

Resistance Spot Weldability of High Strength Steel (HSS) Sheets for Automobiles

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Abstract

Resistance spot welding technologies of high strength steel (HSS) sheets were investigated in order to get high reliability in welded-joints of automobile components. Suitable welding current range shifted to lower current side by the effect of electric resistance increase of steel sheet and the width of this range was affected by electrode force. Vickers hardness at welded zone increased with increase of C content, mainly. Tensile shear strength (TSS) of welded-joints increased with increase of nugget diameter, sheet thickness and base steel strength. Cross tension strength (CTS) increased with increase of nugget diameter, sheet thickness, however, showed peak for the base steel strength and carbon equivalent. Fatigue strength of welded-joints increased with increase of sheet thickness, however, it didn't increase with increase of base steel strength. Suitable welding current range of galvanized HSS sheets shifted to higher current side by the effect of melting of coated material. Electrode tip life of these coated HSS sheets were over 3,000 points and these were practical use level.

1. Introduction

The automobile industry is concentrating efforts on improving fuel efficiency and reducing CO₂ gas emission to save natural resources and curb the deterioration of global environment, and in this respect, weight reduction of the car body is becoming increasingly important. Also, requirement for safety in crashes is also increasing in this field. In such situations, high strength steel (HSS) sheets are expected to attain these objectives. At the early stage, the application of 440MPa class steel sheets was investigated. Nowadays even the application of 980MPa class and also 1470MPa class hot-stamping type steel sheets is also being investigated.

On the other hand, improvement of resistance spot weldability is

becoming an important issue in the expansion of the use of HSS sheets because resistance spot welding has been used mainly for the assembly of automobile bodies. From this point of view, this paper describes the characteristics and problems of HSS sheets for automobile from the viewpoint of resistance spot weldability, and resistance spot welding techniques to solve these problems¹⁾.

2. Properties of HSS Sheets in Terms of Resistance Spot Weldability

The characteristics of HSS sheets in comparison with mild steel sheets from the viewpoint of resistance spot weldability are as follows: (i) suitable welding current range shifts to the lower current side because heat generation in spot welding is higher owing to high

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electric resistance; (ii) Fully contact diameter cannot be obtained between sheets when electrode force is low by the effect of spring back and as a result, bad quality welding sometimes occurs; (iii) Martensite structure is easily formed at welded zone by an increase of carbon equivalent and as a result Vickers hardness at welded zone increases; (iv) Joint strength changes with increase of base steel strength. The characteristics of resistance spot welding of HSS sheets are described hereafter focusing mainly on cold-rolled steel sheets.

3. Resistance Spot Weldability of HSS Sheets

3.1 Suitable welding condition for HSS sheets

Resistance spot welding is a welding method wherein molten zone is formed between steel sheets by Joule heating of current flow and then solidification zone (nugget) is formed by cooling which heat transfer from molten zone to water-cooled electrodes after current flow. The heat generation Q in the above process is expressed as follows:

$$Q = (R_1 + R_2) \cdot I^2 \cdot s / r^4 \quad (1)$$

where: R_1 is the contact resistance between the steel sheets; R_2 is the electric resistance of the steel sheets; I is welding current; s is welding time; and r is the contact diameter between the steel sheets.

In equation (1), contact resistance R_1 and electric resistance R_2 are peculiar values that steel sheets have. On the other hand, as welding current I , welding time s and electrode force affected on the contact diameter r are important parameters affected on the heat generation, these parameters are called the three most important parameters in resistance spot welding. **Table 1** shows the standard spot welding conditions for mild steel sheets²⁾.

The welding conditions shown in Table 1 are also applicable to HSS sheets basically, except for the electrode force. The suitable welding current range (current value from which minimum nugget diameter needed is formed to which expulsion occurs) sometimes becomes narrow in spot welding of HSS sheets because the gap is likely formed between steel sheets by the effect of higher rigidity and spring back, that is, as fully contact diameter cannot be obtained between the sheets and consequently expulsion occurs easily³⁻⁵⁾. Therefore, it is important to increase the electrode force as required in spot welding of HSS sheets, and this may make the suitable welding current range wider³⁻⁵⁾. The electrode force in consideration of the existence of a gap is shown below, for example:

$$P = 2.45 \cdot t \cdot (TS / 300)^{1/2} \quad (2)$$

where: P is the electrode force (kN), t is the sheet thickness (mm),

and TS is the tensile strength (MPa) of the steel sheets.

