RESISTANCE SPOT WELDABILITY OF HIGH STRENGTH STEEL SHEETS FOR AUTOMOBILES AND THE QUALITY ASSURANCE OF JOINTS




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ABSTRACT

Resistance spot weldability of high strength steel (HSS) sheets for automobiles and the quality assurance technique of joints were investigated. The suitable welding current range in spot welding of HSS sheets shifted to the lower current side compared with that of mild steel sheets and it was affected by the electrode force. Vickers hardness at the welded zone increased with an increase of base steel carbon content. Tensile shear strength (TSS) of joints increased with an increase of nugget diameter, sheet thickness, and base steel strength. The cross tension strength (CTS) of joints increased with an increase of nugget diameter and sheet thickness. However, it showed a peak for base steel strength and carbon equivalent. Fatigue strength didn't increase with base steel strength. The suitable welding current range in spot welding of galvannealed HSS sheets shifted to the higher current side compared with that of bare HSS sheets. Electrode tip life for galvannealed HSS sheets was over 3 000 points and it was a practical use level. It's possible to assure the joint strength by estimating the nugget diameter using current and voltage during spot welding.

IIW-Thesaurus keywords: *High strength steels; Quality assurance; Reference lists; Resistance spot welding; Resistance welding; Steels; Sheet; Weldability*.

1 INTRODUCTION

Automobile industries are grappling with improvement of fuel efficiency and reduction of CO_2 gas to save the resources and keep a comfortable atmosphere on earth. Weight reduction of automobiles becomes more and more important to achieve these purposes. In addition to those, the need for improvement of safety in crashes also becomes more important.

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High strength steel (HSS) sheets are proposed as materials to solve these problems such as weight reduction of automobiles and improvement of safety in crashes. Because weight reduction of automobiles can be achieved by using thinner HSS sheets compared with mild steel sheets, and HSS sheets have good properties for crashes. In past automobile bodies, 270 MPa class mild steel sheets were mainly used and 440 MPa class HSS sheets were also used. However, at present, 590 to 1 470 MPa class HSS sheets are being investigated for application in automobile bodies.

On the other hand, resistance spot welding is mainly used for assembly lines of automobiles, and thus improvement of spot weldability of HSS sheets is considered to be very important to apply HSS sheets for automobile bodies.

This paper describes resistance spot weldability of HSS sheets for automobiles and quality assurance technology of spot-welded joints [1].

2 EXPERIMENTAL PROCEDURE

2.1 Materials

Cold rolled bare steel sheets were mainly used in this study, but galvannealed steel sheets were also used. Bare steel sheets were 270 MPa class mild steel sheets and 440 to 1 180 MPa class HSS sheets. Mild steel sheets were IF and Al-k type and HSS sheets were solid solution, precipitation, dual phase, and TRIP type. Sheet thicknesses were 1.0, 1.2, and 1.6 mm. Galvannealed steel sheets were dual phase type and sheet thickness was 1.2 mm. Coating weight was 45 g/m^2 per one side. Table 1 shows the example of mechanical properties of 1.6 mm thickness HSS sheets. In this study, marks of bare steel sheets and galvannealed steel sheets are showed as “JSC” and “JAC”. Steel grades are shown as 270, 440, 590, etc. and types of steels are showed as E, C, W, etc.

2.2 Suitable spot welding condition for high strength steel sheets

Resistance spot welding is a very popular welding method using joule heating. The quantity of heat Q generated at the welded zone is written as follows.

$$Q \propto (R1 + R2) \cdot I^2 \cdot s/r^4 \quad (1)$$

where
R1 is the contact resistance between steel sheets,
R2 is the electric resistance of steel sheets,
I is the welding current,
s is the welding time,
r is the contact diameter between two steel sheets.

R1 and R2 in equation (1) are peculiar values for each steel sheet. On the other hand, the welding current (I), welding time(s), and electrode force that affect the contact diameter (r) are important factors in resistance spot welding because they can be controlled by the welding machine.

Standard resistance spot welding conditions for mild steel sheets are shown in Table 2 [2]. These welding conditions can be used for HSS sheets basically; however, the difference is the electrode force. High electrode force is sometimes needed in case of HSS sheets because the gap sometimes exists between sheets by the effect of spring back. If the gap exists between sheets, expulsion can easily occur at lower current ranges because a full contact diameter cannot be obtained. As a result, a suitable welding current range becomes narrower [3-5]. Therefore, high electrode force is sometimes needed for spot welding of HSS sheets to increase the suitable welding current range. The electrode force to be considered for the gap existence is shown in equation (2) [2].

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

where,
P is the electrode force (kN),
t is the sheet thickness,
TS is the tensile strength of base steel sheet.

It is known that there is a narrowed time of gap decrease by increasing the electrode force with an increase of base steel strength [6-7]. However, the value calculated from equation (2) is rather high, so the electrode force for mild steel sheets shown in Table 1 is sometimes used even in the case of HSS sheets. In that case, high current or high welding time is sometimes needed.

Resistance spot welding conditions in this study are shown in Table 3.

Table 1 – Mechanical properties of HSS sheets used

Marks	Types of steel	Thickness (mm)	YP (MPa)	TS (MPa)	El (%)
JSC270E	IF	1.6	140	293	52.0
JSC270C	Al-k		192	329	46.0
JSC440W	Solid solution		285	449	40.0
JSC590R	Precipitation		432	602	26.0
JSC590Y	DP		363	632	29.0
590T	TRIP		398	608	36.0
JSC780Y	DP		462	823	29.0
780T	TRIP		537	817	20.0
JSC980Y	DP		712	1 060	15.0
JSC1180Y	DP		1 035	1 254	7.0

2.3 Test items and conditions

The relation between welding current and nugget diameters were examined by peel test and observation of macrostructures. Macro and microstructures were observed in cross-sections of welded zones. Vickers hardness was measured in cross-sections of welded zones under the condition of 4.9 N load. Tensile shear strength (TSS) and cross tension strength (CTS) of joints were measured based on a JIS standard. Tensile shear type fatigue tests were conducted based on a JIS standard. The specimen size was 40 × 160 mm and the nugget size was 5$\sqrt{t}$. The stress ratio and frequency in the fatigue test was 0.05 and 25 cycles, respectively. Electrode tip life tests were conducted under the condition of 95 % expulsion current. Welding current and voltage between two electrodes were measured during spot welding to estimate nugget diameter.

