FATIGUE DESIGN FOR SUS301L SPOT-WELDED MULTI-LAP JOINTS SUBJECTED TO TENSILE SHEAR LOAD

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ABSTRACT

The railroad cars or the commercial vehicles are generally manufactured by the spot welding. Among various kinds of spot welded lap joints, multi-lap joints are one of popular joints in manufacturing their body structures. But, fatigue strength of these joints are lower than that of base metal due to high stress concentration at the nugget edge of the spot weld and are known to considerably be influenced by welding conditions as well as the mechanical and geometrical factors. Thus, it is necessary to establish a reasonable and systematic fatigue design criterion for spot welded multi-lap joints. In this paper, the $\Delta P\text{-}N_f$ curves has been rearranged in the $\Delta \sigma\text{-}N_f$ relation with the maximum stress at the nugget edge of spot welded multi-lap joints subjected to tensile shear load. Consequently, the fatigue data were evaluated in terms of fracture mechanics by plotting on the $\Delta P\text{-}N_f$ curves. From the results obtained, both of them have been revealed to be applicable to fatigue design of spot welded multi-lap joints. However, the fracture mechanical approach is found to be more effective than the maximum stress approach in the range of $N_f \geq 2\times10^5$

KEYWORDS

Fatigue design criterion, Spot-welded multi-lap joint, Tensile shear load, Maximum principal stress

1.Introduction

The body of railroad commercial vehicles is typically made through spot welding of pressed thin plates. Structures of railroad commercial vehicles consist of the side-frame, roof-frame, under-frame and end-frame, and each frame is connected to the skin plate to provide sufficient structural rigidity. The thin plate, used in structural reinforcements and frames, is typically made of stainless steel sheets (SUS301L) of 1.0 to 4.5mm thickness, which is then connected to the skin plate, reinforcement, or members. To connect these parts, welding, either electric resistance spot welding or gas arc welding, is used.

In particular, for railroad commercial vehicles, spot-welding of multi-layers with different plate thickness is typically involved. There are a number of differences between spot-welded components with 2 layers and those with multi-layers (more than 3 layers). Firstly, deformation and stress characteristics of multi-layers are different from those of 2 layers. Moreover, as the shape of spot-welded region is circular with the diameter of several mm, it can be a source of stress concentration for fatigue loading and thus cause initiation of fatigue crack.

Therefore, the fatigue strength and life for spot-welded components are much less than those for base metals, and strength and reliability of components in railroad commercial vehicles are determined from those of spot-weldments. Thus it is very important to develop fatigue strength and life evaluation method for spot-welded multi-lap joint in strength and reliability of components in railroad commercial vehicles, as well as establishing long life fatigue design criterion.

However, it is difficult to determine strength and reliability through testing real components, and thus it is a typical practice to develop small, simulated specimens and to develop fatigue life curve from those specimens [1][2].

The objective of this paper is to provide an integrated fatigue design criterion for spot-welded multi-lap joints used in the body of railroad commercial vehicles.

Based on finite element analysis, the fatigue life data for spot-welded multi-lap joints is correlated in terms of the maximum principle stress. Further attempt is made to correlate such data in terms of the stress intensity factor that is the fracture mechanical parameter.

2. Deformation and stress analysis using finite element method

2.1 Finite element modeling

As illustrated in Figure 1(a), TS(Tensile Shear) type lap joints cause complicated deformation behavior around the welded spot due to the combination of in-plane shear force and out-of-plane bending moment. And, since the fatigue crack initiates at the nugget area of inner surface and grows out to outer surface (refer to Figure 1 (a)), it is crucial to obtain the stress and strain distribution around spot weld for the investigation of the fatigue crack growth mechanism [3][4].

In this paper, the fatigue strength of spot welded multi-lap joints of SUS301L rolled plates was investigated. SUS301L are commonly used for the body of railroad commercial vehicle, and its chemical composition and mechanical properties are summarized in Tables 1, 2, respectively. The finite element analysis was performed on 3 different joint types as illustrated in Figure 1. Considering material characteristics and plate thick, 10 different specimens were analyzed as summarized in Table 3.

