Bending Fatigue Strength and the Effect of Assembling Stress on Fillet Welded Joints of Catalyst Muffler Flange Pipes

Gyoko Oh 1)
1) Muffler Designing Department, Tokyo Roki Co., Ltd.
1-9-1 Tana Shioda, Chuo-ku, Sagamihara, 252-0245, Japan

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ABSTRACT: Fatigue strength is affected by assembling stress at flanges. Using samples of exhibiting different degrees of flange surface flatness, local stress was measured with strain gauges, and the effect of assembling strain and stress on fatigue strength was verified through fatigue strength examinations. Bending fatigue strengths were inversely proportional to static assembling stress which was proportional to the degree of flange flatness. Factors causing fatigue to failure, such as welding bead shape, metal structure, and crack state were identified through microscope observations and SEM-EDS chemical composition analyses, while assembling deformation and stress concentration were analyzed through FEM computer simulation.

KEY WORDS: Materials, Stainless steel, Welding, Fatigue, Strength, Microstructure, Assembling stress, Stress concentration, Finite element method [D3]

1. Introduction

As fuel consumption regulations lead to lighter and smaller motor vehicles, thin stainless steel plates, with their high heat-resistance, high corrosion-resistance and excellent workability, are being used increasingly for exhaust systems. In many cases, exhaust gas after-treatment devices such as catalyst mufflers are used for diesel vehicles to satisfy exhaust regulations 1-9). Because catalyst mufflers are usually welded structures, studies are required to shed light on strength improvement and the characteristics and mechanisms involved in welded joints.

When installing a catalyst muffler on a vehicle, the inlet and outlet pipes are usually welded to the flanges which are bolted to the exhaust front pipe and tailpipe flanges. Because the flanges are subjected to welding distortion, static assembling stress also occurs at the weld joints during bolt tightening. When high dynamic stresses exist in the fillet welded joints of inlet and outlet pipes, and when the catalyst muffler flange is subjected to vibrations from the moving vehicle, static assembling stress occurrence and the position of welded joints during bolt tightening could create a structural problem in catalyst mufflers. Modeling this case through the use of samples with different degrees of flatness in their flange surfaces, local stress was measured with strain gauges, and the effect of assembling strain and stress on fatigue strength was verified through fatigue strength examinations. Factors causing fatigue to failure, such as welding bead shape, metal structure, and crack state were identified through microscope observations and SEM-EDS chemical composition analyses. Elastic and plastic assembling deformation behavior and stress concentration were analyzed during strain measurements and FEM computer simulations.

2. Experimental Method

2.1. Materials and Test Samples

A ferritic stainless steel (FSS) sheet (0.2% proof stress $\sigma_{0.2}$: 290MPa; tensile strength $\sigma_b$: 465MPa; elongation at fracture: 33%; strain hardening exponent: 0.21) with a thickness of 1.5mm was molded into a cylindrical pipe with an 80mm outside diameter, and its seam was welded. The pipe end was inserted in a hole with an 80.5mm inside diameter in a low carbon steel (LCS) plate flange which had a thickness of 9mm, and that was welded to the fillet welded joint, as shown in Fig. 1 and Table 1. The fillet weld was performed by a programed robot method under the automatic metal-arc inert gas (MIG) welding process, using a solid wire with a diameter of 1.2mm. An austenitic stainless steel wire (AW) was used for the present experiment, in consideration of the weldability, forming fine-grained metallurgical structure, impact resistance and mass productivity in dissimilar metal welding 1-4).

