Strength Evaluation of Spot Weld in Fatigue Using Double-Cup Specimen

E. Nakayama[1], M. Miyahara[1], H. Fujimoto[1], Y. Hirose[1], K. Fukui[2], T. Kitamura[3]
[1]*Sumitomo Metal Industries, Ltd, Hyogo, Japan;*
[2]*Sumitomo Metal Industries, Ltd, Tokyo, Japan;*
[3]*Kyoto University, Kyoto, Japan*

ABSTRACT

Double-cup (DC) specimen of spot welded joint is newly produced for high strength steel (HSS) sheets with the steel grade ranging from 590MPa to 980MPa, and fatigue tests are conducted under three kinds of loading directions (tensile, shear and combination of both). The fatigue strength is degraded as the load component in the tensile direction increases. The HSSes show higher fatigue strength than the mild steel under the shear loading, whereas the fatigue strength of the tensile-shear (TS) specimen is almost equal regardless of the steel grade. Finite element analyses reveal that the rotation of the spot weld in the DC specimen is smaller than that of the TS specimen due to deformation constraint around the spot weld and the stress state is close to pure shear, which leads to the fair evaluation of the effects of the steel grade.

KEYWORDS

Fatigue, Steel Sheet, Spot Weld, Mixed Mode, Double-Cup Specimen, Mild Steel, High Strength Steel, Finite Element Analysis

1 INTRODUCTION

Spot welding is widely employed to join steel sheets for automotive components. Stress concentration takes place in spot weld due to its shape like a sharp notch and it can lead to fatigue crack initiation. Thus, it is necessary to understand the fatigue strength of spot weld. In general, fatigue strength of spot weld is examined using the two types of standard joint specimens, one for the tensile loading (normal to the sheet interface) and the other for shear loading (parallel with the sheet interface). Based on these specimens, many studies [1-3] have been reported on the fatigue strength of the spot weld. In actual vehicle bodies, however, spot welds are subjected to complex loading under which the tensile and the shear loads are combined, and then the fatigue strength of the standard specimens cannot be directly related to that of automotive structure. Therefore, it is important to develop a flexible fatigue testing method for spot weld under mixed-mode loadings.

The “Committee on Fatigue Strength & Structural Reliability” in the Society of Automotive Engineers of Japan (JSAE) has been conducting the study on fatigue strength of spot weld under mixed-mode loading using the Double-Cup (DC) specimen [4, 5]. The DC specimen well reproduces the stress states around the spot weld in actual vehicles with relative ease [4]. Moreover, based on the fatigue data of the DC specimen and FE analysis, the fatigue lives of the spot welded structures can be accurately predicted [5]. However, the tensile strength of the steel (the steel grade) tested was restricted within 440MPa because of a problem in production of the DC specimen as described later, and the mixed mode fatigue property of steels over 590MPa-grade are not clarified.

Recently, the demand for weight reduction of automotive structures has been increasing for fuel saving. One of the most effective approaches to satisfy this is to reduce the thickness by application of the high strength steel (HSS). Many researchers [1, 3] have been reported that increase of the steel grade does not have significant effect on improvement of spot weld fatigue property in the case of the standard specimens. However, it is imperative for the realization of lightweight automotive design to investigate the effect of the increase of the steel grade by the DC specimen, which highly simulates the stress state of the actual components.

In this paper, the DC specimen of spot welded joint is newly produced for HSSes with the steel grade ranging from 590MPa to 980MPa by overcoming some difficulties, and their fatigue properties are examined. Moreover, the validity of the test results is discussed on the basis of comparison with the standard specimens and the finite element analysis.

2 FATIGUE TEST

2.1 Experimental procedure

2.1.1 Materials

We prepared five kinds of cold-rolled steel sheets of 1.2mm thickness with the steel grade ranging from 270MPa (mild steel) to 980MPa. Table 1 shows their chemical compositions and mechanical properties. All steel sheets are spot welded under the conditions given in Table 2. In this paper, we call each material by its steel grade.