Table 1 Chemical composition of SUS301L

C	Si	Mn	P	S	Ni	Cr	N
0.03	1.00	2.00	0.045	0.03	6.0~ 8.0	16.0~ 18.0	0.2

Table 2 Mechanical properties of specimen

Processing management	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Plate
Solution Treatment	≥215.6	≥548.8	≥441	LT
Skin Pass Mill	≥343	≥686	≥392	DLT
	≥411.6	≥754.6	≥343	ST
	≥686	≥931	≥196	HT

LT: Low tensile	HT: High tensile
DLT: Deatlite tensile	ST: Special tensile

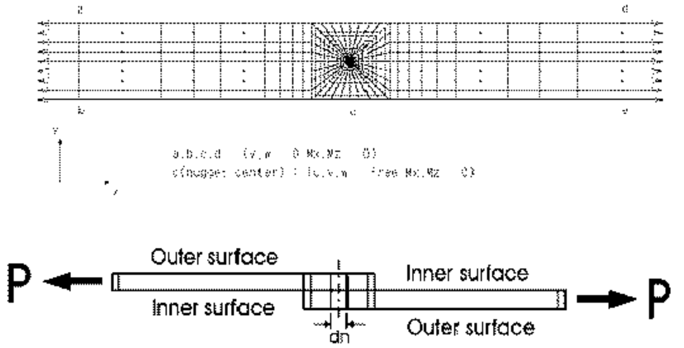
Table 3 Specimen types for FEA

Lapped sheets	Lapped type (plate thickness)	Nugget diameter (mm)
2L	LT(4)+LT(4)	10
	LT(4)+HT(4.5)	10
	ST(2)+ST(2)	7
	DLT(2)+ST(2)	7
3L	ST(2)+ST(2)+ST(2)	7
	DLT(2)+ST(1.5)+HT(4.5)	7
	DLT(2)+DLT(2)+ST(2)	7
	DLT(2)+ST(2)+ST(2)	7
4L	DLT(2)+DLT(2)+ST(2)+ST(2)	7
	LT(4)+HT(4.5)+ST(1.5)+DLT(2)	6

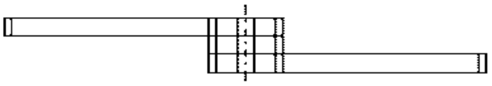
Modeling the specimen, the dimensions were referred from JIS Z 3138 (method for fatigue testing of spot welded joint). In order to consider the offset effect due to overlapping, all specimens were modeled with 3-D solid elements. As illustrated in Figure 1, the focused elements were applied at the nugget area, and upper, mid and lower plates were modeled in the same way.

The thickness of nugget area was modeled to be equivalent to that of plate. Since the nugget area experiences thermal and plastic strain during the spot-welding process, corresponding material properties, such as Young's modulus, should be modified. However, the nugget diameter is very short as summarized in Table 3, and thus, it is very difficult to measure the material property of deformed nugget area. Also, Bae et al.[3] have shown that the change of Young's modulus at the nugget area is not considerably effective in the resulting stress distribution.

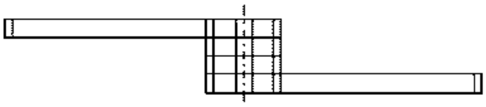
In this paper, therefore, Young's modulus of nugget area was considered to be equivalent to that of plate. The number of nodes and elements for type 2L were 1164, 1922, respectively. Modeling was performed on a commercial CAD modeling software, I-DEAS, and finite element analysis was performed by using ABAQUS.



(a) Two plate lapped joint



(b) Three plate lapped joint



(c)Four plate lapped joint

Fig. 1 Finite Element Model for TS type specimen

2.2 Analysis results

Figures 2-4 show the resulting stress distribution and deformation around the nugget edge on the inner surface of spot welded joint specimens with lapping length, 2L, of 50 *mm*, plate width, W, of 50 *mm* under constant tensile load of 4.9 k*N*.

For all specimens, the maximum stress was observed at the nugget edge on the inner surface of spot welded lap joint as shown in Figure 2 While the maximum stress was observed at the same point for different joint types, the deformation behavior and the maximum stress values were observed to be considerably different.

The stress concentration is mainly caused by the bending moment due to overlapping. This stress concentration and corresponding deformation were observed as decreasing with increasing plate thickness due to the increase of stiffness. While the same stress concentration was observed from outer and inner plates of 3L and 4L types, the mid-plate showed no deformation as shown in Figures 4 and 5. Since the applied load causes rotational bending moment at the nugget area, it seems to be reasonable to show no deformation in the middle plate.

As shown in Figure 5, 4L type showed a similar deformation behavior with that of 3L type. While the increase of bending moment due to the increase of gap between outer and inner plates was expected to cause higher stress concentration, the increased thickness also caused increase of stiffness, and thus, the resulting maximum stress was less than those for 2L and 3L types. In case of lapping different plates in terms of thickness, the maximum stress concentration was observed from the thinnest plate.