Sample B was supplied for the experiment in an as-welded state, while sample A exhibited excellent flatness, due to plane cutting of the flange side after welding. Sample C was in a state modeling poor flange flatness for welding distortion, by inserting a piece of iron (thickness 15; 0.25mm; width: 10mm) between the flange and the installation pedestal, when fixed to the pedestal with bolts. The plane flatness of the pedestal which secured the sample was less than 0.1mm, and four bolt holes (diameters: 11mm) for the flange fixation were distributed equally around the circumference, which took in a diameter (PCD) of 113mm. The flange seal surface was located inside the circle that had the 113mm diameter. As for flange flatness $\gamma$, sample A was eight
mean values, while samples B and C were 20 mean values. The frank angle of weld (180° - θ) of the samples was approximately 135 degrees. Because the flatness degree of all samples in the as-welded state was the same and the frank angle was the same as well, it was considered that residual stress by the welding distortion on all welded joints was the same before the assembly starting.

2.2. Strain and Stress Measurements

As shown in Fig. 1, strain gauge P of 1mm length attached to the welding line of the pipe was defined as the pipe edge stress, and strain gauge M of 1mm length attached to midway point between the half-and-half degree between the weld line and the pipe was defined as the maximum stress near the weld line. Static assembling strain ε caused by flange deformation when the sample was fastened to the pedestal jig with size M10 bolts with a torque of 50Nm was measured, as shown in Table 1 and Fig. 2. The higher measured strain was selected from the samples.

Elastic converting assembling stress was obtained by multiplying the strain by the modulus of longitudinal elasticity of the material, and it is expressed in the following equation (6, 7):

\[ \sigma_e = E \varepsilon \quad (1) \]

where \( \sigma_e \) is the converting assembling stress, \( \varepsilon \) the measured strain, and \( E \) the modulus of longitudinal elasticity (206GPa).

Meanwhile, when the strain was near and over proof stress, the plastic strain could be expressed in an equation with the strain hardening exponent from tensile stress-stain curve of the FSS sheet material as a reference, because the stress-strain curve of the welded joint samples was difficult to be obtained and would be affected by the weld line restraint. Assembling true stress could

![Fig. 1 Schematic welded joint and strain gauge position](image1)

![Fig. 2 Schematic view of fatigue test in ground plan](image2)

| Sample     | Flange flatness γ | Assembling strain ε |
|------------|-------------------|---------------------|
|            | Whole area        | Seal area**         | Maximum | Pipe edge |
| A          |                   |                     |         |           |
| Flange machining |                  | 0.08                | 0.038   | 0.013     |
| B          |                   |                     |         |           |
| Normal     | 0.59              | 0.21                | 0.308   | 0.140     |
| C          | Seam inserting*   | 0.59+0.25           | 0.21+0.13 | 0.522   | 0.323     |

Materials: Low carbon steel flange (LCS), Ferrite stainless pipe (FSS), Austenite welding wire (AW)
Welding method: MIG (Metal-arc inert gas)
Pedestal for setting: Steel with surface machining, flatness 0.1mm
Strain gauges: 1mm length
* Seam thickness \( t_s \): 0.25mm, Equivalent flatness \( \gamma_s \): 0.13mm,
Equivalent flange flatness \( \gamma + \gamma_s \): 0.21+0.13mm
** Seal area: \( \phi 113 \)
be expressed in the following approximate equation \( \sigma_t = K_t \varepsilon^n \) \( (2) \):

where \( \sigma_t \) is the assembling true stress, \( n \) the strain hardening exponent, and \( K_t \) constant.

2.3. Fatigue Tests

Bending fatigue tests were performed using an oil pressure fatigue test machine with a maximum load capacity of 12kN. A fully reversed load \( \pm W \) (the mean load was zero) from a servo actuator through a floating joint was applied to the point at the fixed sample where span distance \( L \) was 282mm from the flange plane of the fillet welding line where fracturing occurred. The load was detected and set using a load cell, and repeated by stroke amplitude control in the 10Hz sine wave frequency. The number of cycles to failure was defined as the number of times that a crack large enough to be distinguishable through dye penetrant testing occurred in the sample.

