The 8th TSME International Conference on Mechanical Engineering
12-15 December 2017
Bangkok, Thailand

AMM0003

Fatigue behavior of resistance spot welded high strength steel sheets with different nugget sizes

Y. Kato[1], T. Kakiuchi[1], Y. Okita[2], H. Matsuda[2], R. Ikeda[2], T. Tagawa[2], and Y. Uematsu[1,*]

[1] Gifu University, 1-1 Yanagido, Gifu, 501-1193, Japan
[2] JFE Steel Corporation, 1 Kawasaki-cho, Chuo-ku, Chiba, 260-0835, Japan

* Corresponding Author: yuematsu@gifu-u.ac.jp

Abstract. Spot welds are fabricated using high strength and mild steel sheets with three different strength levels by a resistance spot welding (RSW) procedure. The nugget sizes are changed by controlling welding process parameters. Subsequently, tensile-shear fatigue tests are conducted to investigate the effects of strength levels of steels and nugget sizes on the fatigue behavior of welds. The fatigue strengths of the welds with $4\sqrt{t}$ nugget sizes are nearly the same irrespective of the strength levels of the steels, because fatigue crack propagation life is dominant in the total fatigue life. In the welds with $3\sqrt{t}$ nugget sizes, the steel with higher strength exhibits lower joint fatigue strengths.

1. Introduction

Recently, ultrahigh strength steel sheets are increasingly used in the automobile industries to fabricate car bodies with light weight and high strength. Accordingly, the understanding of fatigue behavior of the weldments made of ultrahigh strength steels became an important issue from the view point of the reliability of car components. For example, the mechanical properties of the ultrahigh strength steels are superior to those of the conventional mild steels, but it has been reported that the fatigue strengths were nearly comparable between the resistance spot welds made of ultrahigh strengths steel and mild steel sheets [1, 2]. However, researches about the fatigue fracture mechanisms in the resistance spot welds of ultrahigh strength steels [3, 4] are still limited. Furthermore, the effect of welding parameters on the fatigue behavior of welds is not fully understood. In this study, three kinds of steel sheets with different strength levels are used for the fabrication of resistance spot welds. In addition, nugget sizes are changed by changing the welding parameters. Tensile-shear fatigue tests are conducted to investigate the effect of strength levels of steels and nugget sizes on the fatigue behavior of welds.

2. Experimental Procedure

2.1. *Test samples*

Three kinds of steel sheets, namely ultrahigh strength steel (980MPa class), high strength steel (590MPa class) and mild steel (270MPa class) are used in the present study. The strip-shaped samples with the length of 140 mm and the width of 40 mm are cut from the sheets with the thickness of 1.6 mm. Tensile-shear specimens are fabricated in accordance with JIS (Japanese Industrial Standard) Z 3138. The center of 40 mm × 40 mm overlap area is resistance spot welded to form the nugget with the diameter of 4√*t*, where *t* is the sheet thickness of 1.6 mm. By changing the welding parameters, the welds with 3√*t* nugget sizes are also fabricated using 980 MPa and 270 MPa class steel sheets.

2.2. *Procedure*
Tensile tests are conducted using an electro-hydraulic tester with the capacity of 20 kN. The electro-hydraulic fatigue testing machine with the capacity of 50 kN is used for the fatigue tests. Fatigue load waveform is sinusoidal with the frequency of 10 Hz and the load ratio (P_{min}/P_{max}) of -1. Tabs with the thickness of 1.6 mm are welded to the gripping part of the tensile-shear specimens according to JIS Z 3138 to align the tensile loading direction of the upper and lower sheets.

3. Results and Discussion

3.1. *Nugget structures and hardness profiles*
Figures. 1(a), (b) and (c) reveal the macroscopic nugget structures of 270 MPa, 590 MPa and 980 MPa class steel welds, respectively. The structures consist of melted and re-solidified nugget, heat affected zone (HAZ) and base metal in all the welds. The detailed observation reveals that the melted and re-solidified nugget has martensite structures in 590 MPa and 980 MPa class steels, while ferrite structure is dominant in 270 MPa class steel.

Vickers micro hardness profiles are measured at mid-thickness on the cross section of the nugget. The results are shown in figure 2. Due to the melting followed by rapid re-solidification in the nugget, the hardness of the nugget is higher than that of the other areas irrespective of steel classes and nugget sizes.