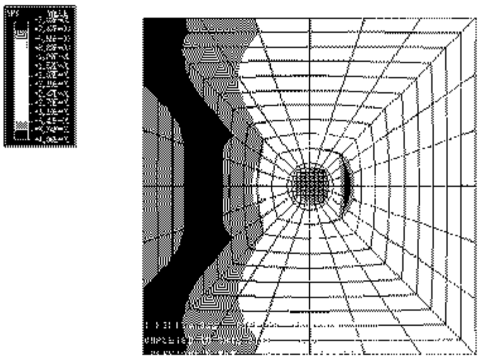


Fig. 2. Stress distribution around the nugget edge on the inner surface of spot welded joint.

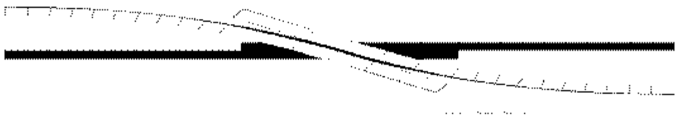


Fig 3. Stress distribution and deformation of 2L type joint. (LT+LT)

Fig 4. Stress distribution and deformation of type joint. (DLT+DLT+ST)

Fig 5. Stress distribution and deformation of 4L type joint (LT+HT+ST+DLT).

3. Fatigue life estimation of spot-welded multi-lap joint

Figure 6 shows the relationship between the fatigue load range applied to spot-welded multi-lap joints and the fatigue life, in terms of the ΔP-N_f diagram [5]. The ΔP-N_f diagram provides relative comparisons of the effect of a number of layers, a size of weld nugget and material properties on fatigue strength and life. However, it shows a large scatter and thus is difficult to provide a proper guideline for integrated design, considering many variables described above, in actual applications. In this respect, Bae et al. [3] proposed that a fatigue life estimation, considering all geometric variable, was possible when the ΔP-N_f relationship was reformulated in terms of the maximum stress at the nugget edge in spot-welded multi-lap joint. Moreover, Shon and Bae [6] [7] showed that, when the spot-welded region is regarded as a ligament crack and when the fatigue life is formulated in terms of the stress intensity factor, the elastic fracture mechanics parameter representing the intensity of the stress singularity at the crack tip, a possibility for fatigue design was provided.

In this paper, an attempt has been made to propose guideline for fatigue life design of spot-welded multi-lap joints by combining test results and FE results. Two attempts were made. Firstly, test data for various geometry and material properties were correlated in terms of the maximum principle stress, determined from the FE analysis. The second attempt is to use the stress intensity factor, again determined from the FE analysis.

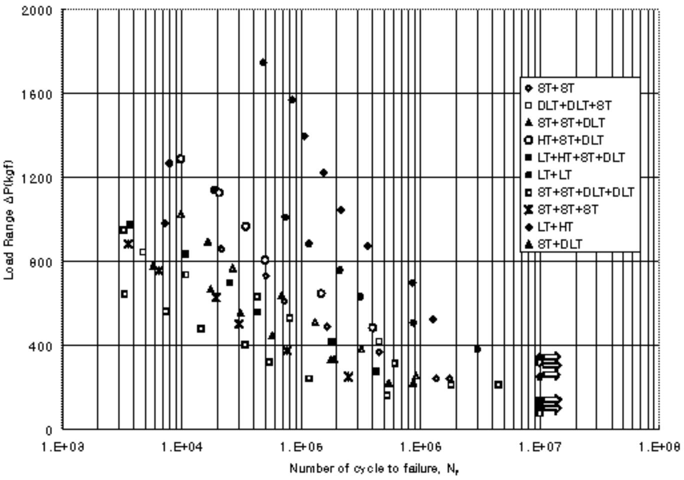


Fig 6. ΔP-N_f relation for various spot welded multi-lap joints.

3.1 Fatigue life estimation based on maximum principle stress

Figure 7 shows the relationship between the stress range and the fatigue life. The results are presented in a semi-logarithm form. The stress here denotes the maximum principle stress, determined from the FE analysis.

Compared to Figure 6, it can be easily seen that the scatter in Figure 6 is significantly reduced. This implies that the fatigue life of components with spot-welded multi-lap joints can be estimated regardless of the geometry of spot-welds and associated material properties. This further implies that a limited test result would be sufficient to design components with spot-welded multi-lap joint.