Table 1 Chemical compositions and mechanical properties of steels tested

Steel	C (mass%)	C_{eq}* (mass%)	0.2% proof stress (MPa)	Tensile strength (MPa)	Elongation (%)
270MPa-grade	0.004	0.006	147	289	52
440MPa-grade	0.13	0.141	320	457	36
590MPa-grade	0.096	0.119	502	616	29
780MPa-grade	0.17	0.199	440	781	33
980MPa-grade	0.17	0.197	712	1045	14

* C_{eq} = C + Si/90 + (Mn + Cr) / 100

Table 2 Spot welding conditions

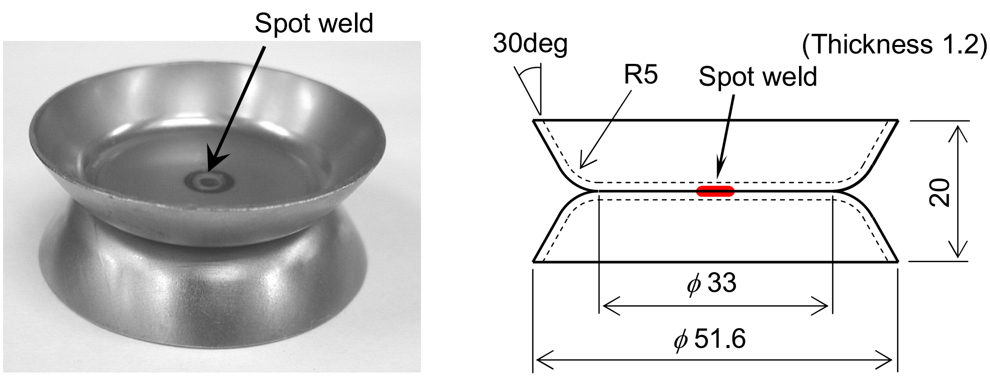
Steel	Electrode force (N)	Welding time (cycle/60Hz)*	Holding time (cycle/60Hz)*	Welding current (A)
270MPa-grade	3430	14	30	8100
440MPa-grade				8000
590MPa-grade				7800
780MPa-grade				7600
980MPa-grade				7000

* 1 (cycle/60Hz) = 1/60 (sec) = 0.017 (sec)

2.1.2 Specimen

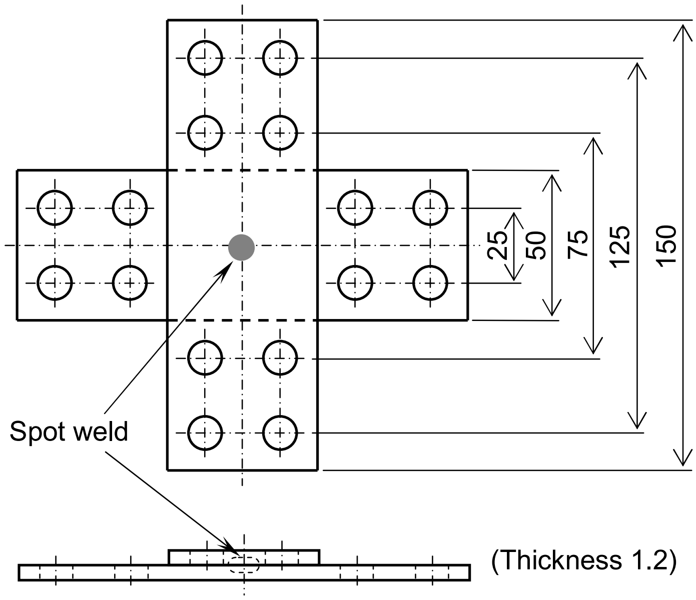
Figure 1 shows the appearance and the dimensions of the DC specimen. Steel sheet is deep-drawn so that the slope of the circumferential wall is about 30 degrees against the normal direction of the bottom plane, and then the center of the bottom planes are spot welded. In the previous studies [4, 5], the steel sheets of more than 590MPa-grade were not examined since they are difficult to be deep-drawn due to their poor formability. By reduction of the specimen height and optimization of the blank holding force, we realize making the DC specimen for the HSSes over 590MPa-grade. All steel sheets listed in Table 1 are tested.

