

Factors to Determine Static Strengths of Spot-weld for High Strength Steel Sheets and Developments of High-strength Steel Sheets with Strong and Stable Welding Characteristics

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Abstract

Considering an application for automotive body structure, variations in TSS and CTS for high-strength steel sheets are summarized with their dependence on sheet strength and thickness, steel chemistry, and coating. In case of so-called “button fracture”, both of TSS and CTS seem to be proportional to the strength and thickness of sheets and nugget diameter, but the proportional constant is not settled. Proportional constant for TSS decreases with increasing sheet thickness, but does not vary with sheet strength and existence of coating. Contrarily, proportional constant for CTS remains same with varied sheet thickness, but decreases with increasing sheet strength. Proportional constant for CTS is larger in GA steel sheets than that in cold-rolled steel sheets. Both of TSS and CTS decrease with increasing carbon content. Increasing silicon content decreases TSS, but increases CTS. Above-mentioned knowledge gives a series of high-strength steel sheets with excellent characteristics for spot-welds up to a tensile strength of 980 MPa, but a large decrease in CTS cannot be avoidable if expulsion occurs in welding.

1. Introduction

The deterioration of formability is cited first of all as the factor of inhibiting the strengthening of steel sheets for automobiles, whereas the first factor of inhibiting the strengthening of ships, bridges, and oil pipelines is the degradation of toughness of and the lowering of confidence in a weld in particular. The reason for those differences in the factors of inhibition of strengthening is more influenced by the fact that most of the steel sheets, used thus far for automobiles, were less than 590 MPa in tensile strength (TS) than by the differences in size and application of steel material. However, for the simultaneous realization of crashworthiness and weight reduction of

auto bodies, the use of high strength steel sheets over 590 MPa in TS is rapidly increasing, accounting for as much as 23% for new cars in recent years¹⁾. Such a change in steel sheets for automobiles will become increasingly significant in the future as seen in the ULSAB-AVC project of International Iron and Steel Institute in line with the growing demands for welding characteristics as in other applications.

Arc welding and projection welding are also used for the assembly of auto bodies together with laser welding increasingly applied recently. However, to major parts is applied spot welding. In this case, tensile shear strength (TSS) and cross tensile strength (CTS) are stipulated by JIS Z 3136 and Z 3137 as the standard of strength quality, while the standard value of TSS is provided for by JIS Z

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3140 according to the performance requirements of steel sheet strength, sheet thickness, and a weld. Again, the changes in TSS due to steel strength TS_{PM} , sheet thickness t , and nugget diameter Dn are put in order empirically in the following two formulae²⁻⁵, and also calculated on trial by the finite element method⁶, respectively, when a weld remains integrated with one steel sheet while the other steel sheet is button-fractured, that is, tear (plug, parent material) -ruptured with α as a constant:

$$TSS = \alpha \cdot Dn \cdot t \cdot TS_{PM} \quad (1)$$

when a welding nugget is cut out between steel sheets, that is, shear (interface, peel) -ruptured with the strength of the nugget part set as nugget strength TS_{WM} and γ as a constant:

$$TSS = \gamma \cdot \pi \cdot (Dn/2)^2 \cdot TS_{WM} \quad (2)$$

In contrast with the foregoing, CTS is considered not to increase like TSS even with an increase in steel sheet strength^{3,7-10}. However, only a few reports systematically made are available relative to its changes according to steel sheet strength, sheet thickness, and a nugget diameter³. Therefore, the conditions of steel sheets and welding, necessary for obtaining weld strength characteristics required for auto bodies, were proposed after investigating the CTS of the spot welds of high strength steel sheets differing in steel sheet strength, sheet thickness, and steel components, and summarizing their governing factors together with those of TSS.

Also, a list has been prepared of high strength steel sheets, excellent in weld strength characteristics, including galvanized alloyed steel sheets (GA) up to a level of 980 MPa on the basis of the expertise obtained as above-described by assuming their applications to the skeletal structure of an auto body, including side members, front and rear, side sills, and center pillars. Therefore, an example will be introduced in the later chapter.