A higher electrode force in consideration of the tensile strength of the steel sheets shortens the time which the gap disappear after welding starts, and as a result, it easily prevents bad quality welding^{6,7)}.

3.2 Factors affected on heat generation at spot-welded zone

As shown in equation (1), contact resistance and electric resistance of steel sheets are important factors affected on nugget formation and growth. However, the effect of the former is only on the first stage of nugget formation, the effect of the later is rather larger on nugget formation. Electric resistance is peculiar value for steel sheets and that of steel sheets increases with amount of additional elements⁸⁾. For example, electric resistance of DP and TRIP steel sheets are twice and three times that of mild steel sheets. Electric resistance of each steel sheet increases with increase of temperature and it reaches almost the same value. Except electric resistance, the effects of welding conditions are also very large and the contribution to nugget formation and growth is in order of contact diameter $r >$ welding current $I >$ welding time s as shown in equation (1).

3.3 Suitable welding current range

The suitable welding current range is from the current under which a minimum nugget diameter (for example, $4 \cdot t$) is formed to that under which expulsion occurs. A wide suitable welding current range is desirable because it is possible to control the nugget diameter within a prescribed range even if welding current fluctuates. **Fig. 1** shows the effect of welding current on nugget diameter in various types of steel sheets. The current value under which a nugget is formed decreases in order of mild steel, 590DP steel and 590TRIP steel. This is presumably because nugget-forming current becomes smaller as electric resistance increases. Welding current that expulsion is occurred decreases with increase of base steel strength because fully contact diameter cannot be obtained, and as a result, suitable welding current becomes to be narrow, however, it is considered that it's only the case for ultra HSS sheets or thicker sheets³⁻⁵⁾.

3.4 Macro and microstructures at welded zone

Fig. 2 shows macro- and microstructure at welded zones of 780MPa class cold rolled TRIP steel sheets. An ellipse nugget is formed between two sheets and heat affected zone (HAZ) is formed around the nugget. Microstructure at nugget is martensite because this area is rapidly cooled by water-cooled electrodes. Microstructure at HAZ changes from martensite to base steel structure depending on reached ultimate temperature. Nuggets are formed at the center of two sheets in case of same type and same thickness steel sheet combination, however, nuggets are formed at thicker side in case of different thickness steel sheet combination and also nugget is formed

Table 1 Standard spot welding conditions for mild steel sheets

Sheet thickness t (mm)	Electrode tip diameter $d = 5 \cdot t$ (mm)	Weld time $s = 10 \cdot t + 2$ (cycles)	Electrode force $P = 2.45 \cdot t$ (kN)	Welding current I (kA)
0.6	4.0	8	1.47	Maximum value practicable without expulsion
0.8	4.5	10	1.96	
1.0	5.0	12	2.45	
1.2	5.5	14	2.94	
1.4	6.0	16	3.43	
1.6	6.5	18	3.92	
2.3	7.5	25	5.64	
3.2	9.0	34	7.84	