3.2. *Tensile properties*
The tensile-shear failure loads of the welds are summarized in Table 1. Figure 3 shows the relationships between tensile-shear loads and cross head displacements. The displacements are much larger in 270 MPa class steel welds than the others, indicating that larger plastic deformation occurred around the nugget only in 270 MPa class steel weld. The macroscopic failure mode was shear-type fracture along the interface of nugget in all the samples. In the welds with 4√*t* nugget sizes, the failure load increases with increasing the strength level of the steels. It should be noted that 980 MPa class steel has 300 % higher tensile strength than 270 MPa one, but the strength of 980 MPa class steel weld

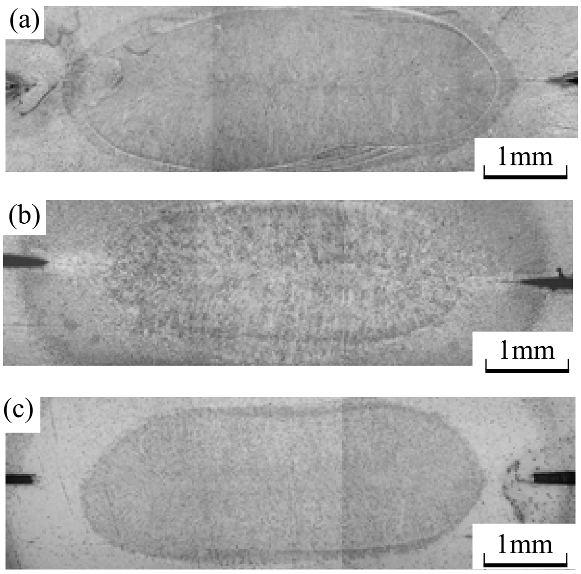

Figure 1. Nugget structures: (a) 270MPa-4√*t*, (b) 590MPa-4√*t*, (c) 980MPa-4√ √.

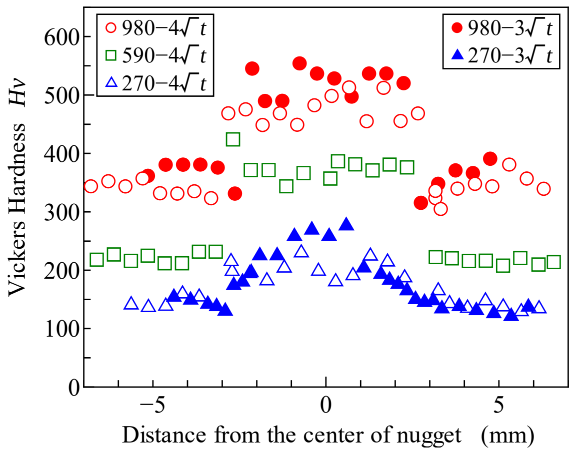

Figure 2. Hardness profiles.

is only about 144 % higher than that of 270 MPa one. Thus, the joint strengths cannot be simply evaluated from the strengths of base metals. The welds with $3\sqrt{t}$ nugget sizes have lower strengths than those with $4\sqrt{t}$ nugget sizes. The tensile-shear failure loads of the welds with $3\sqrt{t}$ nugget sizes are nearly the same between 270 MPa and 980 MPa class steels.

3.3. Fatigue properties

Figure 4 indicates the fatigue test results in terms of the relationship between maximum load, P_{max}, and number of cycles to failure, N_f. Under the high load levels in the fatigue tests, the following two macroscopic fatigue failure modes are dominant. Namely, shear-type failure along the interface of nugget similar to static failure, or plug-type failure, in which a fatigue crack initiates at the edge of the nugget and propagates circumferentially around the nugget to final fracture. Under the low load levels, a fatigue crack initiates at the edge of the nugget, but propagates nearly perpendicular to the loading axis through thickness and width directions of the sheet material.

The fatigue strengths of the welds with $4\sqrt{t}$ nugget sizes are nearly the same among three different class steels. It should be noted that the static tensile-shear failure loads show the dependence on the steel classes, but the fatigue strengths are independent on the steel classes. To investigate the fatigue

Table 1. Tensile-shear failure load.

Sample	Tensile-shear failure load (kN)
980 MPa-$4\sqrt{t}$	16.8
590 MPa-$4\sqrt{t}$	14.6
270 MPa-$4\sqrt{t}$	11.6
980 MPa-$3\sqrt{t}$	9.8
270 MPa-$3\sqrt{t}$	9.8

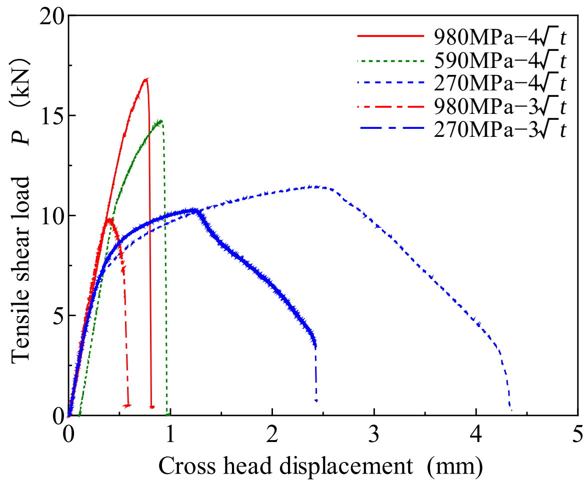

Figure 3. Relationship between tensile shear load and cross head displacement.