The bending moment amplitude was calculated from load \( W \) and span distance \( L \), and nominal stress amplitude was defined as the value divided by section modulus of the pipe cross section \( (6) \). While it is maintaining the static assembling stress caused by flange deformation when the sample was fastened to the pedestal jig, varying stress amplitude was measured after the fatigue test started. The stress amplitude was calculated by multiplying the measured zero-to-peak strain amplitude values by the modulus of longitudinal elasticity 206GPa of the material. During testing, the data was automatically recorded every 60 seconds. Testing was stopped when the stress amplitude reached to the set limit value, then cracks were detected through dye penetrant testing.

In addition, the tests were carried out at room temperature from accuracy and simplicity of experiments, because the temperature of a part equivalent to the weld samples at the time of vehicle moving was usually less than 500 degrees Celsius, and the reduction in fatigue strengths in this temperature range was restrictive from past material examinations.

2.4. Microstructure and Element Analysis

After the fatigue tests, the portion around the crack in the sample was cut out and embedded in resin and polished, to be used as a surface for observation along the D-D section shown in Fig. 1. Then the surface was etched with mixed acids to observe its microstructure with an optical microscope. Element analysis in the same area was carried out using an energy dispersion type X-ray analyzer in a scanning electron microscope (SEM-EDS).

2.5. FEM Stress Analysis

Approximating the shape of the axial center cross-section of the welded joint, the weld leg length was assumed to be 4mm in height and 4mm in width. Using two-dimensional finite element method (2D-FEM), computer elastic stress was simulated in the section model in a partial model with a thickness of 30mm, as shown in Fig. 3a. The point of contact length 1.5mm of the flange and pedestal jig side nearby the pipe was restrained in both vertical axis and horizontal axis directions (X-Y restrained), and the pipe tip 1.5mm of the 20mm distance from the weld line was restrained in vertical axis direction (Y restrained). Assuming triangular division solid elements with a size of about 0.3mm near the strain gauge M position, static maximum principal stress distribution of the section was simulated when fastened load was applied to the bolts so that flange deformation was at the same value as the flange flatness of the seal side of the sample. The modulus of longitudinal elasticity of the material was assumed to be 206GPa, and the Poisson ratio was assumed to be 0.3.

3. Results and Discussion

3.1. Assembling Stress Distribution

Fig. 3a shows the result of a computer assembling stress distribution analysis, which was conducted using the two-dimensional finite element method (2D-FEM) to simulate the shape of the welded joints in sample B. Fig. 3a is a maximum
principal stress distribution map showing conditions at the time of flange deformation in sample B, while Fig. 3b is an enlarged distribution map of the nearby stress concentration point. The maximum principal stress overlaps with the strain gauge M position at the time of the measurement, and exists in the change region of the sample surface configuration. When the point is given the coordinate 0 and the X-axis is charted toward the right along the upper surface of the sample, by extracting and plotting the stress of each division element, the curve of the stress shows the maximum value as a chevron, as shown in Fig. 3c.

Similar stress distributions and maximum stress levels were obtained by changing flange deformation and simulating samples A and C through 2D-FEM analysis. To arrange the relationships of these values with the seal plane flatness of the flanges, a plot diagram is shown in Fig. 4a, the assembling strain being plotted along the right vertical axis and the converted assembling stress being plotted along the left vertical axis. FEM assembling strain or stress is linearly proportional to flange flatness. When the assembling strains or stresses plotted in the same Fig. 4a are compared with samples A, B, and C of Table 1, which were fastened to the pedestal jig with bolts, the measured assembling strains or stresses are seen to be proportional to the degree of the flange flatness but they are not linear. The measured maximum converting assembling stress in sample B almost matches with the FEM analysis value, where as which stress in sample A is lower than the FEM analysis value. The measured flange flatness in sample A was 0.08mm, but this included the portion of the surface roughness due to cutting, so it could be supposed that the deformation between flange mating surfaces was actually smaller.