Figure 2 illustrates the shape and the dimensions of the standard specimens. Fig.2(a) is the cross-tension (CT) specimen for the tensile loading and Fig.2(b) is the tensile-shear (TS) specimen for the shear loading. The objective of the fatigue tests of these specimens is quantitative comparison with the DC specimen under the same conditions such as the steel grade and the welding conditions. The 270MPa-grade and the 590MPa-grade are tested.

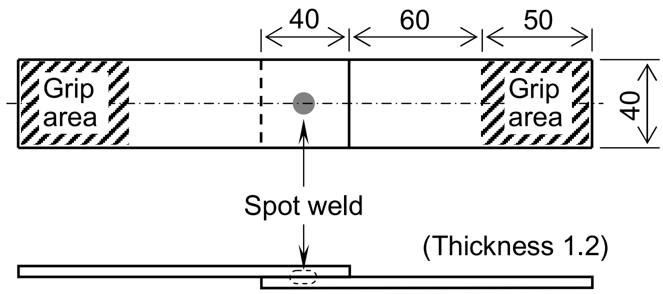


(a) Appearance   (b) Schematic of cross section (unit : mm)

Fig. 1 Double-cup (DC) specimen of spot welded joint



(a) Cross-tension (CT) specimen



(b) Tensile-shear (TS) specimen

Fig. 2 Standard specimen of spot welded joint

2.1.3 Testing equipment and test conditions

The fatigue tests of the DC specimen are conducted by an electro-hydraulic testing machine in air at ambient temperature. Figure 3 is the schematic illustration of the DC specimen and the testing grips. The grips enable us to change the loading direction in every 15 degrees and fix the circumference of the DC specimen. As shown in Fig. 3, three kinds of loading directions are employed; tensile, shear and combination of both (mixed). The loading direction of the mixed mode is rotated by 15 degrees from the shear mode. On the other hand, the fatigue tests of the CT and TS specimen are carried out by an electromagnetic resonance testing machine in air at ambient temperature.

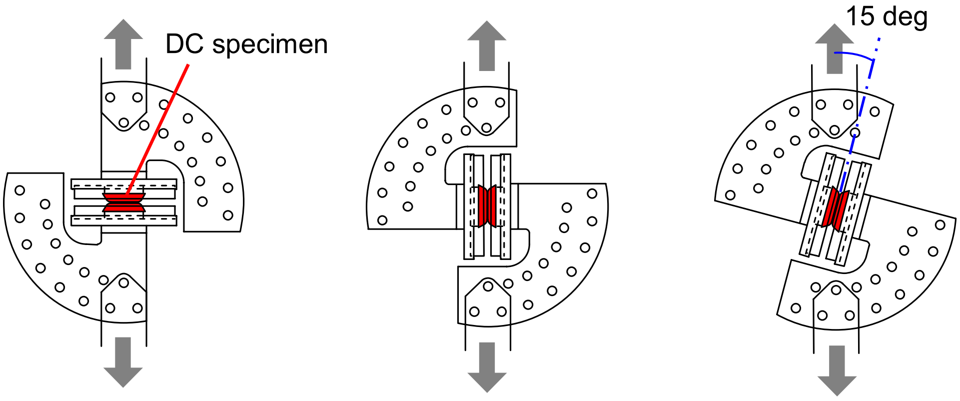


Fig. 3 Schematic of DC specimen and testing grips

The force waveform for all tests is sine with a force ratio of 0.1. The frequency is 3Hz for the DC specimen and 50-100Hz for the CT and TS specimen. We define the number of cycles to failure, N_f, as the cycles when the surface crack length is about the same as the diameter of the electrode indentation.