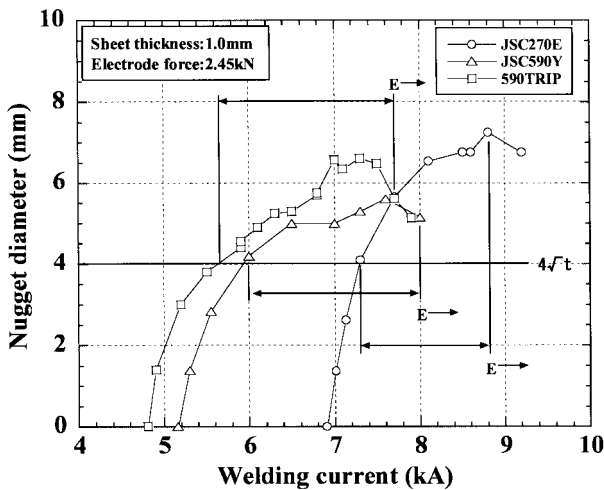


Fig. 1 Effect of welding current on nugget diameter

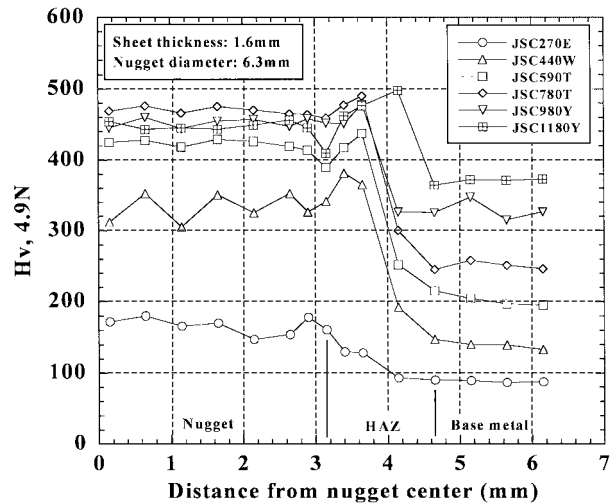
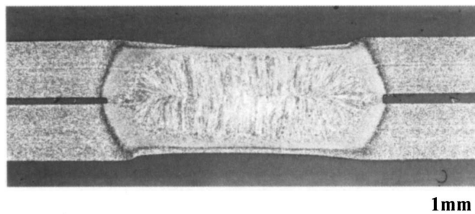


Fig. 3 Distribution of Vickers hardness at welded zone



(a) Macro structure



(b) Micro structure

Fig. 2 Macro and micro structures at welded zone of 780TRIP steel sheets

at higher electric resistance side in case of different type steel sheet combination.

3.5 Vickers hardness distribution at welded zone

Fig. 3 shows distribution of Vickers hardness at welded zones of same steel sheet combination joints. Vickers hardness at nuggets shows considerably higher value than that at base steel sheets because nugget zones are cooled rapidly and martensite are formed at these zones. Vickers hardness at HAZ also shows higher value than that at base steel sheets and this values decrease from nugget side to base steel sheet side. Softening zone is observed at HAZ of over 980MPa class HSS sheet joints³⁾. However, it is considered that this softening zone doesn't affect on joint strength because the width of this

softening zone is very narrow and in that case restriction force is worked around this area.

Vickers hardness at nugget increases with an increase of base steel strength, however, it doesn't increase over 780MPa class HSS sheets. This is because Vickers hardness increases with an increase of carbon equivalent. Equations shown below are proposed as carbon equivalent (Ceq) for Vickers hardness at welded zone. Other equations are also proposed^{2,4,5,9)}.

$$Ceq = C + Si / 40 + Cr / 20 (\%) \quad (3)$$

$$Ceq = C + Si / 40 + Mn / 200 + Cr / 300 (\%) \quad (4)$$

$$Ceq = C + Si / 90 + (Mn + Cr) / 100 (\%) \quad (5)$$

Fig. 4 shows the effect of carbon equivalent calculated from equation (3) on Vickers hardness at nugget. Vickers hardness at the nugget increases in proportion to carbon equivalent not depending on sheet thickness except of IF steel sheets. Vickers hardness ratio between