Sample C was subjected to a large strain caused during assembly, which suggests that partial plastic deformation occurred relevant to the difference in plane flatness from the strain inhomogeneity in the length range of the strain gauge and inserted piece of iron. When total value of the flange flatness and the seam thickness is used as the horizontal axis, the value of the actual measurement and the simulation does not match completely with each other as shown in Fig. 4a. However, when equivalent flange flatness $\gamma + \gamma_s$ is used as the horizontal axis considering the deformation in the pipe region of $\phi$80 as a half degree of the seam thickness simultaneously, the value of the converting assembling stress $\sigma_t$ matches with the simulation one as shown in Fig. 4b.

In all above cases, the maximum converting assembling stress at the weld zone of the pipe-pipe welded joints is about twice as that of the pipe edge. The stress concentration exists and the tendency of the distribution is given by the assembling stress curve from the FEM analysis as shown in Fig. 3.

On the other hand, when the assembling true stress $\sigma_t$ from the equation (2) taking account of the plastic strain used as the vertical axis, the values of the maximum and the pipe edge are close to each other as shown in Fig. 4c. The values are lower greatly than the simulated results because only elastic stresses were calculated in the FEM analysis.

### 3.2. Stress Amplitude and Fatigue Strength

Fig. 5 shows the nominal stress, measured pipe edge stress, and measured maximum stress amplitude when the multiple-stage amplitude of varying loads was applied to sample B. Each of stress amplitudes is proportional according to an upswing in bending moment amplitude, and rises linearly. This is expressed in the following approximate equation:

$$\sigma_a = k_i M$$  \hspace{1cm} (3)

where $\sigma_a$ is the stress amplitude, M the bending moment amplitude, and $k_i$ constant.

By comparing the stress amplitude values obtained at the time of the same bending moment amplitude, the levels are seen to increase in order of nominal stress, measured pipe edge stress, and measured maximum stress amplitude, suggesting that the stress concentration has occurred through a change in geometric shape. The amplitude ratio of the measured maximum stress to the nominal stress is 3.1. In addition, because the measured maximum stress amplitude here is the converted value in the strain gauge which was 1mm in length, the stress is represented as a mean value in the 1mm range, and the actual maximum stress that actually occurred would be slightly higher than...
this value. The value of the stress concentration factor (the ratio of the actual maximum stress to the nominal stress) would be slightly higher than the value of the stress ratio (the amplitude ratio of the measured maximum stress to the nominal stress).

Bending fatigue tests that applied for multiple-stage amplitudes of varying loads to sample B made it possible to plot the relationship between bending moment amplitude and the number of cycles to failure as a regression line (M - N curve) (3). This is expressed in the following approximate equation in a certain load range:

\[ M = \alpha N^{-\beta} \]  

(4)

where M is the bending moment amplitude, N the number of cycles to failure, and \( \alpha \) and \( \beta \) are constants.

From above equation (4) and from the equation (3) of the plotted regression lines in Fig.5, the relational expressions of the nominal stress, measured pipe edge stress, maximum stress amplitude and the number of cycles to failure in sample B were obtained (namely, approximate equations of the S - N curve). The fatigue strengths at 200,000 cycles which are close to the endurance life cycles of an actual vehicle running on rough roads, extracted from the equations are shown in Table 2 and Fig. 6. Observations of the nominal stress, measured pipe edge stress and maximum stress amplitude indicate that fatigue strength levels increase in that order. The ratio of fatigue strength converted from the maximum stress to fatigue strength converted from the nominal stress is 3.1.

3.3. Assembling Stress Effects on Fatigue Strength

In the same way in the cases of samples A and C, fatigue strengths at 200,000 cycles were extracted from the S - N curves which were converted from the M - N curves obtained from the bending fatigue tests as shown in Table 2. In conjunction with the result from above sample B, the results are plotted in Fig. 7 with a horizontal axis as the equivalent flange flatness in seal area, as well as in Fig. 8 with a horizontal axis as the maximum converting

| Sample | Bending moment Nominal* | Pipe edge | Maximum |
|--------|-------------------------|-----------|---------|
|        | Nm | MPa | MPa | MPa |
| A      | 820 | 115 | 175 | 375 |
| B      | 670 | 94  | 143 | 290 |
| C      | 544 | 76  | 116 | 235 |

