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Fatigue Design of Various Type Spot Welded Lap Joints Using the Maximum Stress

Wonseok Jung, Dongho Bae*
Mechanical Engineering,
Sungkyunkwan University, Suwon, Kyonggi-do 440-746, Korea
Ilseon Sohn
Computer Applied Machine Design Engineering,
Osan College Osan, Kyunggi-Do 447-060, Korea

Recently, a new issue in designing spot welded structures such as automobile and train car bodies is to predict an economical fatigue design criterion. One of the most typical and traditional methods is to use a $\Delta P-N_f$ curve. However, since the fatigue data on the $\Delta P-N_f$ curve vary according to the welding conditions, materials, geometry of joint and fatigue loading conditions, it is necessary to perform the additional fatigue tests for determining a new fatigue design criterion of spot-welded lap joint having specific dimension and geometry. In this study, the stress distributions around spot welds of various spot welded lap joints such as in-plane bending type (IB type), tension shear type (TS type) and cross tension type (CT type) were numerically analyzed. Using these results, the $\Delta P-N_f$ curves previously obtained from the fatigue tests for each type were rearranged into the $\Delta\sigma$-N_f relations with the maximum stresses at the nugget edge of the spot weld.

Key Words : Spot Welding, In-plane Bending Type Joint, Tension Shear Type Joint, Cross Tension Type Joint, Fatigue Design Criterion, Stress Concentration, Maximum Stress, Fatigue Limit

1. Introduction

Spot welding is a very useful technology in the fabricating process of thin sheet structure such as automobiles and railroad car bodies. However, since the shape of the spot weld is circular with a diameter of several mm, it can be a source of the fatigue crack initiation as well as the stress concentration for fatigue loading. Therefore, the fatigue strength of the spot welded components is lower than that of base metals. The fatigue strength of spot-welded joints affects the structural rigidity and durability of spot-welded structures. Thus, it is an important factor in determining safety and structural integrity. To determine the long-life fatigue design criterion of spot welded structures, accurate stress analysis and systematic fatigue strength evaluation are needed. However, since it is very difficult to directly determine the fatigue design criterion for actual structures, it is a typical practice to evaluate fatigue strength with mock-up specimens satisfying the structural and mechanical characteristics of actual structures.

Many investigators have numerically and experimentally studied on fatigue strength evaluation, and provided a considerable amount of fatigue strength data on various spot-welded joints (Hujimoto et al., 1985 ; JSAE, 1987 ; Radaj et al., 1990 ; Bae, 1991 ; Radaj, 1995). In general, one of the most typical and traditional methods for fa-

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* Corresponding Author,
E-mail : dhbae@skku.edu
TEL : +82-31-290-7443; **FAX** : +82-31-295-1937
Mechanical Engineering, Sungkyunkwan University, Suwon, Kyonggi-do 440-746, Korea. (Manuscript **Received** March 11, 2003; **Revised** June 19, 2003)

tigue strength evaluation is to use a $\Delta P-N_f$ relation. It is, however, difficult to synthetically determine an integrated fatigue design criterion considering the effects of the various geometrical factors because the relationship between fatigue load range (ΔP) and fatigue life (N_f) depends on material properties, geometry, and the loading condition (Nied, 1984; Bae et al., 1988). Furthermore, in order to predict the fatigue strength and fatigue life of a specific spot welded joint, it is also necessary to conduct many additional fatigue tests for obtaining its $\Delta P-N_f$ curve, which costs much labor and time. If the fatigue strength and life of a spot welded joint having a specific geometry can be predicted by a reliable systematic fatigue strength evaluation method from the fatigue data already accumulated, an integrated fatigue design criterion can then be determined without any additional fatigue tests according to the geometrical factors.

For the fatigue analysis, fatigue strength and fatigue life are generally evaluated using the stress categories such as nominal stress, structural hot spot stress, and notch stress considering stress concentration effects. The choice of the stress category depends on the method used to express fatigue strength data in the fatigue analysis (Niemi, 1995). Among these categories, the nominal stress and notch stress can be considered as the mechanical parameters for fatigue strength evaluation of spot welded joints. In this paper, in order to develop an economical and reasonable fatigue design method for various spot welded lap joints, the maximum principal stress at the nugget edge of the spot weld, instead of the nominal stress, was applied.