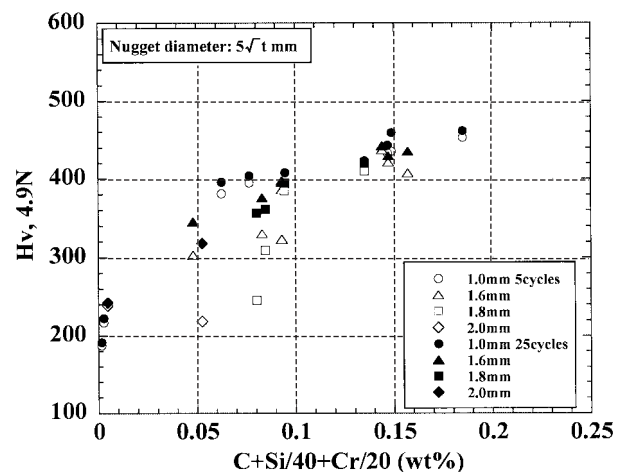


Fig. 4 Effect of carbon equivalent on Vickers hardness at nugget

the nugget and base steel sheet (nugget / base steel) decreases with increase of base steel strength because Vickers hardness doesn't increase with base steel strength.

3.6 Tensile shear strength (TSS) and cross tension strength (CTS) of welded joint

Tensile shear strength (tensile strength in shear direction: TSS) and cross tension strength (tensile strength in peel direction: CTS) are one of the important parameters to show reliability of spot-welded joints. Fig. 5 shows the effect of nugget diameter on tensile shear strength of joints. Tensile shear strength increases in proportion to nugget diameter and also increases with sheet thickness. This is the same as cross tension strength.

Up to now, in case of mild steel sheets, chisel hammer test and peel test were always conducted for the purpose of checking joint strength because this relation between nugget diameter and tensile shear strength, cross tension strength was recognized. It is considered that this checking method can be applied to HSS sheet joints because same relation is recognized. However, non-destructive nugget measuring method is needed because fracture inside the nugget is easily occurred in chisel hammer test. Fracture mode changes from shear type that fracture is occurred inside the nugget to plug type that fracture is occurred around the nugget (HAZ, base steel or sometimes partly inside the nugget). Nugget diameter that fracture mode changes from shear type to plug type increase with increase of base steel strength and sheet thickness as mentioned after. Generally, plug type is desire from the viewpoint of product liability (PL) law.

Fig. 6 shows the effect of base steel sheet strength on tensile shear strength and cross tension strength when nugget diameter is constant value of 6.7mm (plug type fracture is occurred). Tensile shear strength increases with increase of base steel strength, however, the ratio of tensile shear strength increase over 590MPa is lower than under 590MPa. On the other hand, cross tension strength increases with increase of base steel strength, however, it shows peak at 590MPa and decrease after 590MPa. Generally, the reason why CTS decreases with base steel strength is explained that carbon equivalent increases with increase of base steel strength⁶⁾. However, cross tension strength decreases over 780MPa even though carbon equivalent is almost the same in this strength range. Therefore, it is considered that the reason why cross tension strength decreases is

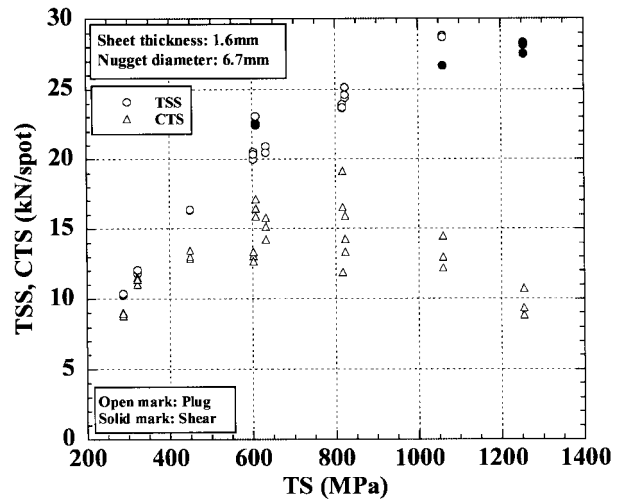


Fig. 6 Effect of base steel strength on TSS and CTS of joints

caused by not only the carbon equivalent effect but also the increase of stress concentration around nugget accompanied with increase of base steel strength³⁾. Scattering of tensile shear strength and cross tension strength increases in case of expulsion and it is remarkable in CTS²⁾. Tensile shear strength in dynamic tensile shear test shows almost the same value as in static tensile shear test.