2.2 Results

Figure 4 shows the relationships of the DC specimen between the load range, ΔL, and the number of cycles to failure, N_f. The fatigue strength is degraded as the increase of the load component in the tensile direction. In each material, the fatigue strength of the mixed mode is approximately equal to the average of those of the tensile and the shear mode.

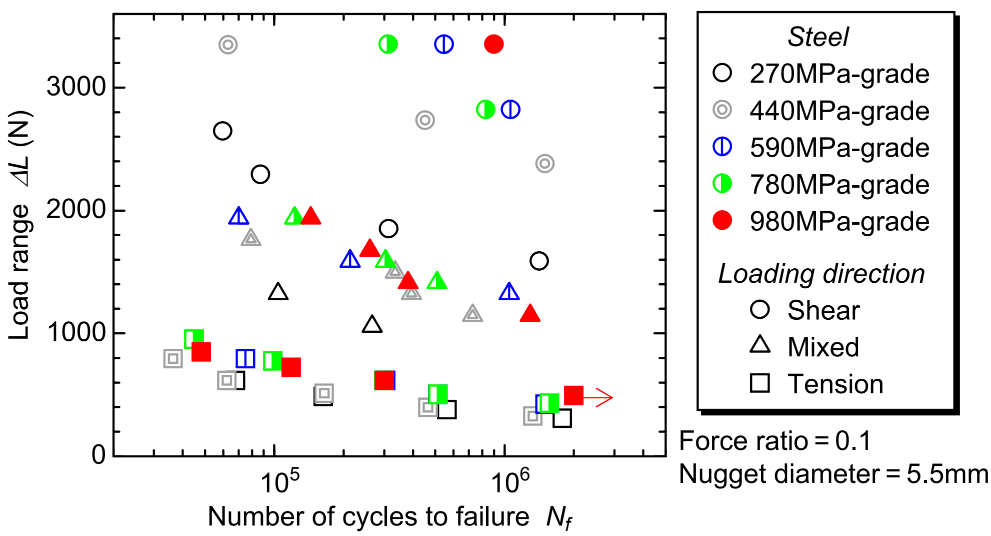


Fig. 4 L-N relationships of DC specimen

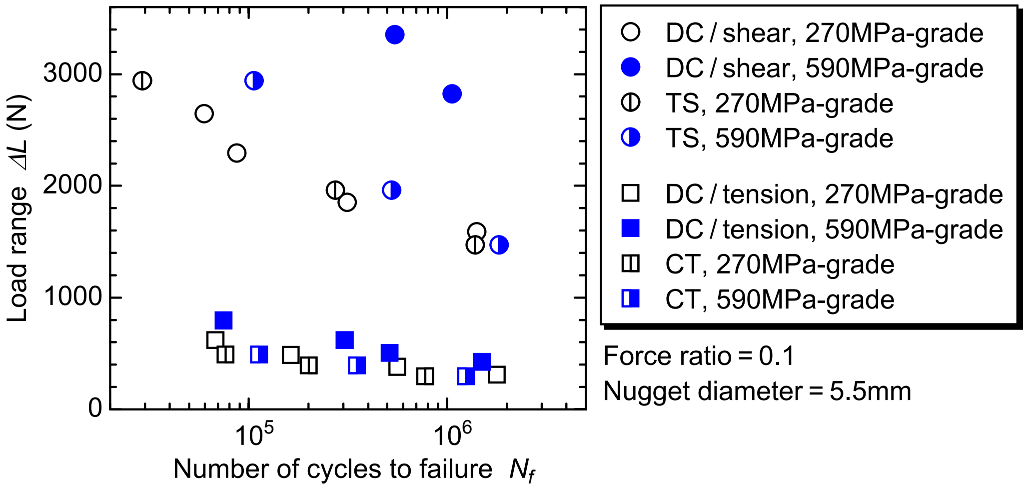


Fig. 5 Comparison of L-N relationships between DC specimen and standard specimens

The fatigue strength of the tensile mode is almost equal regardless of the steel grade. On the other hand, the HSSes show higher fatigue strength than the mild steel in the shear mode.