3 RESULTS AND DISCUSSION

3.1 Properties of HSS sheets from the viewpoint of resistance spot weldability

The properties of HSS sheets from the viewpoint of resistance spot weldability are as follows.

Table 2 – Standard resistance spot welding conditions for mild steel sheets

Sheet thickness t (mm)	Electrode tip diameter $D = 5\sqrt{t}$ (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	

Table 3 – Resistance spot welding conditions

Items	Condition
Welding machine	Air-pressure control type Single phase AC 60 kVA (Voltage control type)
Electrode type	Cone radius type, Tip diameter: 5.0 to 6.5 mm, Curvature in tip: 40 mm, Materials: Cu-Cr alloy
Electrode force (kN)	$2.45 \cdot t \cdot (TS / 300)^{1/2}$
Welding current (kA)	4.0 to 12.0
Welding time (cycles)	$10 \cdot t + 2$
Hold time (cycles)	5 to 10 (Depends on sheet thickness)

a) Welding current ranges of HSS sheets exist on the lower side because electric resistance of HSS sheets are higher than that of mild steel sheets.

b) Bad quality welding (nugget diameter is very small or nugget cannot be formed) easily occurrs when electrode force is low because of the gap existence between sheets.

c) The microstructure in the welded zone becomes martensite easily and Vickers hardness increases with an increase in carbon equivalent.

d) Joint strength changes with an increase of base steel strength.

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 that affect nugget formation and growth. However, contact resistance only affected the first stage of nugget formation, while electric resistance affected nugget formation and growth mainly. Electric resistance is a peculiar value for each material and for steel sheets it increases with an amount of additional elements [8]. In practice, electric resistance of HSS sheets shows a higher value than that of mild steel sheets and for DP and TRIP steel sheets it is twice or three times, for example. Electric resistance of each steel sheet increases with an increase of temperature and reaches almost the same value. Effects of welding conditions are also very large and the contribution to nugget formation and growth is contact diameter (r) > welding current (I) > welding time (s), as shown in equation (1).

3.3 Suitable welding current range

At first, resistance spot weldability of HSS sheets was investigated by using cold rolled bare steel sheets. Figure 1 shows the effect of welding current on nugget diameter. In this study, a suitable welding current range is defined as the range from the current value that a nugget having $4\sqrt{t}$ diameter is formed to the current value that expulsion occurs. If a suitable current range is wide, it is desirable because the target nugget diameter is obtained even if welding current changes. A suitable welding current range for each steel sheet is different and it decreases with order of mild steel, 590DP steel, and 590TRIP steel. This is because a suitable welding current range decreases with an increase of electric resistance of steel sheets. A welding current that allows expulsion to occur decreases with an increase of base steel strength and as a result, a suitable welding current becomes narrow; however, it is considered that it's only the case for ultra HSS sheets or thicker sheets [3-5].

3.4 Macro and microstructure at welded zone

Figure 2 shows the macro- and microstructure at the welded zone of 780TRIP steel sheet. An ellipse nugget is formed between two sheets and the heat-affected zone (HAZ) is formed around the nugget. The microstructure in the nugget is martensite because this area is rapidly cooled by water-cooled electrodes. The microstructure in the HAZ changes from martensite to base steel structure (residual austenite and ferrite), depending on reaching the ultimate temperature. A nugget is formed at the centre of two sheets in the case of the same type and same thickness steel sheet combination; however, the nugget is formed at the thicker

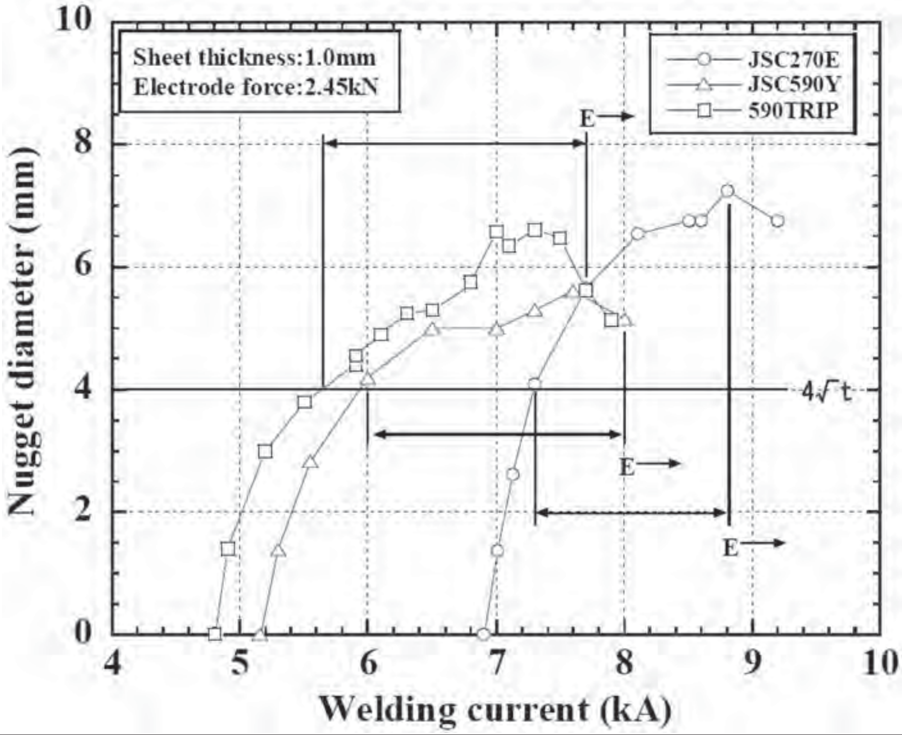
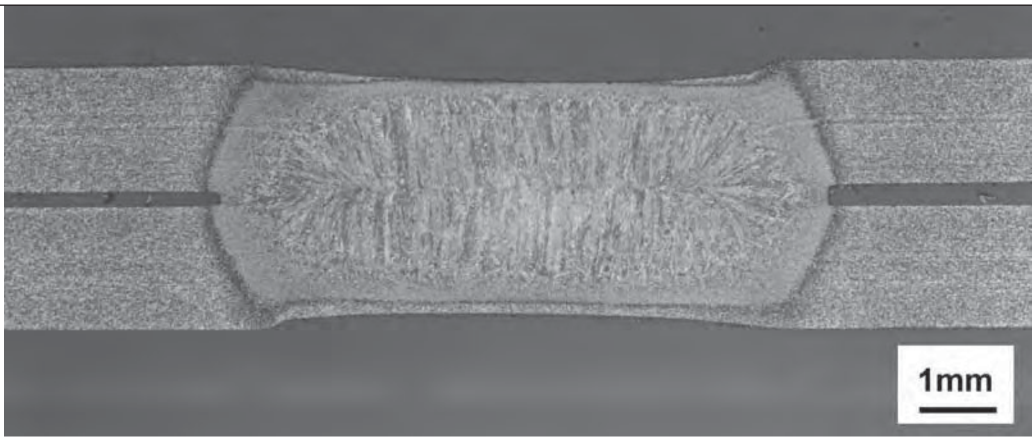
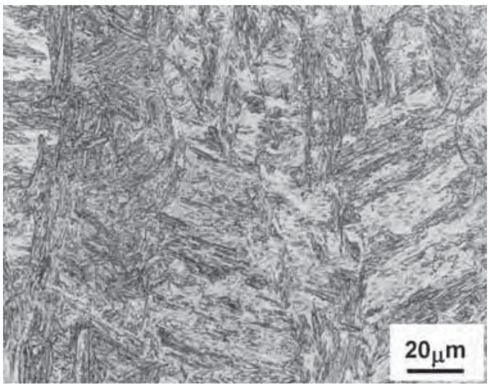