2. Study of factors governing spot weld static strength

2.1 Sample steel sheets and welding conditions

Table 1 gives the thickness, main chemical components, strength, and surface state of steel sheets offered for investigation. The GA steel sheets, (1), (2), and (3b), are unexceptionally 1.8 mm thick with the amounts of C almost at the same level, but differ in tensile strength ranging between 390 and 780 MPa. This enables to study the influ-

ence of steel sheet strength on weld strength. Similarly, the influence of sheet thickness can be checked by comparing the GA steel sheets, (3a), (3b), and (3c), with the cold-rolled ones (cold thin in the table), (1a), (1b), and (1c), and the influence of steel components by comparing with the cold-rolled steel sheets, (1b), (2), and (3). It is also possible to check the difference in coated or uncoated high strength steel sheets by comparing the GA steel sheets, (3a) and (3b) with the cold-rolled ones, (1a) and (1c), without being bothered by the differences in strength, sheet thickness, and components of steel sheets.

Although welding conditions are listed together in Table 1, an electrode force was considered constant for steel sheets at a level above 590 MPa when they are flat with no trouble of insufficient contact between the electrode and the steel sheet during welding. Again, the electrode is of type DR, made of Al_2O_3 -dispersed reinforced Cu. A tip diameter for steel sheets above 1.8 mm in thickness was set at 8 mm with the principal objective of forming a large-diameter nugget that will tear-rupture during TSS measurement¹¹.

2.2 Changes in weld strength due to a nugget diameter

Fig. 1 shows the examples of changes in cold-rolled steel sheets (1c) at a level of 780 MPa. A nugget diameter increases as welding current increases together with TSS and CTS. However, as is well

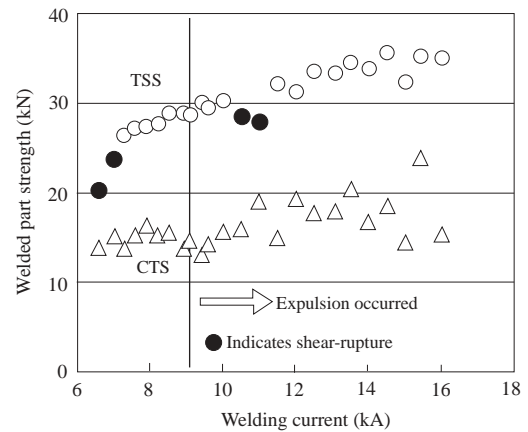


Fig. 1 Changes in spot-welded part strength due to welding current of 1.8-mm-thick 780-MPa cold-rolled steel sheet (1c)

Table 1 Sheet thickness, steel composition, tensile strength value, coating, if any, and welding conditions of steel sheets for study

Kinds of steel	Sheet thickness (mm)	Chemical composition (mass%)			Tensile strength value			Coating weight (g/m ²)	Spot welding conditions			
		C	Si	Mn	YP (MPa)	TS (MPa)	E1 (%)		Electrode tip diameter (mm)	Welding force (kN)	Welding time (cycle)	Holding time (cycle)
GA(1)	1.8	0.07	0.02	1.25	314	423	41	52 / 51	8	4.0	17	10
GA(2)	1.8	0.07	0.47	2.07	385	616	32	48 / 48	8	5.6	17	10
GA(3a)	1.0	0.07	0.54	2.22	508	820	19	42 / 51	6	3.4	10	10
GA(3b)	1.8	0.07	0.54	2.22	519	780	19	53 / 54	8	5.6	17	10
GA(3c)	2.6	0.07	0.54	2.22	546	790	22	54 / 54	8	7.9	26	10
Cold thin(1a)	1.0	0.08	1.39	1.75	456	797	23	-	6	3.1	10	25
Cold thin(1b)	1.4	0.08	1.39	1.75	467	831	23	-	6	4.3	14	25
Cold thin(2)	1.4	0.14	0.46	2.09	443	809	19	-	6	4.3	14	25
Cold thin(3)	1.4	0.17	1.68	1.44	435	816	27	-	6	4.3	14	25
Cold thin(1c)	1.8	0.08	1.39	1.75	479	782	24	-	8	5.6	17	25