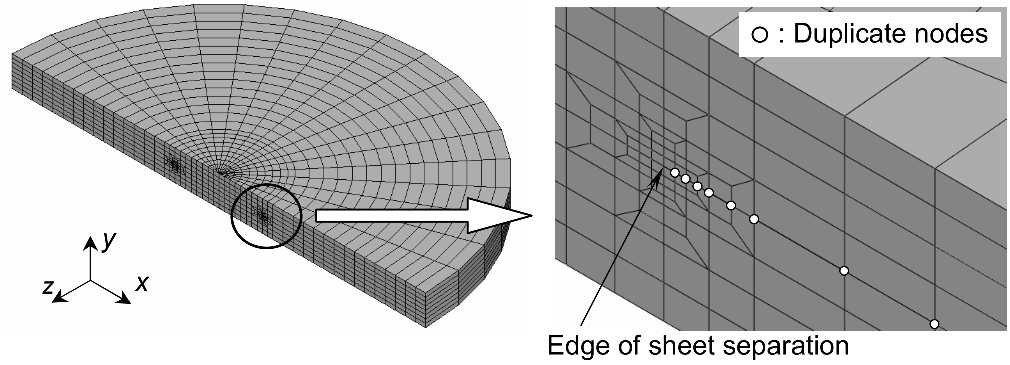
Figure 5 compares the fatigue strength of the DC specimen (the tensile and the shear mode) and the CT/TS specimens on the 270MPa-grade and the 590MPa-grade. There is no significant difference between the DC specimen of tensile mode and the CT specimen. This indicates that the stress state is similar between both specimens. As to the TS specimen, the fatigue strength in long-life region is almost equal between both steels and is also similar to that of the DC specimen of the 270MPa-grade in the shear mode.

3 FINITE ELEMENT ANALYSIS

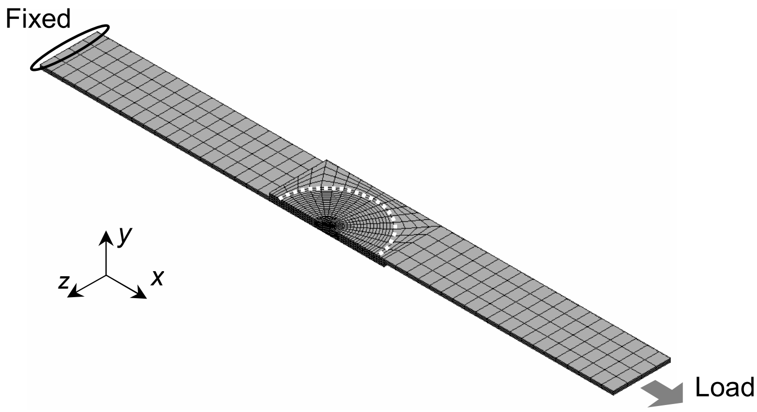
3.1 Analytical procedure

In order to clarify the reason why the effect of the steel grade is different between the DC specimen of the shear mode and the TS specimen, finite element analyses are carried out on the 270MPa-grade and the 590MPa-grade.

Figure 6 shows the finite element models. The dimensions and the mesh division are all same for both steels. Considering the geometric symmetry, half of the specimen is modeled with three-dimensional 8 nodes hexahedral elements. Only the bottom planes are modeled for the DC specimen. The minimum mesh size is about 80μm in the vicinity of the edge of the sheet separation, which is the crack initiation site in the fatigue test. Duplicate nodes are assigned to the faying surfaces of the sheets and the initial distance between these nodes are zero. For the DC specimen model, all nodes of the circumference in the lower sheet are fixed and the load to *x* direction is applied to those in the upper sheet. For the TS



(a) DC specimen



(b) TS specimen

Fig. 6 FE models of spot welded joint

specimen, one side of the model is fixed and load is applied to the other side. The applied load is 2000N, which is the maximum load in the actual fatigue tests of the TS specimen at N_f= 1x10^6 cycles (see Fig.5).