Figure 1 – Effect of welding current on nugget diameter

side in the case of different thickness steel sheet combinations and also the nugget is formed at the higher electric resistance side in the case of different type steel sheet combinations. A rectangular nugget is formed at the centre of three sheets in the case of a three-sheet combination. If a thinner mild steel sheet under 0.8 mm thickness is existed on one side, it is sometimes difficult to form a nugget on the thinner mild steel sheet side because of the sheet thickness and electric resistance effect.



a) Macrostructure



b) Microstructure

Figure 2 – Macro and microstructure at welded zone of 780TRIP steel sheet

3.5 Vickers hardness at welded zone

Figure 3 shows the distribution of Vickers hardness at the welded zones of HSS sheet joints. Vickers hardness at the nuggets shows considerably higher values than that at base steel sheets because nugget zones are cooled rapidly and martensite is formed at these zones. Vickers hardness at the HAZ also shows higher values than that at base steel sheets and these values decrease from the nugget side to base steel sheet side. A softening zone is observed at the HAZ of over 980 MPa class HSS sheet joints as shown in Figure 3 [3]. However, it is considered that this softening zone doesn't affect joint strength because the width of this softening zone is very narrow and in that case a restriction force is worked around this area.

Vickers hardness at the nugget increases with an increase of base steel strength; however, it doesn't increase over 780 MPa class HSS sheets. This is because Vickers hardness increases with an increase of carbon equivalent. The equations shown below are proposed as carbon equivalent for the Vickers hardness at the welded zone. Other equations are also proposed [2, 4-5, 9].

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

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

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

Figure 4 shows the effect of the carbon equivalent calculated from equation (3) and Vickers hardness at the nugget. Vickers hardness at the nugget increases in proportion to the carbon equivalent not depending on sheet thickness, except for IF steel sheets. The Vickers hardness ratio between the nugget and base steel sheet (nugget / base steel) decreases with an increase of base

