, $\Delta \sigma_{b}$ (MPa)</th>
<th>$\Delta \sigma_{s}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node A</td>
<td>M1 (N-mm)</td>
<td>-11490</td>
<td>-1149</td>
<td>549.184</td>
<td>54.918</td>
<td>494.266</td>
<td>580.166</td>
</tr>
<tr>
<td></td>
<td>M2 (N-mm)</td>
<td>-2.929e-10</td>
<td>-2.884e-11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shear1 (N)</td>
<td>-6.675</td>
<td>-667.5</td>
<td>644.629</td>
<td>64.463</td>
<td>580.166</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shear2 (N)</td>
<td>-4.897e-11</td>
<td>-4.608e-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Axial (N)</td>
<td>85.4</td>
<td>8.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Torque (N-mm)</td>
<td>9.185e-15</td>
<td>8.526e-16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Node B</td>
<td>M1 (N-mm)</td>
<td>3532</td>
<td>35.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M2 (N-mm)</td>
<td>-1.827e-10</td>
<td>-1.847e-11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shear1 (N)</td>
<td>-6.675</td>
<td>-667.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
</tbody>
</table>

### 4. S-N Curve and prediction method

#### 4.1 Fitting S-N curve

The test data were fitted in a double-logarithmic coordinate system using the least-squares method by plotting the equivalent-structural-stress amplitude $\Delta \sigma_{s}$ along the ordinate and the fatigue life $N$ along the abscissa, and the S-N curves of the spot-welded joints of the same material and of different materials were obtained as shown in Fig. 6.

In the processing of the fatigue test data, five times the lifespan (hereinafter referred to as "5×lifespan") is typically used to evaluate the S-N curve. If the data points are within the 5×lifespan, the S-N curve is considered to have a high correlation [2, 20, 22, 23]. It can be observed from Fig. 6 that all the spot-welding data points of the same material were within the 5×lifespan, the data points were relatively compact, and the squared correlation coefficient ($R^2$) of the S-N curves were greater than 0.8769; however, the spot-welding data points in the case of different materials were more dispersive, and $R^2$ was only 0.8667 in the S-N curve. Thus, the S-N curve of the spot welding of the same material had a higher correlation and a better fitting effect. The dispersion of the spot-welding data points for different materials resulted in a weak correlation of the overall S-N curve with $R^2$ of only 0.8742. It can be observed that the material had a significant influence on the S-N curve; therefore, the influence of the material cannot be ignored in the fatigue analysis of the spot-welded joints. It is necessary to distinguish the materials of spot-welded joints for the fatigue evaluation.
4.2 S-N curve prediction method

The standard-power-function expression of the S-N curve is shown in Eq. 8, and all the spot-welding test fatigue lives $N$ can be equivalent to the fatigue life $N_e$ when the fatigue limit is $5 \times 10^6$ cycles as shown in Eq. 8 [24] and the equivalent equation is given by Eq. 9.

$$S^m N = C \quad (8)$$

where $m$ and $C$ are parameters related to the material properties, specimen form, stress ratio, and loading mode, respectively.

$$N_e = N \left( \frac{\Delta \sigma}{S_e} \right)^m \quad (9)$$

where $S_e$ is the stress amplitude corresponding to the S-N curve of the spot welding when $N$ is $5 \times 10^6$ cycles.

The equivalent S-N curves are presented in Fig. 7, and it can be observed that the S-N curves of the spot-welded joints of all the materials after equivalence are almost parallel. The slopes and relative deviations of the S-N curves of the spot-welded joints are listed in Table 5. It can be
observed that the relative deviations of all the slopes are within 5%. Within the acceptable error range, the S-N curves of the spot-welded joints of various materials were considered to be parallel. This indicates that the ratio of fatigue limit or that of the fatigue strength under different cycles of spot welding is a constant value, and the spot-welding S-N curve of one material can be derived from that of another material.

Because the fatigue limit of the material has a good correlation with the tensile strength [25], the tensile strength of the spot-welded joint material was compared with the fatigue limit, and the results are shown in Table 6. It can be observed that the ratio of the tensile strength of each material is very close to that of the fatigue limit, and the ratio deviation is within 3%. This shows that the spot-welding S-N curve of other materials can be derived from the known spot-welding S-N curve of one material according to the ratio relationship of the tensile strength.

According to the ratio relationship of the tensile strength of spot-welding materials, the spot-welding S-N curve of other materials was derived from the known spot-welding S-N curve of one material, as shown in Table 7. It can be observed that the derived fatigue limit of the spot welding was very close to the fatigue limit fitted according to the test data, and the corresponding error was within 3%. Therefore, according to the ratio relationship of the tensile strength of the spot-welding materials, the spot-welding S-N curve of other materials can be predicted relatively accurately from the known spot-welding S-N curve of one material. In engineering applications, it is not necessary to perform tests on spot-welded joints of each material individually. Using the S-N-curve prediction method, the predicted S-N curves of other materials can be obtained, which is timesaving, labor-saving, and more universal and provides references for the design of spot-welding structures and life predictions in engineering applications.
can be further investigated. A more pronounced effect on the fatigue life and fatigue properties of spot-welded joints under tensile loads is expected with a higher degree of material stress. In the future, investigations on the influence of residual stresses and the effect of different materials on the fatigue life of spot-welded structures are necessary to improve the accuracy of the predictions. In the future, the influence of residual stresses and the effect of different materials on the fatigue life of spot-welded structures should be further studied.

Supplementary tests were performed to validate the accuracy of the simulation results. However, some data points were dispersive and did not provide accurate solutions; therefore, supplementary tests are recommended to improve the accuracy of the results.

The correlation of the derived fatigue curves of the spot-welded joints was calculated based on the structural-stress calculation model, and the correlation of the derived curves was non-universal. To avoid the influence of materials on the derived curves, a method for predicting the fatigue curves of the spot-welded joints was proposed. The following conclusions were drawn.

The stress of the spot-welded joint can be easily obtained by extracting the force and moment of the beam-element nodes in the spot-welded shell-element model. Using the equivalent-structural-stress calculation model, the equivalent structural stress of the spot-welded joint can be accurately obtained.

The correlation of the derived fatigue curves of the spot-welded joints was weak, and the materials had a significant influence on the correlation. When predicting the fatigue life of the spot-welded joints with different materials, fatigue tests had to be performed for each structure; therefore, the derived fatigue curves were non-universal.

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A method for prediction of S-N curve of spot-welded joints based on numerical simulation