As mentioned above, carbon equivalent is well known factors affected on cross tension strength and the equations shown below are proposed^{4,5,9)}. If carbon equivalent value exists within the range shown below equations, fracture mode in cross tension test is well (plug fracture mode which fracture is occurred outside the nugget) and CTS doesn't decrease.

$$Ceq = C + Si / 30 + Mn / 20 + 2P + 4S \quad 0.24 (\%) \quad (6)$$

$$Ceq = C + Si / 90 + (Mn + Cr) / 100 + 1.5P + 3S \quad 0.21 (\%) \quad (7)$$

$$Ceq = C + 2P / 3 + 2P \quad 0.153 (\%) \quad (8)$$

$$Ceq = C + Si / 30 + (Mn + Cr) / 20 + 2P + 3S < 0.248 (\%) \quad (9)$$

Fig. 7 shows the effect of carbon equivalent calculated from equation (6) on cross tension strength. Over 0.24% of carbon equivalent, fracture is occurred in nugget partially and cross tension strength decreases. This result is the same as past study^{4,6,9)}.

Fig. 8 shows the effect of carbon equivalent on ductility ratio (CTS/TSS) of joints. Ductility ratio decreases with increase of carbon equivalent, however, minimum value is about 0.3.

The factors affected on tensile shear strength are (i) Nugget diameter, (ii) Sheet thickness, (iii) Base steel strength, (iv) Expulsion and (v) Out of plane deformation in tensile shear test. Also, factors affected on CTS are (i) Nugget diameter, (ii) Sheet thickness, (iii) Carbon equivalent, (iv) Expulsion and (v) Deformation condition around nugget in cross tension test.

In a past study, these equations shown below are proposed to estimate the TSS of spot-welded joints for the case of shear fracture mode^{4,5)}.