* Calculated using the load amplitude and section modulus of the pipe cross section

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**Table 2: Bending fatigue strength at 200,000 cycles**

**Fig. 5 Stress amplitude vs. bending moment amplitude**

**Fig. 6 Bending fatigue strength at finite life**

**Fig. 7 Fatigue strength vs. equivalent flange flatness**

**Fig. 8 Fatigue strength vs. maximum converting assembling stress \( \sigma_e \) (MPa)**

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assembling stress and an upper horizontal axis as the measured assembling strain with the gauge M. Fatigue strengths decreased in proportion linearly to the equivalent flange flatness, maximum assembling strain or converting assembling stress.

Compared with sample A, sample B has a rate of decline of 23%, while sample C has a rate of decline of 37%. The relationships between fatigue strength, equivalent flange flatness, and maximum converting assembling stress are expressed as regression lines in the following approximate equations:

\[
\sigma_a = \sigma_w - f_1 (\gamma + \gamma_s) \quad (5)
\]

\[
\sigma_a = \sigma_w - f_2 \sigma_e \quad (6)
\]

where \(\sigma_a\) is the stress amplitude, \(\sigma_w\) the fatigue strength while the assembling stress is zero, \(\gamma + \gamma_s\) the equivalent flange flatness, \(\sigma_e\) the maximum converting assembling stress, and \(f_1\) and \(f_2\) are constants.

Meanwhile, when the results are plotted in Fig. 9 with a horizontal axis as the maximum assembling true stress, the fatigue strengths decrease in proportion to the assembling true stress, but present a knee-point around the proof stress \(\sigma_{0.2}\). When the assembling true stress is over the proof stress, the fatigue strengths decrease sharply. The form is similar roughly to a conventional fatigue strength diagram with its horizontal axis as dynamic mean stress. This suggests that the static assembling stress contributes to fatigue strength as much as conventional dynamic mean stress does to some extent, due to the fact that partial plastic deformation caused by the fastening had occurred from the measured strain data but it would be restrained by the weld line in the weld joint sample even the sheet material had a high elongation coefficient.

\[\text{Fig. 9 Fatigue strength vs. maximum assembling true stress}\]

In addition, mean stress effect on fatigue strength is usually small near a stress concentrator, because fatigue notch factor is usually smaller than stress concentration factor.

3.4. Welding Metal Structure

Fig. 10 shows cross-sectional views of optical microstructure of the welded joint in sample B, while 10b is a magnification inside the region of the square in 10a. The weld zone, heat affected zone (HAZ), and matrix zone could be observed. The ferrite phase (F) in the heat affected zone of the pipe adjoining the weld zone presents crystal grain coarsening, and the average crystal grain size grows into approximately 150μm in the heat affected zone, from approximately 20μm in the matrix.

\[\text{Fig. 10 Microstructure of welded joint in sectional view}\]

| Part        | Mark | C  | Si  | Mn  | Ni  | Cr  | Ti  | Mo  | Ni eq | Cr eq | Cr eq / Ni eq |
|-------------|------|----|-----|-----|-----|-----|-----|-----|-------|-------|--------------|
| Flange      | LCS  | 0.10 | 0.03 | 1.20 | 3.60 | 0.05 |     |     | 3.60   | 0.05   |              |
| Pipe        | FSS  | 0.01 | 0.01 | 0.30 | 0.20 | 16.56 | 0.20 | 1.02 | 0.50   | 18.00  |              |
| Welding wire| AW   | 0.02 | 0.39 | 1.74 | 13.56 | 23.51 |     |     | 14.88  | 24.10  | 1.62         |
| Weld zone   | Weld | 0.02 | 0.52 | 1.58 | 11.02 | 21.88 | 0.04 | 0.22 | 12.41  | 22.96  | 1.85         |