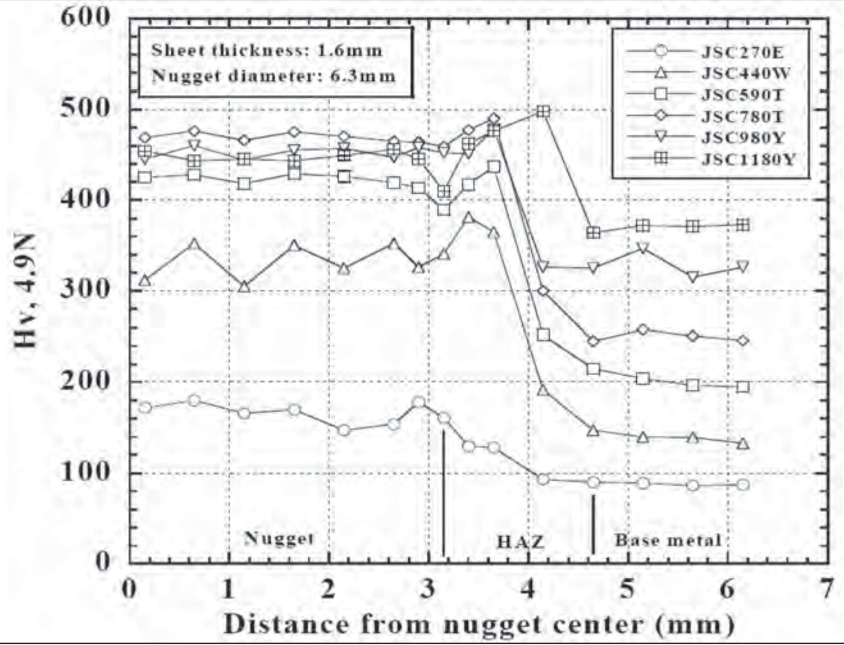


Figure 3 – Distribution of Vickers hardness at welded zone

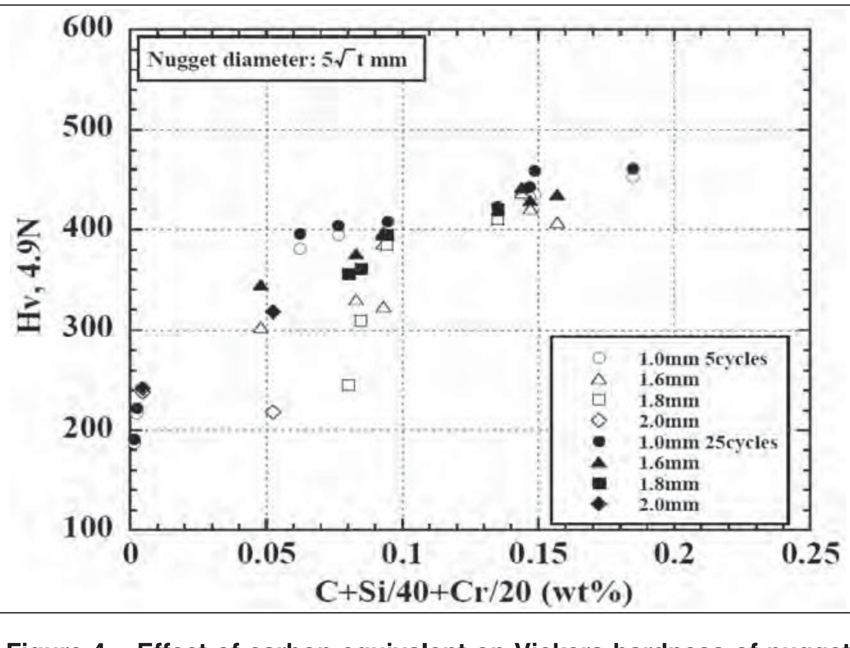


Figure 4 – Effect of carbon equivalent on Vickers hardness of nugget

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 joints

Tensile shear strength (TSS) and cross tension strength (CTS) are two of the important parameters to show reliability of spot-welded joints.

Figure 5 shows the effect of nugget diameter on TSS of joints. TSS increases in proportion to nugget diameter and also increases with sheet thickness. This is the same as CTS. Up to now, in the case of mild steel sheets, the chisel hammer test and the peel test were always conducted for the purpose of checking joint strength, and because of this relation between nugget diameter and TSS, CTS was recognized. It is considered that this checking method can be applied to HSS sheet joints because the same relation is recognized as shown in Figure 5. However, a non-destructive nugget measuring method is needed because fracture inside the nugget can easily occur in the chisel hammer test. In addition, the peel test is very difficult to conduct in the case of HSS sheets joints, especially in the case of ultra HSS sheets or thicker HSS sheets. An in-process control system to keep a suitable nugget diameter is also needed to avoid the chisel hammer test or peel test.

The fracture mode changes from shear type to plug type. Shear type means that fracture is occurring inside the nugget. Plug type means that fracture is occuring around the nugget (HAZ, base steel, or sometimes partly inside the nugget). The nugget diameter where the fracture mode changes from shear type to plug type increases with an increase of base steel strength and sheet thickness as mentioned later. Generally, a plug type is requested from automobile industries.

Figure 6 shows the effect of base steel sheet strength on TSS and CTS. In Figure 6, the nugget diameter is 6.7 mm and plug type fracture is occurring. TSS increases with an increase of base steel strength; however, the ratio of the TSS increase over 590 MPa is lower than under 590 MPa. On the other hand, CTS increases with increase of base steel strength; however, it shows a peak at 590 MPa and decreases after 590 MPa. This tendency is almost the same when the fracture mode is shear type. Generally, the reason why CTS decreases with base steel strength is explained by the fact that the carbon equivalent increases with an increase of base steel strength [6]. However, CTS decreases over 780 MPa even though the carbon equivalent is almost the same in this strength range. Therefore, it is considered that the reason why CTS decreases is caused by not only the carbon equivalent effect but also the increase of the stress concentration around the nugget accompanied by an increase of base steel strength [3]. Scattering of TSS and CTS increases in the case of expulsion and it is remarkable in CTS [2]. TSS in a dynamic tensile shear test show almost the same value as in the static tensile shear test.

As mentioned above, the carbon equivalent is a well known factor affecting CTS. Equations shown below are proposed as the carbon equivalent for the fracture mode. If the carbon equivalent value exists within the range shown below in the equations, the fracture mode in cross tension test is correct (plug fracture mode in which fracture occurs outside the nugget) and CTS doesn't decrease.