Spot welded joints considered in this paper are the in-plane bending type (IB type), tensile shear type (TS type) and cross tension type (CT type), which are typical of spot welded structures. Their stress distributions around the spot weld were numerically analyzed. Since the objective of this paper is to provide an integrated fatigue design criterion for various spot-welded lap joints, based on finite element analysis, fatigue strength data for spot-welded lap joints were rearranged in terms of the maximum principal stresses at the nugget edge of the spot weld.

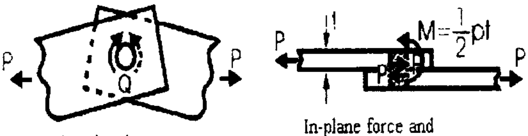
2. Finite Element Analysis on the Deformation and Stress Distribution of Various Spot Welded Joints

2.1 Analysis models

When the external tensile load or tensile shear load is applied to single spot-welded lap joints, as illustrated in Fig. 1, three internal forces of in-plane shear force (P), in-plane bending force (Q), and out-of-plane bending moment (M), act on the spot weld. These internal forces yield a very complicated deformation (Bae et al., 1988). Thus fatigue cracks are generally generated at the nugget edge on the inner surface and propagated to the outer surface of the plate by this deformation mechanism and stress concentration. Therefore, it is very important to calculate the accurate stress and strain distributions around the weld nugget for reasonable fatigue strength evaluation as well as analysis of fatigue crack initiation and behavior mechanism at the nugget edge of the spot weld (Bae et al., 1988; Bae, 1991; Sohn, 1998).

Since the local plastic strain due to the stress concentration around the nugget edge was predicted to occur, the elasto-plastic finite element analysis was performed in this paper for the stress distribution analysis. Analysis models include TS type, IB type, and CT type simulation models, and all of them were modeled in three-dimensions to consider the offset effect due to overlapping of spot welded lap joint.

Eight nodes plain strain elements were entirely used. Mesh generation for the upper and lower plates was symmetrically performed. Particularly, the weld nugget of each model was formed by getting together the node numbers of the elements



In-plane bending moment

In-plane force and
out of plane bending moment

Fig. 1 Internal forces acting on the nugget contacting each other on the inner surfaces of the upper and lower plates. The thickness of the nugget area was also modeled to be equivalent to that of the lapped plate.

Since the nugget area experiences the thermal strain and plastic strain resulting from heat generation and electrode force during the spot-welding process, corresponding material properties such as Young's modulus should be modified. However, since the nugget diameter is very small, it is very difficult to measure the material properties of the deformed nugget area. Bae et al. (1988) also showed that the change of Young's modulus at the nugget area does not considerably influence the result of stress analysis. Therefore, Young's modulus of the nugget area was considered to be equivalent to that of the plate. I-DEAS and ABACUS, commercial FEA packages, were used for modeling and numerical analysis.

For confirming deformation conditions, tensile load or tensile shear load of 9.81 MPa was applied to each model on the directions illustrated in Figs. 2-4. However, assessing fatigue strength of each model, the maximum principal stresses were calculated with actual loads applied to each fatigue specimen.

The specimen materials of spot welded lap joints in this paper consist of the cold rolled high strength steel (SPCC) sheet for the IB and CT types and the stainless steel (STS 301) sheet for the TS type. These materials are typically used for the automobile and train body structure. The chemical composition and mechanical properties are listed in Tables 1-4.

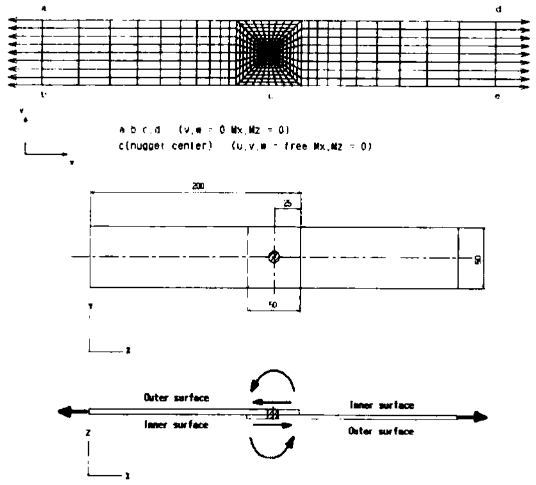


Fig. 2 FEM model for TS type specimen subjected to tensile shear load

2.2 Analysis results

2.2.1 TS type

Figure 5 shows the results of the stress distribution and deformation around the nugget edge on the inner surface of the TS type spot welded