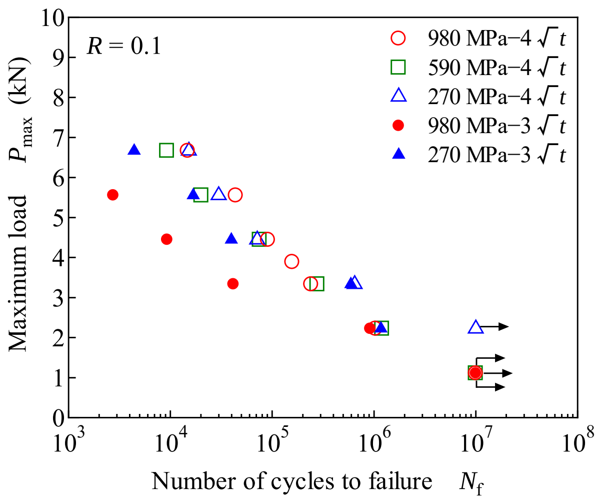

Figure 4. Relationship between maximum load P_{max} and N_f.

crack initiation life of welds, the fatigue tests were conducted using 270 MPa and 980 MPa class steel welds at the maximum fatigue load of 5.56kN. Subsequently, the fatigue tests were terminated at N/N_f = 10%, and specimens were cut parallel to the loading direction to investigate fatigue crack initiation around the nugget. Figures. 5(a) and (b) show the longitudinal sections of the nuggets in 270 MPa and 980 MPa class steel welds, respectively. At 10% of total fatigue life, fatigue cracks with the lengths about 200 μm are recognized at the edges of the nuggets in both welds as shown in figure. 5. It proves that the fatigue crack initiated in the early stage of fatigue life (shorter than 10%) and total fatigue life was mainly dominated by fatigue crack propagation life. It is known that long fatigue crack propagation rates are insensitive to the strength levels of steels [5]. Consequently, it is considered that the fatigue strengths of the welds with $4\sqrt{t}$ nugget sizes are nearly the same among three kinds of steel sheets, because the total fatigue lives of the welds are mainly occupied by fatigue crack propagation lives. As shown in figure 5(b), the fatigue crack initiation cannot be related to the corona bond between the upper and lower sheets. Furthermore, the crack initiation behavior shown in figure 5(b) is predominantly seen in the other fatigue-fractured specimens. Thus, it is assumed that the corona bonds do not play important role for fatigue crack initiation, and basically have joint strength between the upper and lower sheets.

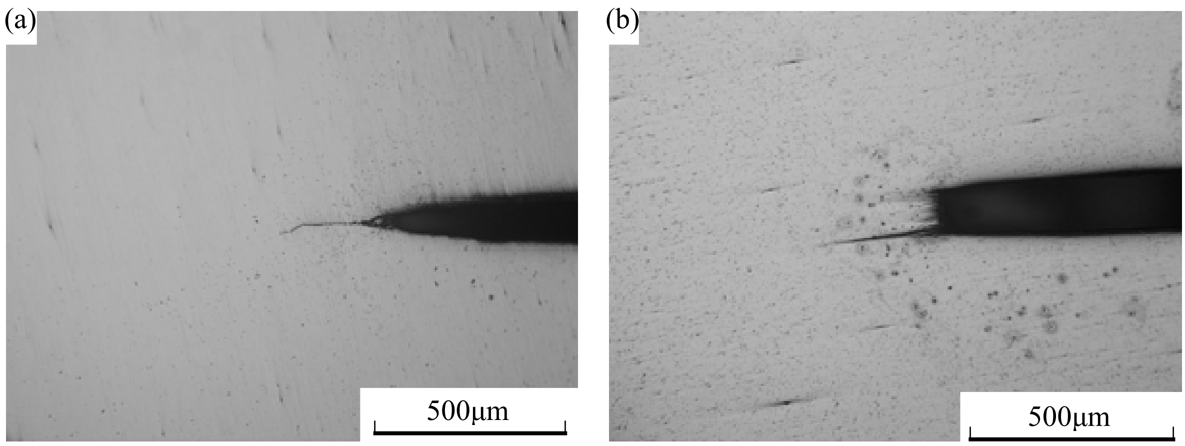

Figure 5. Cross section of the nugget in the interrupted specimens at N/N_f = 10% (P_{max} = 5.56kN): (a) 270MPa-$4\sqrt{t}$, (b) 980MPa-$4\sqrt{t}$.