Figure 7 shows the stress-strain relationships for the analyses. These curves are the tensile test results of the small specimen [6] taken from the edge of the sheet separation, whose microstructure is heat affected zone (HAZ). Figure 8 shows the geometry and the sampling location of the small specimen. These stress-strain curves are used for the whole elements. For both steels, Young's modulus and Poisson's ratio are 205900MPa and 0.3, respectively. As shown in Fig.8, spot weld consists of base metal, HAZ and weld metal (nugget), whose tensile properties are quite different each other [6]. However, the plastic zone size near the edge of the sheet separation is relatively small under the condition of the fatigue loading. Therefore, it is considered that the stress and strain at the sheet separation edge can be accurately analyzed by giving the tensile property of HAZ to the total model. The elasto-plastic analysis is conducted by a commercial FEM code, Abaqus.

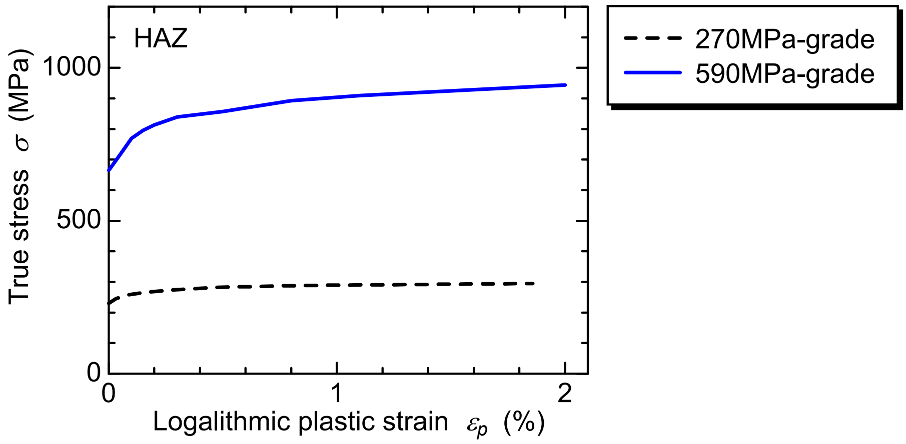


Fig. 7 Stress-strain curves for FE analysis