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

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

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

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

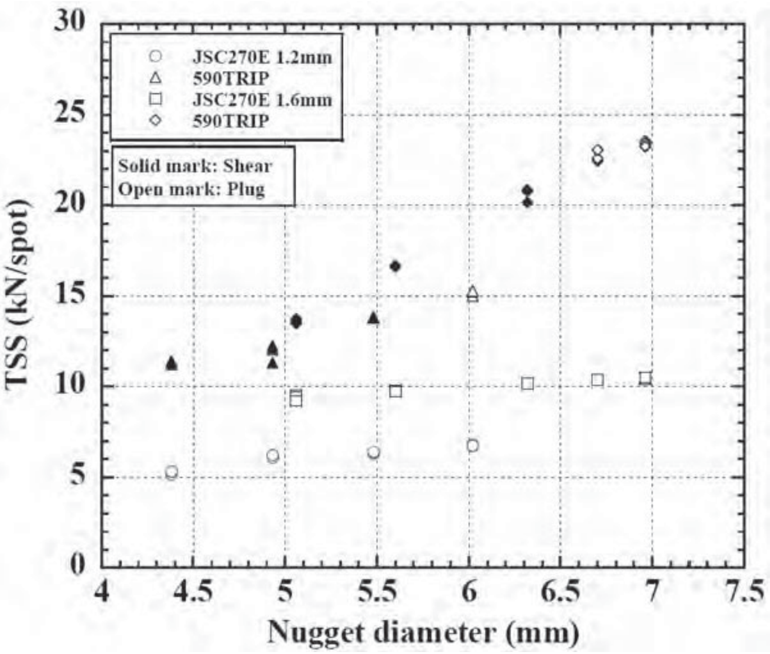


Figure 5 – Effect of nugget diameter and sheet thickness on TSS of joints

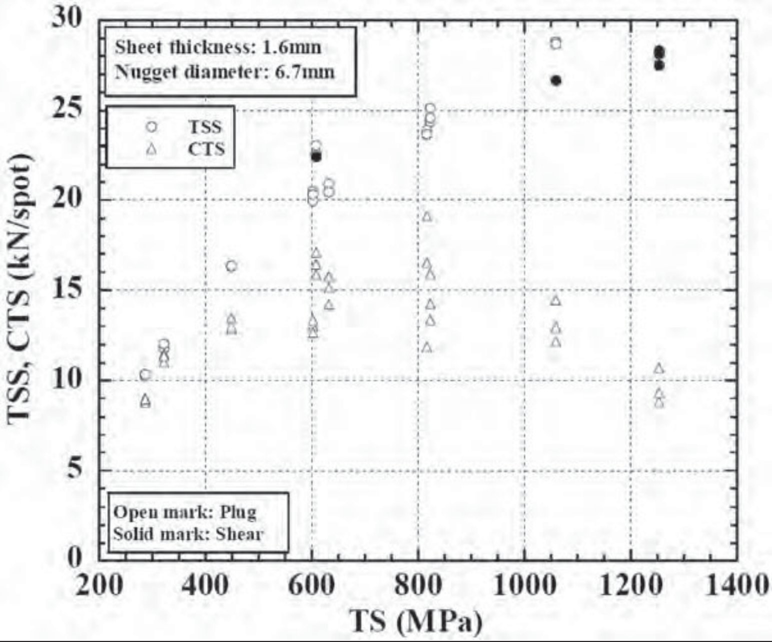


Figure 6 – Effect of steel strength on TSS and CTS of joints

Figure 7 shows the effect of the carbon equivalent calculated from equation (6) on CTS. CTS decreases with an increase of the carbon equivalent over 0.24 %. In that case, fracture is occurring in the nugget partially. This result is the same as past studies [4-6, 9].

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

Factors that affect the TSS are

1) Nugget diameter,
2) Sheet thickness,
3) Base steel strength,
4) Expulsion and
5) Out of plane deformation in tensile shear test.

Also, factors that affect the CTS are

1) Nugget diameter,
2) Sheet thickness,
3) Carbon equivalent,
4) Expulsion and
5) Deformation condition around nugget in cross tension test.

Equations shown below are proposed as the TSS estimation when shear type fracture occurs [4-5].

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

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

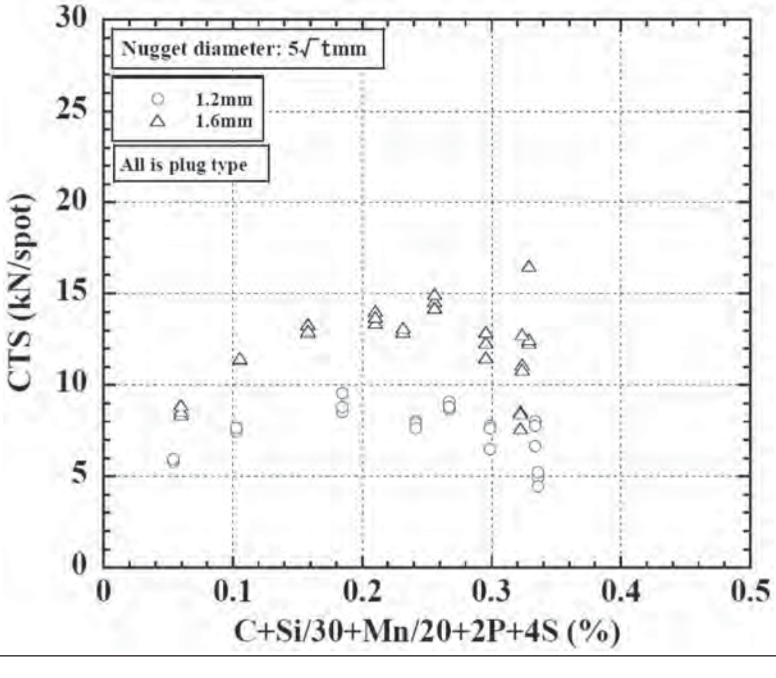


Figure 7 – Effect of carbon equivalent on CTS of joints

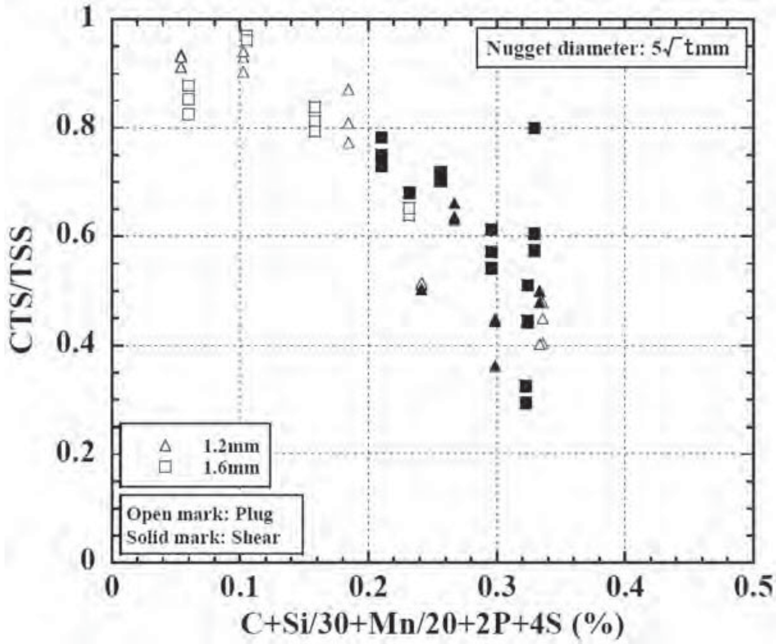


Figure 8 – Effect of carbon equivalent on ratio of CTS/TSS

On the other hand, equations shown below are proposed as the TSS estimation when plug type fracture occurs [3-5].

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

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

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

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

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

where

A to D are coefficients,
d is the nugget diameter,
TS_N is the tensile strength of the nugget,
H_{VN} is the Vickers hardness at the nugget,
t is the sheet thickness,
TS_B is the tensile strength of steel sheets
Pd is the fracture diameter,
El is the elongation of steel sheets

As mentioned above, the critical nugget diameter, d_c, when the fracture mode shifts from shear type to plug type is shown from equations (10) and (12).