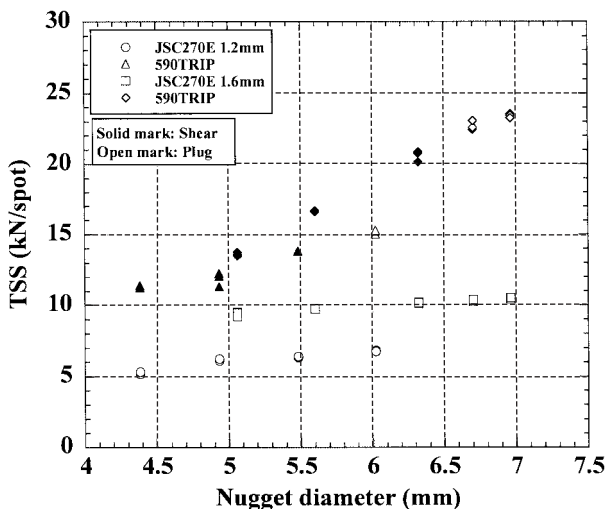


Fig. 5 Effect of nugget diameter and sheet thickness on TSS of joints

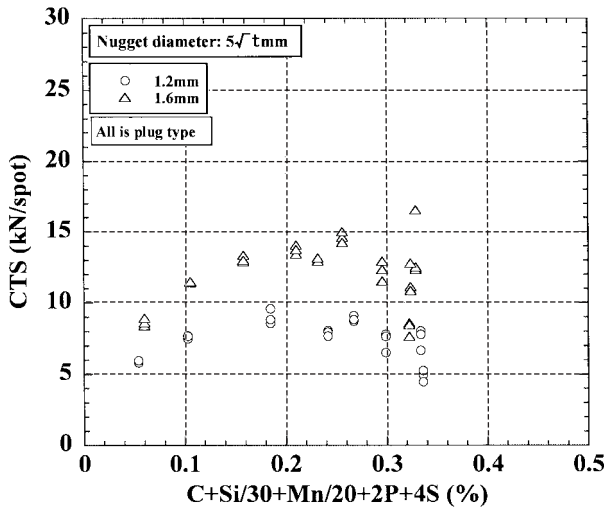


Fig. 7 Effect of carbon equivalent on CTS of joints

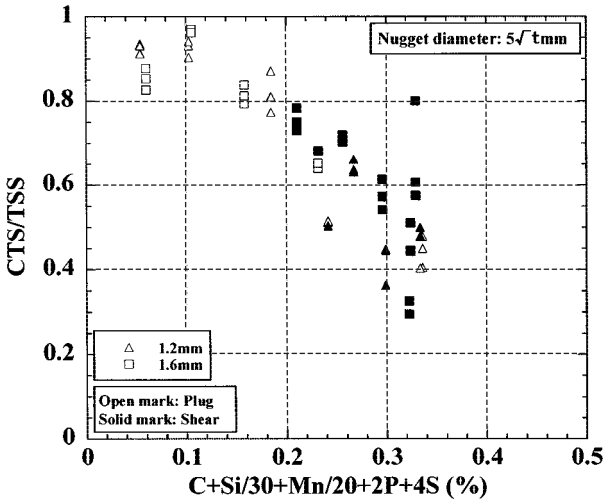


Fig. 8 Effect of carbon equivalent on ratio of CTS/TSS

$$TSS = A \cdot 2 / 3 \cdot / 4 \cdot d^2 \cdot TS_N \quad (10)$$

$$TSS = 9.8 \cdot \cdot (d / 2)^2 \cdot H_{VN} / 3^{1.5} \quad (11)$$

These equations shown below are proposed for the case of plug fracture mode^{3,5)}.

$$TSS = B \cdot t \cdot TS_B \cdot d \quad (12)$$

$$TSS = C \cdot t \cdot TS_B \cdot Pd \quad (13)$$

$$TSS = D \cdot t^{1.26} \cdot TS_B^{0.76} \quad (14)$$

$$TSS = 36.4 \cdot t^{1.42} \cdot TS_B^{0.84} \quad (15)$$

$$TSS = 2.05 \cdot t \cdot TS_B \cdot (1 + 0.0059 \cdot El) \cdot (d + 2.09) \quad (16)$$

In these equations, A to D are coefficients, d is the nugget diameter, TS_N is the tensile strength of the nugget, H_{VN} is the hardness of the nugget, t is the sheet thickness, TS_B is the tensile strength of the base steel sheets, Pd is the fractured diameter and El is the elongation of the base steel sheets.

As mentioned above, critical nugget diameter d_c at which the fracture mode changes from shear type to plug type is shown from equation (10) and (12).

$$d_c > 2 \cdot 3 \cdot B / A \cdot TS_B / TS_N \cdot t \quad (17)$$

Therefore, critical nugget diameter increases with an increase of Vickers hardness ratio between base steel and nugget (base steel/nugget) and sheet thickness.

On the other hand, equations shown below are proposed as cross tension strength estimation when shear type fracture is occurred^{4,5,10)}.

$$CTS = E \cdot / 4 \cdot d^2 \cdot TS_N \quad (18)$$

$$CTS = 9.8 (1.4 - 0.003 \cdot H_{VN}) \cdot \cdot (d / 2)^2 \cdot (H_{VN} / 3) \quad (19)$$

Also, equations shown below are proposed as cross tension strength estimation when plug type fracture is occurred^{4,5,10)}.

$$CTS = F \cdot 2 / 3 \cdot \cdot d \cdot t \cdot TS_N \quad (20)$$

$$CTS = 645 \cdot t \cdot d^{1.27} \quad (21)$$

$$CTS = 5 \cdot t \cdot d \cdot TS_N \cdot (1 - (100 / (100 + 0.5 \cdot El))^2)^{1.46} \quad (22)$$

In these equations, E and F are coefficients.

Some of the equations shown in (10) to (16) can estimate experimental TSS values of mild steel sheet joints accurately^{4,5)}, however, there are no equations to estimate experimental tensile shear strength values of HSS sheet joints completely, yet. Therefore, it is needed to establish equation to estimate tensile shear strength estimation. This situation is the same as cross tension strength estimation.

The fracture mode change from shear type to plug type in tensile shear test, however, it is almost a plug type except for a very small nugget diameter in cross tension test. From the result of FEM analysis, it is clear that stress distribution is uniform inside the nugget in tensile shear test, however, it shows high value around the nugget in cross tension test. Therefore, it is considered that these types of fracture are occurred in each tensile test³⁾.