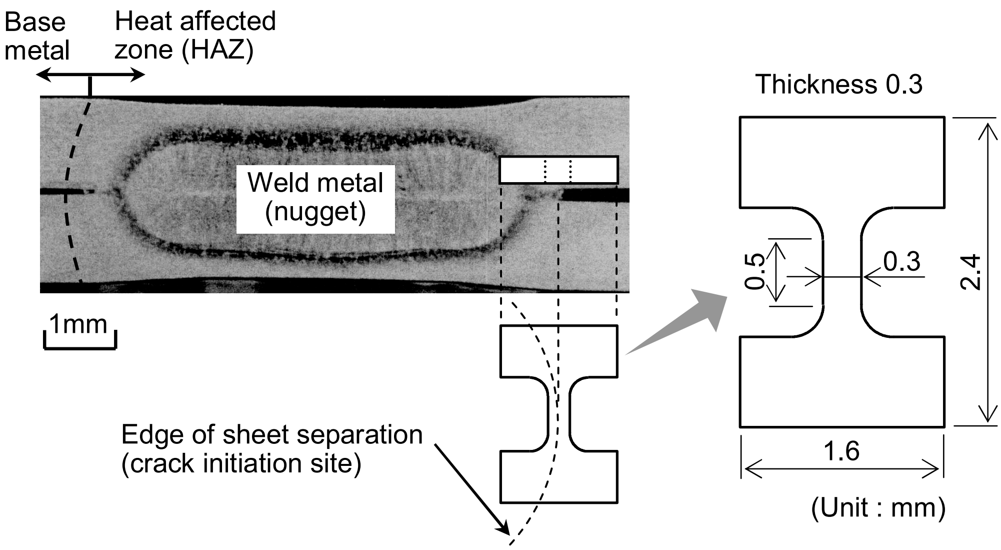


Fig. 8 Dimensions and sampling location of small tensile specimen

3.2 Results

Figure 9 shows the deformation state from the viewpoint of the symmetrical plane. The rotation of the spot weld in the DC specimen is much smaller than that in the TS specimen because the DC specimen has high rigidity against the out-of-plane bending.

Figure 10 shows the normal stress, σ_x (loading direction), σ_y (peel direction) and the shear stress, τ_{xy}, at the edge of the sheet separation on the symmetrical plane. The σ_x and σ_y of the DC specimen are much lower than that of the TS specimen in both steels. This means that the stress states of the former is predominantly pure shear and that of the latter is the multiaxial condition. The τ_{xy} is approximately equal in both specimens. In the TS specimen, the 590MPa-grade exhibits higher values in all stress components than the 270MPa-grade.

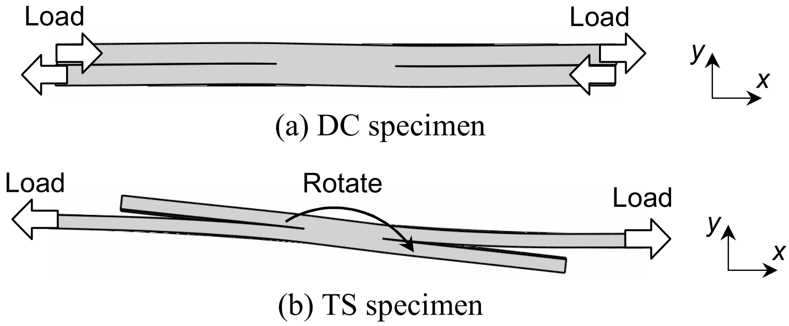
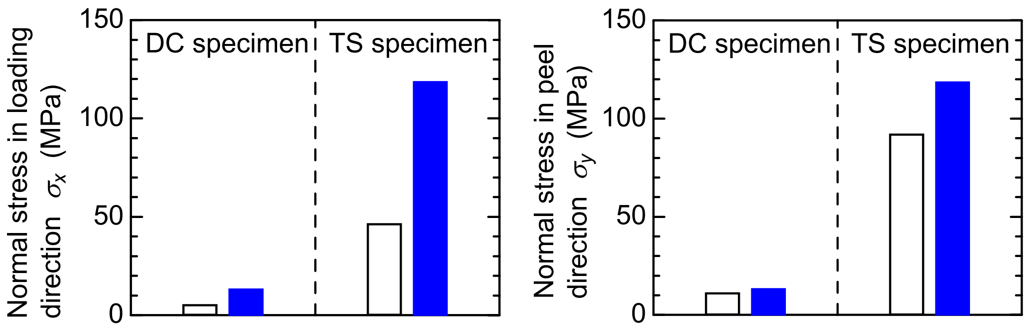
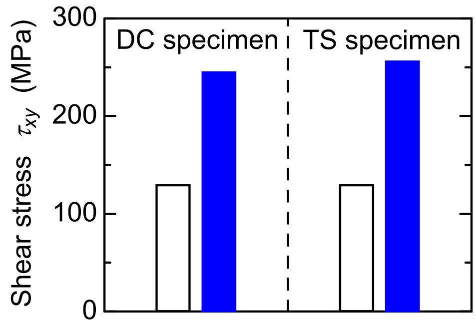