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

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

On the other hand, the equations shown below are proposed as the CTS estimation when shear type fracture occurs [4-5, 10].

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

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

Also, the equations shown below are proposed as the CTS estimation when plug type fracture occurs [4-5), 10]

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

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

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

where,

E, F are coefficients

One of the equations shown in (12) to (16) can estimate experimental TSS values of mild steel sheet joints accurately [4-5]; however, there are no equations to estimate experimental TSS values of HSS sheet joints completely at this time. Therefore, it is necessary to establish an equation to estimate the TSS accurately. This situation is the same as the CTS estimation.

The fracture mode change is from shear type to plug type in tensile shear test; however, it is almost the plug type except for a very small nugget diameter in cross tension test. From the result of FEM analysis, it is clear that the stress distribution is uniform inside the nugget in tensile shear test; however, it shows a high value around the nugget in the cross tension test. Therefore, it is considered that these types of fracture occur in each tensile test [3].

3.7 Fatigue property of welded joints

The second important parameter to show reliability of spot-welded joints is fatigue strength. Figure 9 shows the L-N (Load - Number of cycles to failure) curves when spot-welded joints were loaded in the shear direction. In this paper, fatigue limit is definite as the load when fracture has 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 an increase of base steel strength. This is caused by the notch effect at the nugget edge. Indeed, fatigue cracks initiate from the nugget edge [3-4].

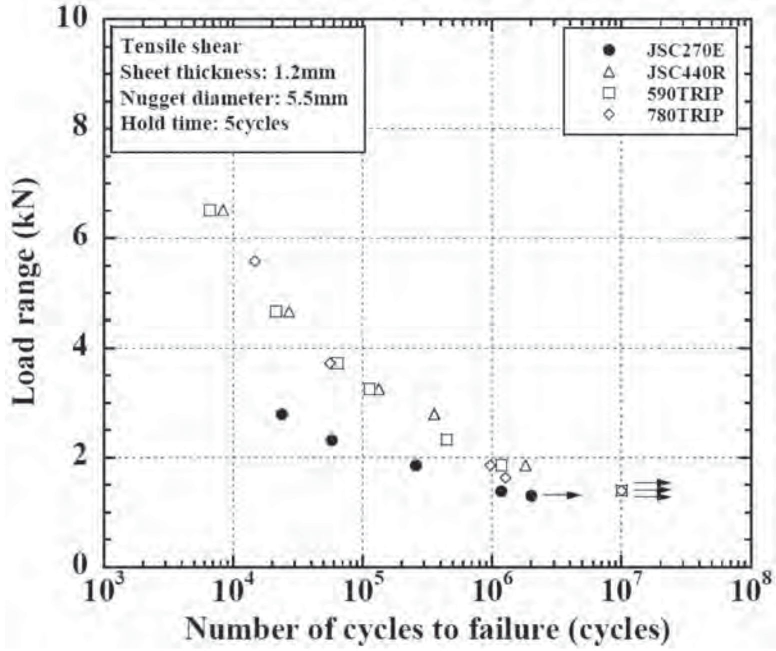


Figure 9 – Effect of steel types on fatigue property of joints

Figure 10 shows the effect of sheet thickness on L-N curves of joints. Fatigue limits increase with an increase of sheet thickness. As a matter of course, these results have an effect on nugget diameter because nugget diameters increase with an increase of sheet thickness. However, the effect of nugget diameter is hardly recognized in mild steel sheet and HSS sheet joints, so the effect of nugget diameters is considered to be very small.

It is considered that base steel strength hardly affects fatigue limits of joints; however, fatigue limits show slightly lower values in the case of over 980 MPa class HSS sheet joints.