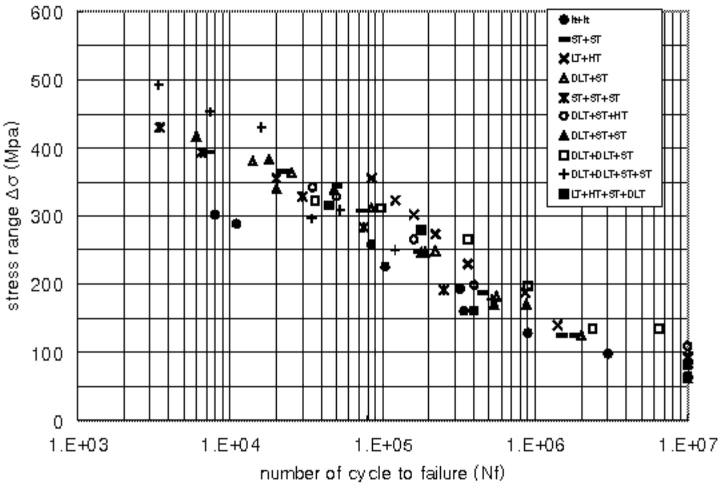


Fig. 7 $\Delta\sigma$ - N_f relation for various spot welded multi-lap joints.

3.2 Fatigue life estimation based on stress intensity factor

In section 3.1, it has been shown that formulation of the fatigue life test results using the maximum principle stress range reduces the scatter in fatigue life, compared to using the load range, and thus obtaining a unique fatigue design curve for components with spot-welded multi-lap joint, independent of geometry and material properties, would be possible. In this work, another approach using the stress intensity factor, based on elastic fracture mechanics[8], is also tried. Consider the specimen depicted in Figure 1, subject to tensile shear loads. Static analysis shows that the spot-welded region is subject to in-plane shear and out-of-plane bending, as illustrated in Figures 3-5. It should be noted that the dominating parameter in such case is the Mode II stress intensity factor, K_{II}, due to in-plane shear, rather than the Mode I stress intensity factor K_I, due to out-of-plane bending. Thus an attempt is made to re-draw the results shown in Figure 6, using the Mode II stress intensity factor.

Figure 8 shows the resulting plot for fatigue life in terms of the Mode II stress intensity factor. It can be seen that the scatter in lower fatigue life is quite large, but that in higher fatigue life is significantly reduced. As high cycle fatigue life design is sought in typical application of components with spot-welded multi-lap joints, this approach using the stress intensity factor would be useful.

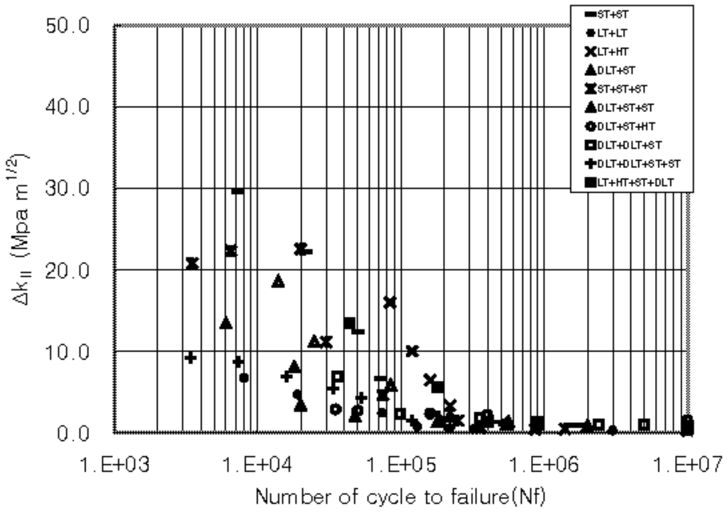


Fig. 8 ΔK_{II}-N_f relation for various spot welded multi-lap joints.

4. Conclusion

This paper provides guideline for integrated design of SUS 301L plates with multiple spot welds, typically used for a train body. Both geometric parameters and material properties are simultaneously considered. Comparing test results with stress and deformation characteristics obtained from detailed FE analyses, following conclusions are drawn.

(1) Although the ΔP-N_f relationship permits relative comparison for the effect of geometric variables and material properties on fatigue life, it does not provide guideline for integrated design considering both geometric variables and material properties.

(2) Using $\Delta\sigma$-N_f relationship, resulting from the maximum stress within weld nuggets, a proper guideline for integrated design considering both geometric variables and material properties can be established.

(3) Reformulating the ΔP-N_f relationship using the stress intensity factor within nuggets permits fatigue life design rule independent on geometric variables and material properties for multiple spot welded components.

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