YP: Yield strength El: Elongation

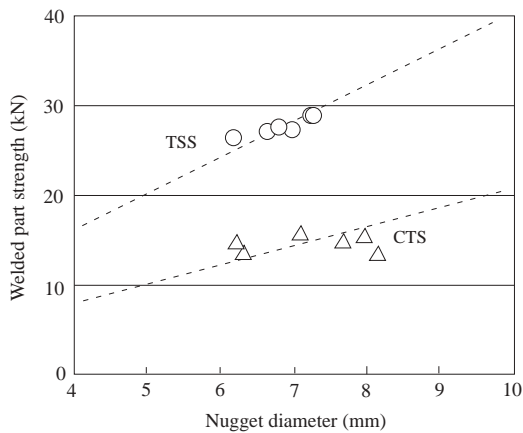


Fig. 2 Relationships between a nugget diameter and a spot-welded part strength in 1.8-mm-thick 780-MPa cold-rolled steel sheet (1c) (In case the welded part where no expulsion is observed is tear-ruptured)

known, when welding with overcurrent that will lead to expulsion, TSS may increase to a certain extent, whereas CTS is extremely lowered in some cases because of its large scattering in comparison with the case in which no expulsion is observed.

It was therefore decided to study the influences of steel sheet strength, sheet thickness, and steel components on TSS and CTS relative to the weld formed with no expulsion occurring, and an attempt was made to exclude the influence due to the difference in nugget diameter. In other words, it was decided to obtain α in formula (1) relative to TSS. Investigation was also made as to whether the similar relationship can be applied to CTS³⁾.

$$CTS = \beta \cdot D_n \cdot t \cdot TS_{PM} \quad (3)$$

Fig. 2 puts in order the influence of steel sheet strength only on the weld formed without expulsion as the interrelation to a nugget diameter out of the influences of the strength of cold-rolled steel sheet (1c) shown in terms of the changes with welding current as **Fig. 1** shows, revealing that formula (3) holds true to the nugget obtained under the conditions of Table 1.

2.3 Changes in weld strength due to steel sheet strength

Fig. 3 shows the findings in which α and β of formulae (1) and (3) were obtained relative to the 1.8-mm-thick GA steel sheets, (1), (2), and (3b). Although constant α to TSS does not change greatly

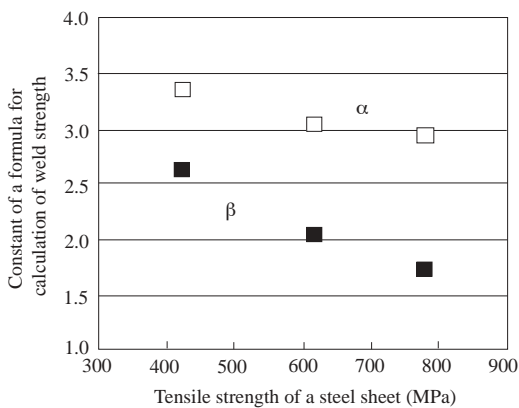


Fig. 3 Changes in proportional constant of weld strength to a nugget diameter due to steel sheet strength (adjustment of the 1.8-mm-thick GA steel sheets, (1), (2), (3b))

even with an increase in steel sheet strength, β to CTS clearly decreases with an increase in steel sheet strength. This is true to the conventional expertise that TSS increases whereas CTS does not always increase in proportion to steel sheet strength. However, a ratio of β to α , that is, a ductility ratio, is short of 0.6, a value not extremely small, even in case of a steel sheet at a level of 780 MPa. As described in the later chapter, this may be accounted for not only by a comparatively low content of C as the steel sheet at a level of 780 MPa, but also by the feature of the steel components containing a significant amount of Si and that of the GA steel sheets.

2.4 Changes in weld strength due to sheet thickness

Fig. 4 shows the findings in which α and β of formulae (1) and (3) were obtained relative to the GA steel sheets at a level of 780 MPa, (3a), (3b), and (3c), and the cold-rolled steel sheets, (1a), (1b), and (1c). Although no significant change was observed due to sheet thickness in constant β to CTS, constant α to TSS lessens with a ductility ratio increasing in proportion to sheet thickness. Such a change in α is assumed to be due to the rotation of a test piece. However, TSS itself increases in proportion to sheet thickness due to the influence of increased sheet thickness even if the nugget diameter is same. Again, when a nugget diameter is small and a test piece is shear-ruptured in the tensile shear test, a case may also be observed in which a ductility ratio grows larger because of a decrease in TSS based on formula (2).