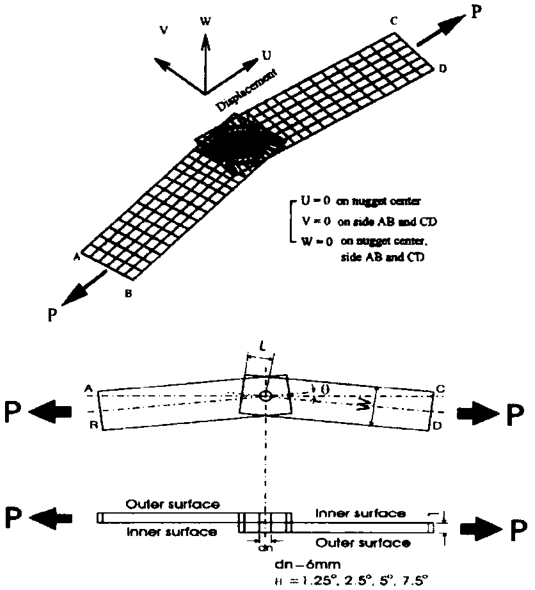


Fig. 3 FEM model for IB type specimen subjected to tensile shear load

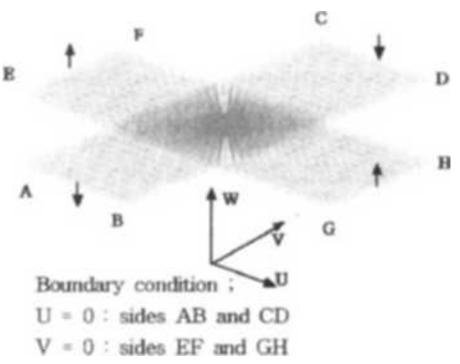


Fig. 4 FEM model for CT type specimen subjected to tensile load

Table 1 Chemical composition of SPCC (Unit : wt. %)

C	Si	Mn	P	S	Ni	Al
0.12	0.01	0.127	0.015	0.007	0.025	0.045

Table 2 Mechanical properties of SPCC

Y.S.(MPa)	T.S.(MPa)	El.(%)
168.4	307.0	47

Table 3 Chemical composition of STS301L

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 4 Mechanical properties of STS301L

Processing management	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Plate
Solution Treatment	≥215.4	≥548.8	≥441	LT
Skin Pass Mill	≥343	≥686	≥393	DLT
	≥411.6	≥754.6	≥343	ST
	≥686	≥931	≥196	HT

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

joint. The TS type spot welded lap joint causes complicated deformation behavior around the spot weld due to combination of the in-plane shear force and out-of-plane bending moment. Since the fatigue crack initiation occurs around the nugget edge of the inner surface and grows out to the outer surface of the plate, it is crucial to obtain the stress and strain distributions at the nugget area for investigation of the fatigue crack growth mechanism. In this paper, three kinds of TS type spot welded multi-lap joints : 2-, 3-, and 4-layers of the sheets were considered. For all specimens, the maximum principal stresses occurred at the nugget edge on the inner surface of spot welded lap joint as shown in Fig. 5. While the maximum principal stresses were observed at the same point for the different joint types, the deformation behavior and maximum principal stress values were considerably different.

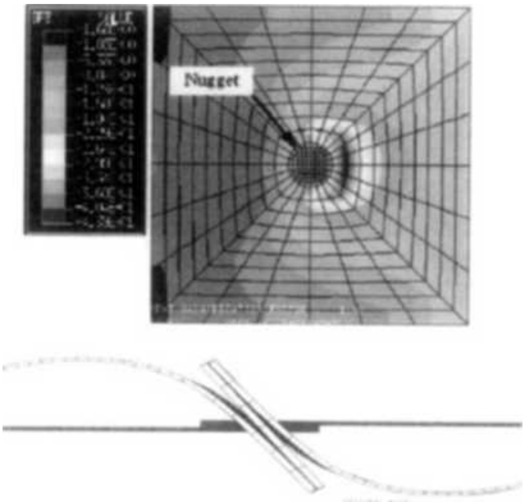


Fig. 5 Stress distribution around the nugget edge on the inner surface and deformation of TS type (for example, 3-layer multi-lap spot welded joint)