3.8 Spot weldability of galvannealed steel sheets

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

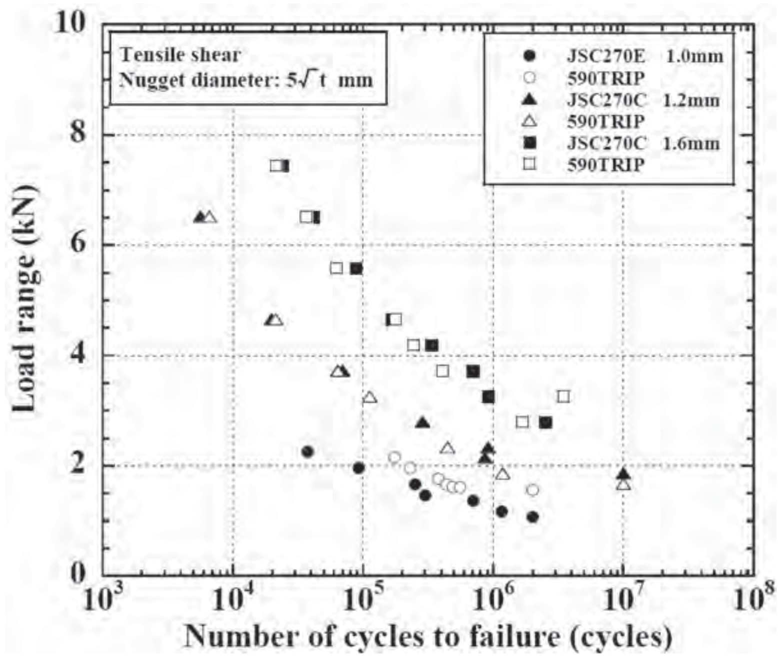


Figure 10 – Effect of sheet thickness on fatigue property of joints

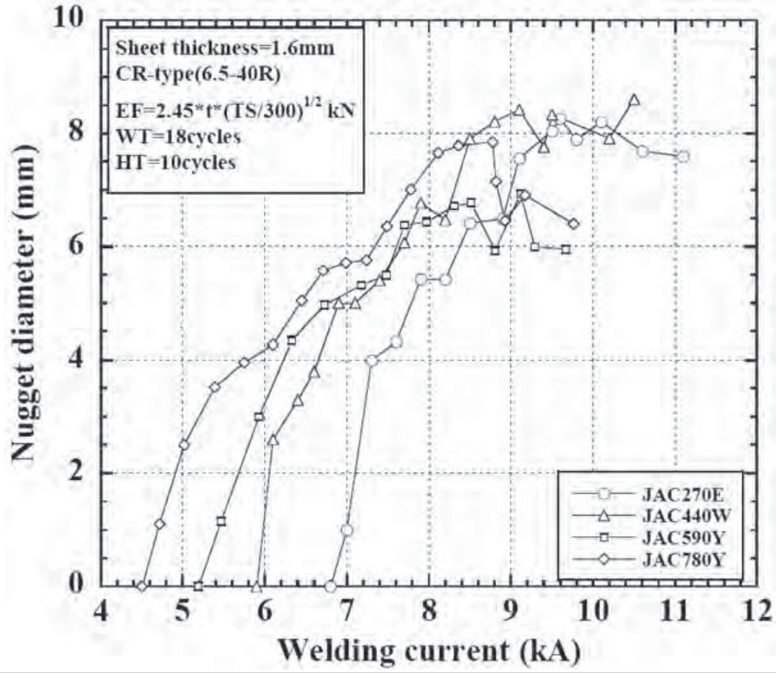


Figure 11 – Effect of welding current on nugget diameter

Electrode tip life is very important in spot welding of GA steel sheets. Figure 12 shows the change of nugget diameter in the electrode tip life test when 780 MPa class galvannealed DP steel sheets are used and the electrode force is set based on equation (2) and welding current is set at 95 % of expulsion current. Electrode tip life is over 4 000 points and it is a practical use level. Electrode tip life decreases with an increase of base steel strength and the electrode tip life for 590, 780, and 980 MPa class galvannealed DP steel sheets are 14 600, 4 000, and 2 580 points, respectively (in this test, the under limit of the nugget diameter is determined by $4\sqrt{t}$ mm).

3.9 Quality assurance technique

As mentioned above, TSS and CTS increase in proportion to the nugget diameter. So, if the nugget diameter can be estimated during spot welding, it is possible to assure joint strength. As the nugget diameters closely relate to the average temperature at the nugget, the nugget diameter can be estimated by estimating the average temperature at the nugget using voltage and current during spot welding. The average temperature at the nugget can be estimated by using numerical simulation software developed by Dr. Matsuyama [11]. Figure 13 shows the relation between the average tem-