3.7 Fatigue property of welded joint

Another important parameter to show reliability of spot-welded joints is fatigue strength. Fig. 9 shows the L-N (Load-Number of cycles to failure) curves when spot-welded joints were loaded to shear direction. In this paper, fatigue limit is definite as the load when fracture is not occurred at 2×10^6 cycles. Generally, fatigue limits of base steel sheets increase with increase of base steel strength, however, those of joints don't increase with increase of base steel strength. This is caused by the notch effect at nugget edge. Indeed, fatigue cracks initiate from nugget edge^{3,4)}.

Fig. 10 shows the effect of sheet thickness on L-N curves of joints. Fatigue limits increase with increase of sheet thickness. As a matter off course, these results have an effect of nugget diameters because nugget diameters increase with increase of sheet thickness. Indeed, some data indicate that while fatigue limit of spot-welded joints of mild steel sheets tends to increase with an increase in nugget diameter,

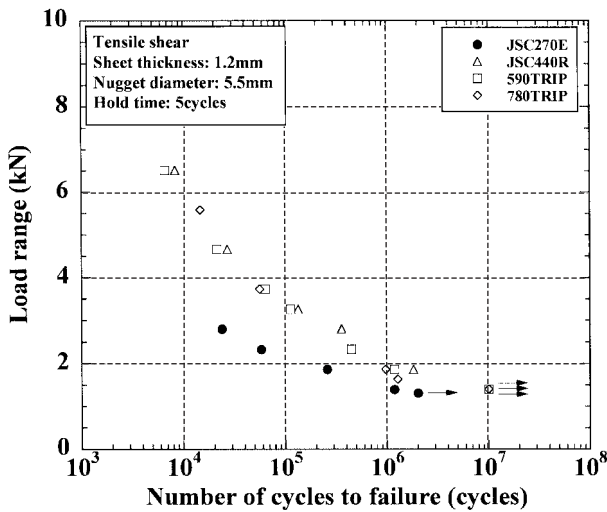


Fig. 9 Effect of steel types on fatigue property of joints

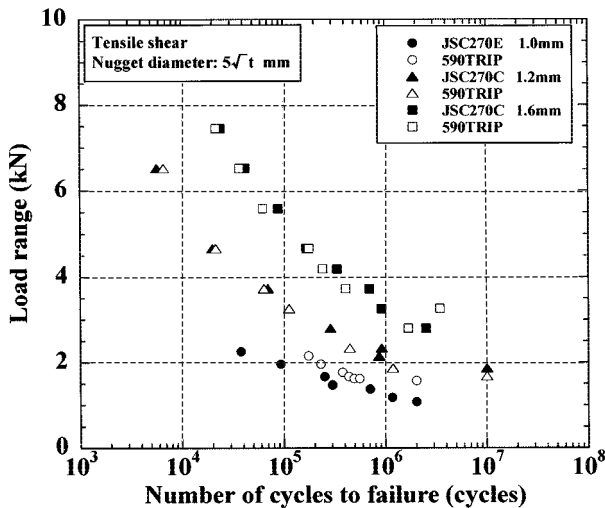


Fig. 10 Effect of sheet thickness on fatigue property of joints

however, other data indicate the effect of nugget diameter on fatigue limit is smaller in case of HSS sheet joints.

The fatigue limit when spot-welded joints were loaded to peel direction (cross tension fatigue test) is smaller than that when spot-welded joints were loaded to shear direction (tensile shear fatigue test) by one order of magnitude^{3,5)}. This is because stress concentrations around nuggets are higher in case of cross tension fatigue test than that in case of tensile shear fatigue testes similarly to the static tensile strength³⁾.

Conventionally, it was thought that base steel strength did not affect on the fatigue limit of spot-welded joints, however, fatigue limit of steel sheet joints over 980MPa class shows slightly lower values. It is possible to estimate the relation between load range and number of cycles to failure by using many data because sheet thickness and nugget diameter are considered to affect the limit of spot-welded joints, and indeed, some equations used power functions are proposed for example⁴⁾.