The stress concentration at the nugget edge of the spot weld is mainly caused by the bending moment due to overlapping. This stress concentration and corresponding deformation were decreased with the plate thickness increase due to the increase of bending rigidity. While the same stress concentration and deformation were observed from the outer and inner plates of 3L and 4L types, the mid-plate showed no deformation as shown in Fig. 5. Since the applied load causes rotational bending deformation at the nugget area, it seems to be reasonable to show no deformation in the mid- plate. Furthermore, while the increase of the bending moment due to the increase of gap between the outer and inner plates was expected to cause higher stress concentration, the resulting maximum stress was less than those for 2L and 3L types because the increased thickness also caused an increase of stiffness. In case of lapping the plates of which the thickness is different, the maximum stress was observed from the thinnest plate.

2.2.2 IB type

When a tensile shear load is applied to the IB type specimen as shown in Fig. 6, mechanical

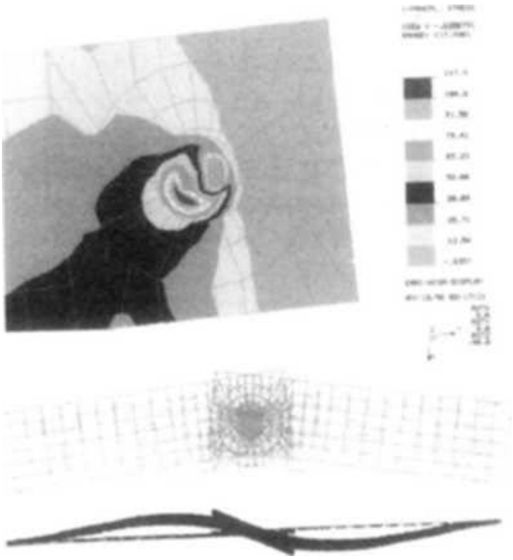


Fig. 6 Stress distribution around the nugget edge on the inner surface and deformation of IB type

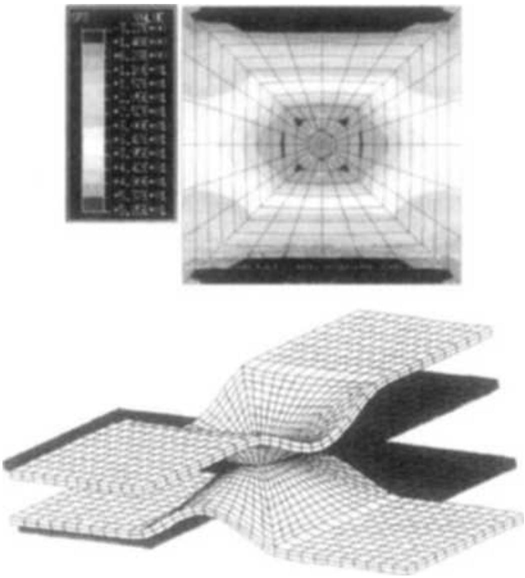


Fig. 7 Stress distribution around the nugget edge on the inner surface and deformation of CT type

components of the in-plane force, in-plane bending and out-of-plane bending moments partially act on the spot weld. These components cause very complicated deformation, and affect the stress distribution around the nugget edge.

Due to this mechanism, the stress concentration occurred at the nugget edge on the loading side of the plate, and its range is influenced by the various geometrical factors such as joint angle, plate thickness and width of the plate. The maximum principal stress distribution created at the nugget edge lies between $-20°$ and $+40°$ from the centerline of the plate as shown in Fig. 6.

2.2.3 CT type

Figure 7 shows the deformation and stress distribution around the nugget edge of the CT type spot-welded lap joint subjected to the out of plane tensile load. The CT type spot welded lap joint showed dominantly the out of plane deformation, but the complicated deformation due to the out-of-plane bending moment caused around spot weld. By this influence, the stress concentration and maximum principal stress according to the variation of the plate thickness caused around the nugget edge of the spot weld, but the deformation and maximum stress value were different. Increasing the thickness of the plate, the bending deformation and maximum stress at the nugget edge decreased due to the increase of bending rigidity.