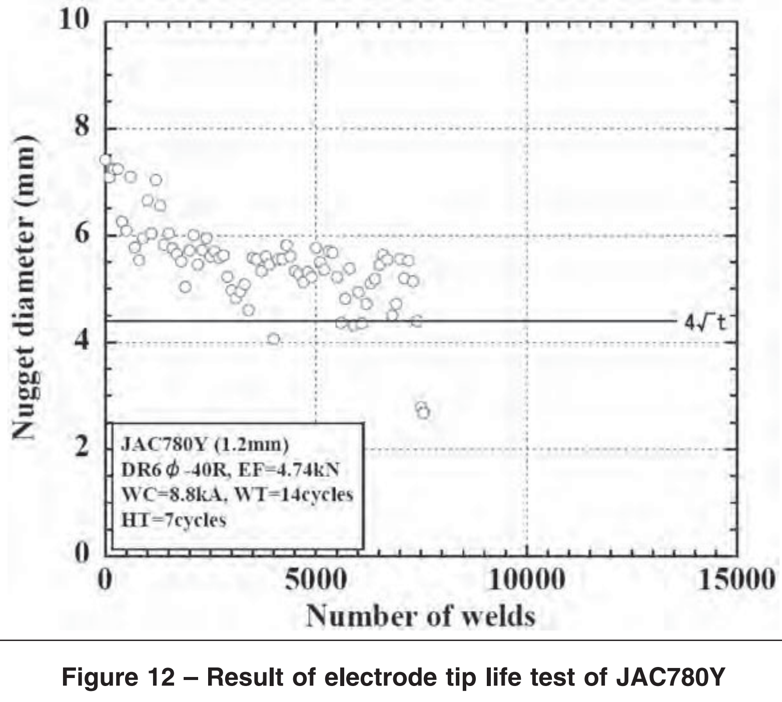


Figure 12 – Result of electrode tip life test of JAC780Y

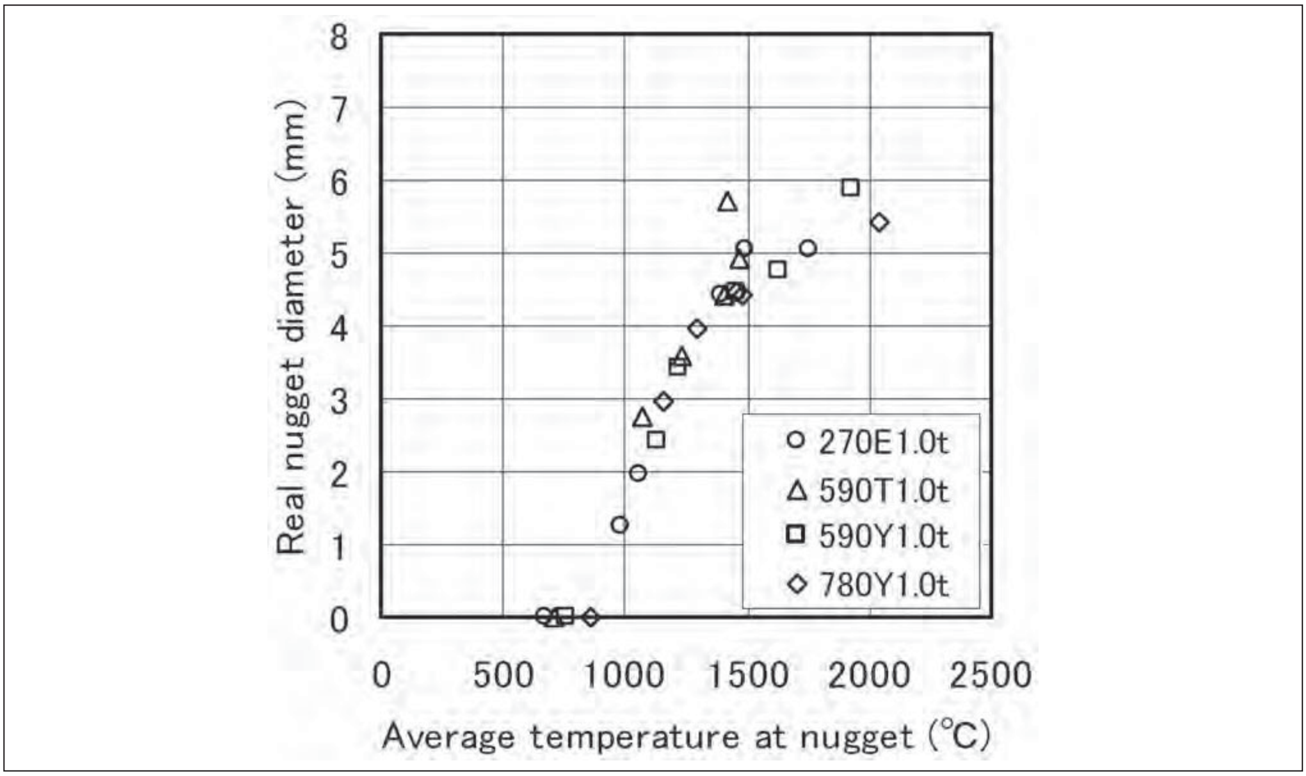


Figure 13 – Relation between average temperature at nugget and real nugget diameter

perature at the nuggets and real nugget diameters. An obvious relation is recognized between the average temperature at the nuggets and nugget diameters. Therefore, nugget diameters can be estimated by using this relation.

Figure 14 shows an example of estimating the result of nugget diameters. Estimated nugget diameters are coincident with real nugget diameters. From these results, it is concluded that it is possible to assure the joint strength by estimating the nugget diameter using current and voltage during spot welding.

4 CONCLUSIONS

As a result of this investigation concerning spot welding of HSS sheets, the following conclusions can be drawn.

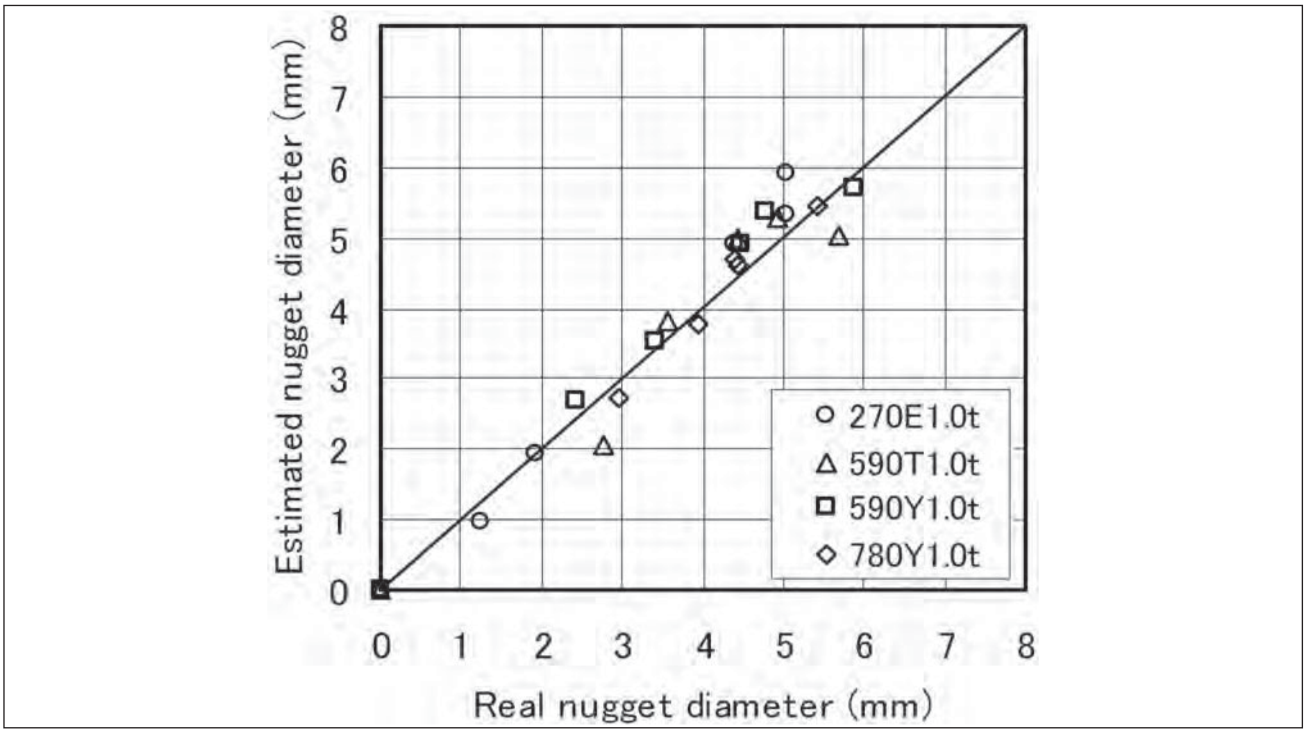


Figure 14 – Relation between real nugget diameter and estimated nugget diameter

1) The suitable welding current range of HSS sheets in spot welding shifted to the lower current side compared with that of mild steel sheets and it was affected by the electrode force.

2) The Vickers hardness at the welded zone increased with base steel carbon content.

3) The tensile shear strength of joints increased with nugget diameter, sheet thickness, and base steel strength.

4) The cross tension strength of joints increased with nugget diameter and sheet thickness; however, it showed a peak for base steel strength and carbon equivalency.

5) The fatigue strength didn't increase with base steel strength.

6) A suitable welding current range of galvannealed HSS sheets in spot welding shifted to the higher current side compared with bare HSS steel sheets.

7) Electrode tip life for galvannealed steel sheets was over 3 000 points and it was a practical use level.

8) It is possible to assure the joint strength by estimating the nugget diameter using current and voltage during spot welding.

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