2.5 Changes in weld strength due to steel components

A significant difference in chemical composition among the cold-rolled steel sheets, (1b), (2), and (3), lies in C and Si, and **Fig. 5** puts in order the difference between α and β as being attributable to their influence. There is a tendency that constant α to TSS lessens in proportion to the amounts of C and Si in steel even in the case of the same steel strength. It is assumed that this increases the hardness of a nugget with its sensitivity to stress concentration sharpened. On the other hand, β to CTS is almost equal between the cold-rolled steel sheets, (1b) and (3). It decreases when the content of C in steel is high, but increases if the amount of Si is increased even at a level of 780 MPa. Such a Si-induced change in CTS is considered to be due to the moderate change in hardness from a nugget to a parent material¹⁰⁾.

2.6 Changes in weld strength due to coating

Fig. 4 previously given reveals that while no difference in α of formula (1) is observed between GA steel sheets and cold-rolled ones,

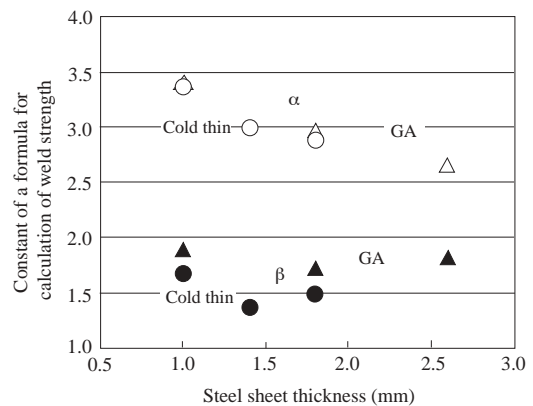


Fig. 4 Changes in proportional constant of weld strength to a nugget diameter due to steel sheet thickness (adjustment of the 780-MPa GA steel sheets, (3a), (3b), and (3c), and the cold-rolled steel sheets, (1a), (1b), (1c))

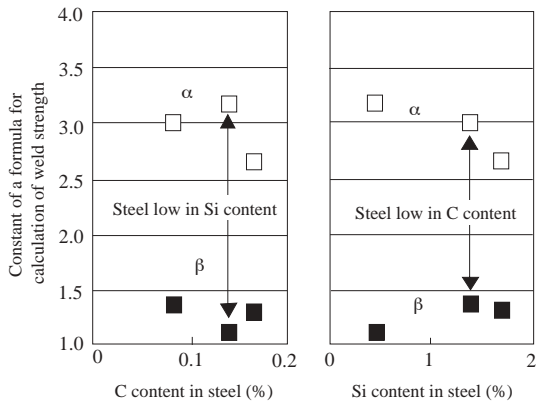


Fig. 5 Changes in proportional constant of weld strength to a nugget diameter due to steel composition (adjustment of the 1.4-mm-thick 780-MPa cold-rolled steel sheets, (1b), (2), and (3))

β of formula (3) is greater in GA steel sheets than in cold-rolled ones with a ductility ratio also increasing. This is considered due to the coalescence of the coated alloy layer at a corona-bonded part outside the nugget.

2.7 Changes in weld strength due to the occurrence of expulsion

The foregoing tendency refers to the expertise concerned with the part welded in an ideal state without the occurrence of expulsion. However, at the part where expulsion is taking place, an aspect changes drastically. Therefore, Figs 6 and 7 are given to show how much TSS and CTS differ in their maximum values when expulsion occurs and when not. A phenomenon in which expulsion occurs should be studied statistically. However, due to the limitation in the number of experiments here as Fig. 1 shows, deviation of the lowest

welding current from the original when expulsion was occurring was divided into three stages with the changes in TSS and CTS from their maximum values limited only to histogramming. Contrary to the general recognition relative to the thick high strength GA steel sheets, (3b) and (3c), their TSS sometimes decreases by a little over 20% when expulsion occurs. One of the reasons for this is explained by the change in the form of rupture to shear when a nugget diameter decreases due to expulsion because of a large critical diameter changing from shear rupture to tear rupture.