3.8 Resistance spot weldability of galvanized steel sheets

Fig. 11 shows the effect of welding current on nugget diameter used galvanized HSS sheets. Tendency of suitable welding current range is almost the same as cold rolled bare steel sheets, however, suitable welding current ranges exist in high current side. This is because current density during spot welding decreases with melting of coating. It is known that suitable welding current range of Galvanized (GI) steel sheets is very narrow compared with that of galvanized (GA) steel sheets.

Electrode tip life is very important in spot welding of GA steel sheets. Fig. 12 shows the change of nugget diameters in electrode tip life test when 780MPa class galvanized DP steel sheets are used and electrode force is set based on equation (2) and welding current is set 95% of expulsion current. Electrode tip life is over 4000 points and it is a practical use level. Electrode tip life decrease with increase of base steel strength and the electrode tip life for 590, 780 and 980MPa class galvanized DP steel sheets are 14600, 4000 and 2580

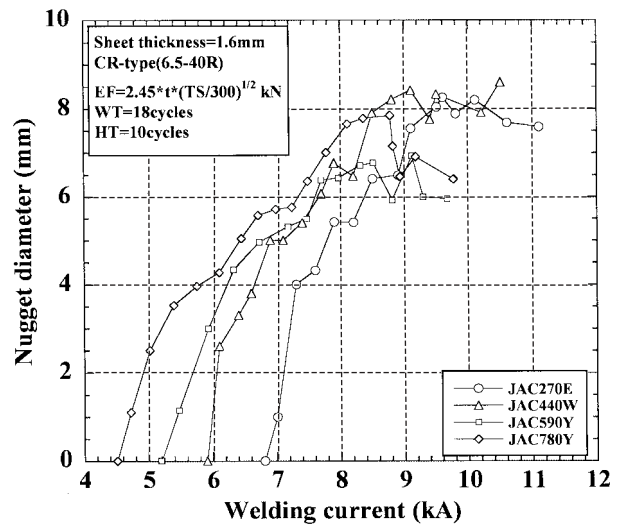


Fig. 11 Effect of welding current on nugget diameter

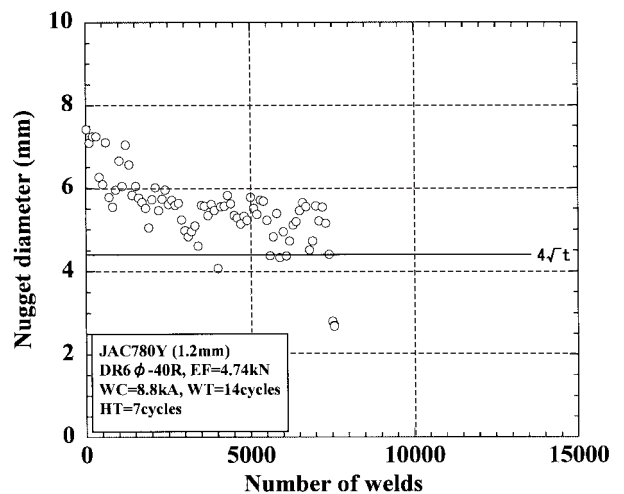


Fig. 12 Result of electrode tip life test of JAC780Y

points, respectively (in this test, under limit of nugget diameter is determined 4 t mm).

4. Summary

The problems of resistance spot welding of HSS sheets and its welding techniques to solve these problems were described in consideration of expansion of use of HSS sheets for automobile bodies for the purpose of weight reduction and increasing safety in crash. Laser welding is pay attention as a new welding method for automobile assembly at present, however, this method still has various problems, and so resistance spot welding is expected to continue to be the main welding method in this field for the unforeseen future. Because we can foresee the highest strength level of steel sheets used for automobile bodies in the near future, a next step is the technical developments to improve the quality and reliability of spot-welded joints of HSS sheets. We would like to make sincere efforts in the development of resistance spot welding techniques.

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