3. Fatigue Strength Evaluation of Spot-Welded Lap Joint

Figures 8~10 show the relationship between the fatigue load range applied to each spot-welded lap joint and fatigue cycles ($\Delta P - N_f$ relation). The geometrical factors and mechanical properties of various spot welded lap joints affect fatigue strength. However, since the fatigue data on the $\Delta P - N_f$ relation in Figs. 8-10 are scattered by the effects of the geometrical and mechanical factors of the joints, it is very difficult to determine the integrated design criterion systematically estimating the effects of the geometrical factors on fatigue strength, although the influence of the geometrical factors on the fatigue strength and life of them can be compared each other.

Therefore, it is necessary to develop a systematic fatigue design method synthetically considering the geometrical and mechanical factors of

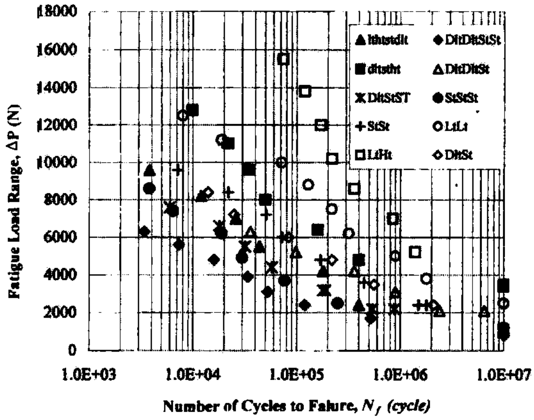


Fig. 8 $\Delta P - N_f$ relation of TS type spot welded lap Joint

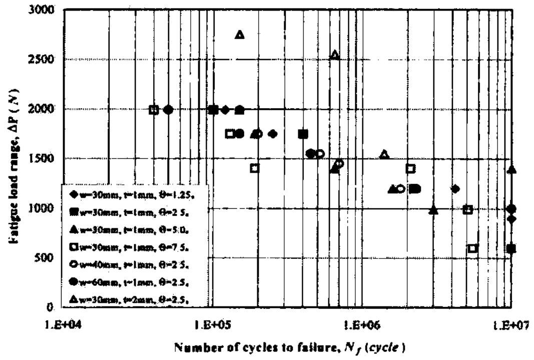


Fig. 9 $\Delta P - N_f$ relation of IB type spot welded lap Joint

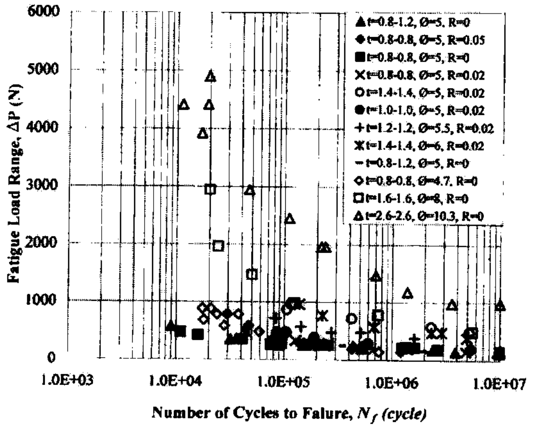


Fig. 10 $\Delta P - N_f$ relation of CT type spot welded lap Joint

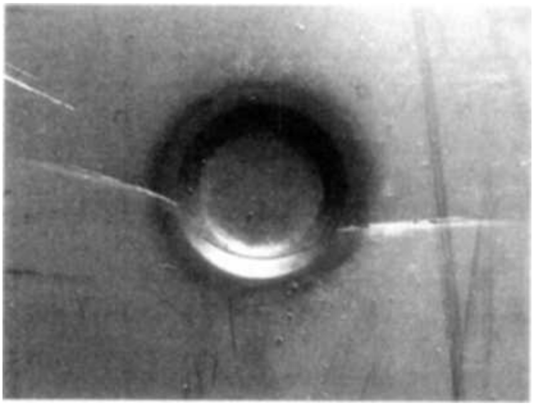


Fig. 11 Fatigue crack revealed at the nugget edge on the outer surface of the specimen

spot-welded joint. Bae and coworkers (Bae et. al, 1988 ; Sohn et al., 1998 ; Sohn and Bae, 2000, 2001) have proposed a systematic fatigue strength evaluation method considering the geometrical factors, materials and welding condition of spot welded lap joints. They represented the $\Delta P - N_f$ relations with the maximum stress at the nugget edge of the spot weld where the position of fatigue cracking is shown in Fig. 11. Thus, in this paper, the method proposed by them was applied to determine the fatigue design criteria of various spot welded lap joint.