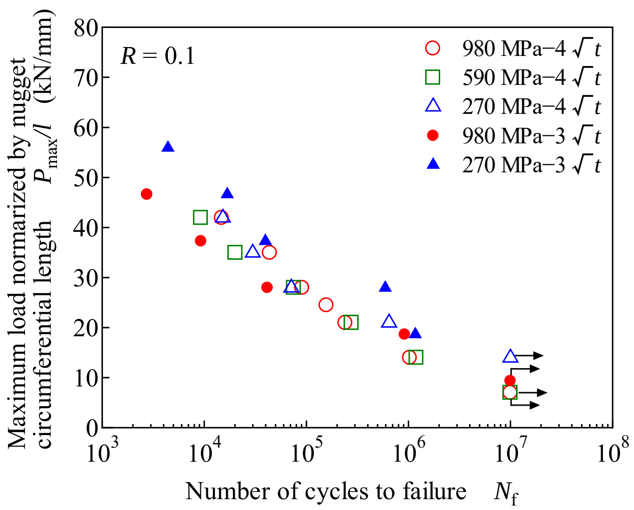

Figure 6. Relationship between maximum load normalized by nugget circumferential length P_{max}/l and N_f.

The welds with $3\sqrt{t}$ nugget sizes exhibit lower fatigue strengths than the welds with $4\sqrt{t}$ nugget. This tendency is similar to the static tensile-shear failure loads. The fatigue strengths in terms of maximum loads are normalized by the circumferential length of the nugget [6], and the results are shown in figure 6. The difference of the fatigue strengths among the welds becomes smaller when the maximum load is normalized by the circumferential length of the nugget as seen in figures 4 and 6. It should be emphasized that the fatigue strengths of the welds with $3\sqrt{t}$ nugget sizes are different between 270 MPa and 980 MPa class steels, in which 980 MPa steel welds have lower fatigue strengths in figure 6. The dependence of fatigue strengths on the strength levels of steels is seen in the welds with $3\sqrt{t}$ nugget sizes but not in the welds with $4\sqrt{t}$ nugget. This discrepancy could be explained as follows. As mentioned above, the total fatigue lives are mainly dominated by fatigue crack propagation lives in all the welds with $4\sqrt{t}$ nugget sizes. However, the stress concentration states around the nuggets are different between $4\sqrt{t}$ and $3\sqrt{t}$ nuggets. It is considered that the fatigue crack initiation life becomes longer in 270 MPa class steel weld with $3\sqrt{t}$ nugget size due to the change of stress concentration. However, the sensitivity against stress concentration is higher in the ultrahigh strength steel, and consequently the crack propagation life is still dominant in 980 MPa class steel welds with $3\sqrt{t}$ nuggets. In figure 6, only 270 MPa class steel welds with $3\sqrt{t}$ nugget sizes have slightly higher fatigue strengths than the others, and it would be reasonable if only 270 MPa welds with $3\sqrt{t}$ nugget have longer fatigue crack initiation life.

4. Conclusion

Tensile-shear fatigue tests are conducted using the resistance spot welds made of three different strength level steels. When the nugget size is $4\sqrt{t}$, fatigue strengths are nearly the same among three steels, because fatigue propagation lives are dominant in the total fatigue lives. On the other hand, 980 MPa class steel welds with $3\sqrt{t}$ nugget sizes have lower fatigue strengths than 270 MPa class ones.

References

[1] Tohgo K, Adomi R, Araki H, Syoko K, Tanaka H, Usuda . and Shimamura Y 2006 *J. Soc. Mater. Sci. Japan* **55**-12 pp 1095-1101.
[2] Long X and Khanna SK 2007 *Int. J. Fatigue* **29** pp 879-886.
[3] Fujii T, Tohgo K, Suzuki Y, Yamamoto T and Shimamura Y 2017 *Int. J. Fatigue* **87** pp 424-434.
[4] Wu G, Li D, Su X, Peng Y, Shi Y, Huang L, Huang S and Tang W 2017 *Int. J. Fatigue* **103** pp 73-85.
[5] Schijve J 2009 *Fatigue of Structures and Materials* (Dordrecht, Heidelberg, London, New York: Springer) chapter 8.
[6] Satoh Y, Ito Y, Shida T and Minakawa S 1986 *Quarterly J. Japan Weld. Soc.* **4**-3 pp 646-652.