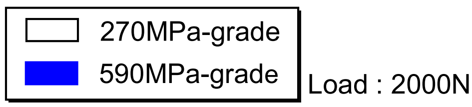
Fig. 9 Comparison of deformation state between DC specimen under shear loading and TS specimen (590MPa-grade, displacement magnification factor = 10)



(a) Normal stress in loading direction (b) Normal stress in peel direction



(c) Shear stress



Steel grade / specimen		Equivalent plastic strain (%)
270MPa	DC	0.31
	TS	0.36
590MPa	DC	0
	TS	0.01

Fig. 10 Stress and strain at edge of sheet separation

These differences in the stress state between both steels under the identical load arise from the dissimilarity of the tensile properties shown in Fig.7. The static strength of the 270MPa-grade is lower and the larger plastic strain takes place than the 590MPa-grade in both specimens as shown in Fig.10. It then follows that the stresses of the 590MPa-grade are higher than the 270MPa-grade. In the case of the DC specimen with little normal stress, the fatigue strength of the 590MPa-grade is superior to that of the 270MPa-grade because the strain of the former is much smaller. In the TS specimen, on the other hand, the higher normal stresses in the 590MPa-grade significantly degrade its fatigue strength, which is consequently equal to the fatigue strength of the 270MPa-grade.

4 CONCLUSIONS

The Double-Cup (DC) specimen of the spot welded joint is newly produced for the high strength steel (HSS) sheets with the steel grade of more than 590MPa. The fatigue tests under three kinds of the loading direction (tensile, shear and combination of both) are conducted to investigate the effect of the loading mode and the steel grade. Furthermore, the test results are validated by comparison with the standard joint specimens (cross-tension ; CT and tensile-shear ; TS) and finite element analyses. The results obtained are summarized as follows.

(1) The fatigue strength of the DC specimen is degraded as the load component in the tensile direction increases.
(2) The tensile fatigue strength of the DC specimen is approximately equal regardless of the steel grade, which is the same tendency as the CT specimen.
(3) The shear fatigue strength of the DC specimen of the HSSes are higher than that of the mild steel, while the fatigue strength of the TS specimen hardly varies according to the steel grade.
(4) The spot weld of the TS specimen rotates and it is subjected to the mixed-mode stress, under which the normal stress of the HSS is higher than that of mild steel under the identical load. On the contrary, rotation of spot weld in the DC specimen is smaller and the stress state is predominantly pure shear, which results in the fair evaluation of the effects of the steel grade.

REFERENCES

[1] R. W. Rathbun, D. K. Matlock, J. G. Speer, Fatigue behavior of spot welded high-strength sheet steels, Welding Journal, August (2003), p.207-s to p.218-s.
[2] H. Lee, N. Kim, T.S. Lee, Overload failure curve and fatigue behavior of spot-welded specimen, Engineering Fracture Mechanics, 72 (2005), pp.1203-1221.
[3] X. Long, S. K. Khanna, Fatigue properties and failure characterization of spot welded high strength steel sheet, International Journal of Fatigue, 29 (2007), pp.879-886.
[4] Y. Nakahara, M. Takahashi, A. Kawamoto, M. Fujimoto, N. Tomioka, Method of fatigue life estimation for spot-welded structures, SAE Paper, 2000-01-0779 (2000).
[5] K. Seto, A. Kawamoto, E. Nakayama, H. Ishizu, K. Tsunoda, M. Kaneko, N. Fujita, Y. Yoshida, N. Tomioka, M. Takahashi, M. Fujimoto, A new method of stress calculation in spot welded joint and its application to fatigue life prediction of actual vehicle, SAE Paper, 2003-01-2809 (2003).
[6] E. Nakayama, M. Fukumoto, M. Miyahara, K. Okamura, H. Fujimoto, K. Fukui, Fatigue strength prediction of spot-welded joints using small specimen testing, Proceedings of the 16th European Conference of Fracture (2006).