Measured by SEM-EDS except the carbon was estimated (mass%)
The chemical composition of materials and the weld zone subjected to SEM-EDS analysis inside the circle are shown in Table 3. Nickel equivalent $\text{Ni}_{eq}$ and chromium equivalent $\text{Cr}_{eq}$ were calculated using the following equations, and their values are shown in the same table:

$$\text{Ni}_{eq} = \%\text{Ni} + 30 \%\text{C} + 0.5 \%\text{Mn}$$  \hspace{1cm} (7)

$$\text{Cr}_{eq} = \%\text{Cr} + \%\text{Mo} + 1.5 \%\text{Si} + 0.5 \%\text{Nb}$$  \hspace{1cm} (8)

where $\%E_c$ is the mass percentage content of element $E$.

From these equivalents, the structure at room temperature and contained amount of the ferrite were estimated according to the Schaeffler diagram. The sample has a mixed microstructure composed of austenite ($A$) 88% + ferrite ($F$) 12% and its appearance are shown in Fig. 10b. Defects in welding such as high temperature solidification cracking were not observed.

The $\text{Cr}_{eq}/\text{Ni}_{eq}$ value of the sample is 1.85, as seen in the equivalent ratio in Table 3. Based on Fe-Cr-Ni phase diagram, solidification process from a high temperature could be assumed to be two-phase solidification of the primary crystal ferrite + (ferrite + austenite crystallizing). The volume fraction of the ferrite decreased from $F \rightarrow A$ phase transformation during cooling to room temperature, and at room temperature the ferrite in the $A$ + $F$ structure takes on a morphology close to the lathy phase as shown in Fig. 10b. The phase transformation process from the liquid is expressed as the following equation:

$$L \rightarrow L + F \rightarrow L + A + F \rightarrow F + A \rightarrow (F + A) + A$$  \hspace{1cm} (9)

where $L$ is the liquid metal phase, $F$ the ferrite phase, and $A$ the austenite phase.

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Fig.11 Element distribution maps of welded joint by SEM-EDS

Fig.12 Element distribution profiles of weld zone
3.5. Element Distribution and Crack State

Fig. 11 shows element distribution maps for nickel (Ni), chromium (Cr) and molybdenum (Mo) which were analyzed using SEM-EDS inside the region of the square in Fig. 10. Fig. 11a is a back-scattered electron (BSE) image, 11b is a Ni-Kα X-ray count map, 11c is a Cr-Kα X-ray count map, and 11d is a Mo-Kα X-ray count map. The shape of the crack and the nearby element distribution infer that the crack initiated from the boundary between the weld metal and the heat affected zone of the pipe (weld interface), and then entered into the heat affected zone after propagating along that interface to some extent.

Element distribution line profiles of the Ni, Cr, and Mo counts of the sample along the arrow in Fig. 11a are shown in Fig. 12. Because Ni and Cr contents diminished from the weld metal region toward the pipe region, and because the crystal structure changed, this interface is a change line exhibiting physical and mechanical characteristics in the material, and is considered as to be one of the determinant factors of fatigue strength in the sample. The stress concentration point was overlapped with this interface in the sample. In addition, the starting points of cracks in samples A and C were similar to that in sample B through observations.

4. Conclusions

1. The measured maximum assembling stress at a weld zone of flange pipe welded joints is about twice that at the pipe edge. This indicates that stress concentration exists and the tendency of the distribution is given by assembling stress curves obtained from FEM analysis.

2. Bending fatigue strengths at 200,000 cycles on welded joints are machining 375MPa, normal 290MPa, and seam inserting 235MPa when based on measured maximum stress amplitude.

3. Bending fatigue strengths are inversely proportional linearly to static assembling strain or converting assembling stress which is proportional to the degree of flange flatness. Meanwhile, the fatigue strengths decrease sharply when assembling true stress is near and over the knee-point of proof stress, even though decrease in proportion to the assembling true stress.

4. The microstructure of the ferrite distributed in an austenite matrix depends on the equivalent chromium and nickel content in a weld zone. Fatigue cracks occur from the weld interface, which is a change line in the metal structure.

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