4. Fatigue Strength Evaluation Using the Maximum Stress

As afore mentioned, an attempt has been made to propose a guideline for fatigue design of various spot-welded lap joints. Thus, the fatigue strength of TS, IB, and CT type spot welded lap joints was rearranged with the maximum principal stresses ($\sigma_{\max}$) calculated from the FE analysis.

Figures 12-14 show the relationship between stress range and fatigue life for various spot welded lap joints. The results are presented in semi-logarithmic coordinates, and the stress here denotes the maximum principal stress determined from the FE analysis. It can be easily seen that the scatters in Figs. 8-10 are significantly reduced. This means that fatigue design criterion of the spot welded structural components can be economically determined in regardless of the

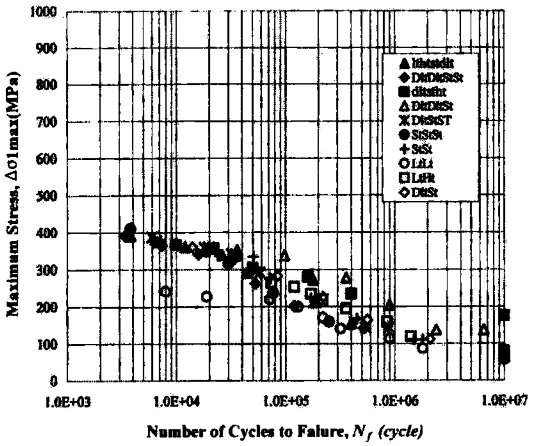


Fig. 12 $\Delta\sigma-N_f$ relation of TS type spot welded lap joint

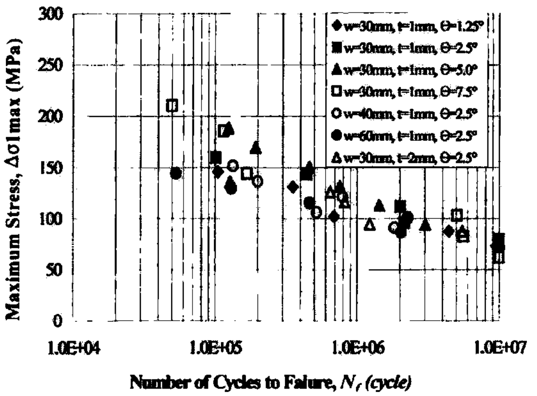


Fig. 13 $\Delta\sigma-N_f$ relation of IB type spot welded lap joint

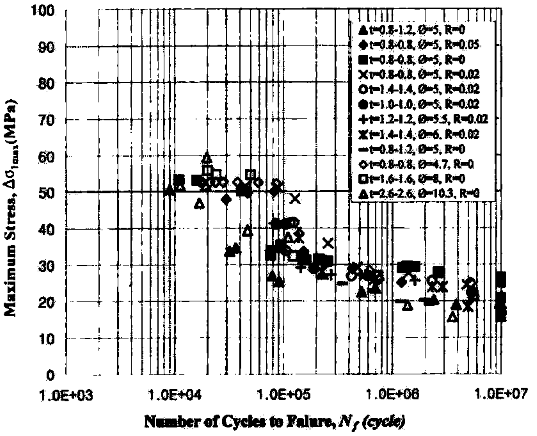


Fig. 14 $\Delta\sigma-N_f$ relation of CT type spot welded lap joint

geometry of joints and associated material properties.

5. Conclusions

In order to develop an economical fatigue design method for spot welded thin sheet structures such as automobile and train car bodies, the stress distributions around the spot weld of various simulated spot welded lap joints such as IB, TS, and CT type were numerically analyzed. Using these results, the $\Delta P-N_f$ curves previously obtained from the fatigue tests for each type were rearranged into the $\Delta\sigma-N_f$ relations with the maximum principal stresses at the nugget edge of the spot weld. From the results, following conclusions were drawn.

(1) Spot welded joints of TS, IB and CT types are considerably influenced by the geometrical factors, and their maximum principal stresses are generated at the nugget edge on the loading side of the plate.

(2) Although the $\Delta P-N_f$ relationship permits relative comparison for the effects of the geometric variables on fatigue strength, it does not provide a guideline for integrated fatigue design criterion considering the geometric variables.

(3) Using the $\Delta\sigma-N_f$ relationship, a proper guideline for integrated fatigue design considering both the geometric variables and material properties can be established.

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