In GA steel sheet (1) at a low strength level of 390 MPa and cold-rolled steel sheet (1b), as thin as 1.4 mm and low in C content, even at a level of 780 MPa, CTS scatters in value only a little with almost no decrease as compared with a case in which no expulsion occurs. However, in other steel sheets, CTS scatters large when expulsion occurs, simultaneously showing a tendency of decreasing. Particularly worthy of note is that in cold-rolled steel sheets (2) and (3) with a C content of over nearly 0.15% and thick high strength GA steel sheets (3b) and (3c) though low in C content, CTS scatters largely due to expulsion, sometimes scattering even to 1/3 of the value with no expulsion. In case of thick high strength GA steel sheets, welding overcurrent sometimes leads to cracking on the steel sheet surface¹²⁾. However, blowholes and shrinkage cavities near the perimeter of a nugget are assumed to have a larger influence.

3. Development of a series of high strength steel sheets excellent in weld strength characteristics

It is evident from the foregoing that it is important to select a composition containing a constant amount of Si for cold-rolled steel sheets comparatively low in CTS while controlling the amount of C so that TSS and CTS at the spot-welding part of a high strength steel sheet can be secured. With the above taken into consideration, an

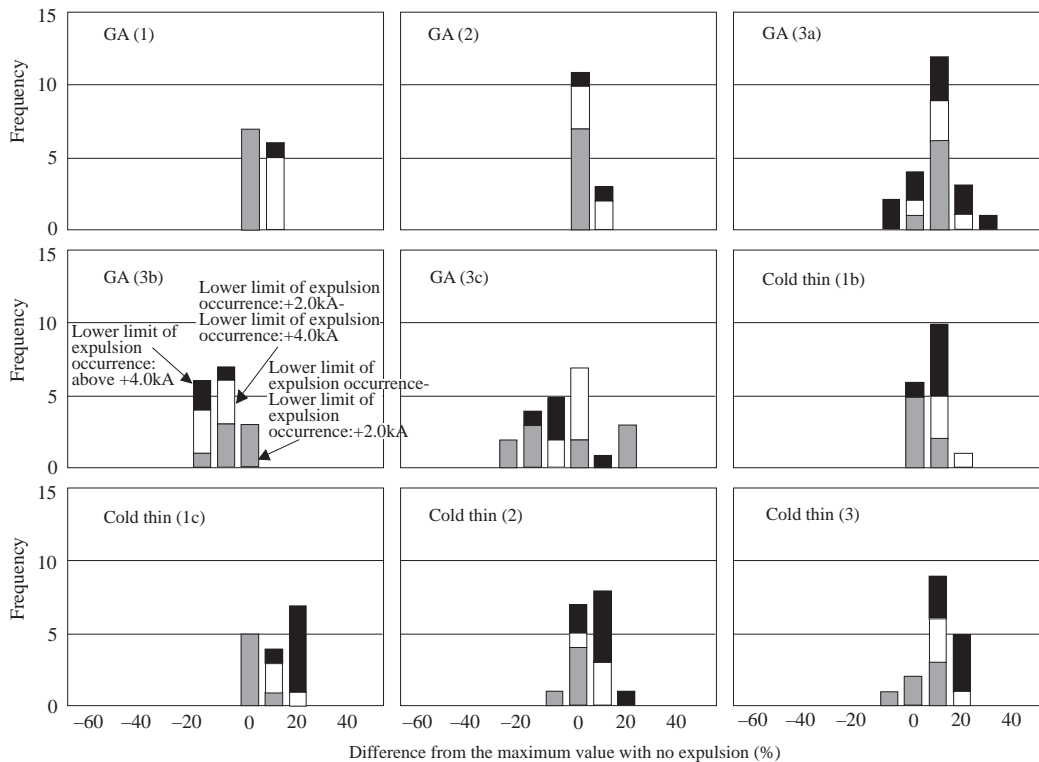


Fig. 6 Lowering of TSS due to the occurrence of expulsion

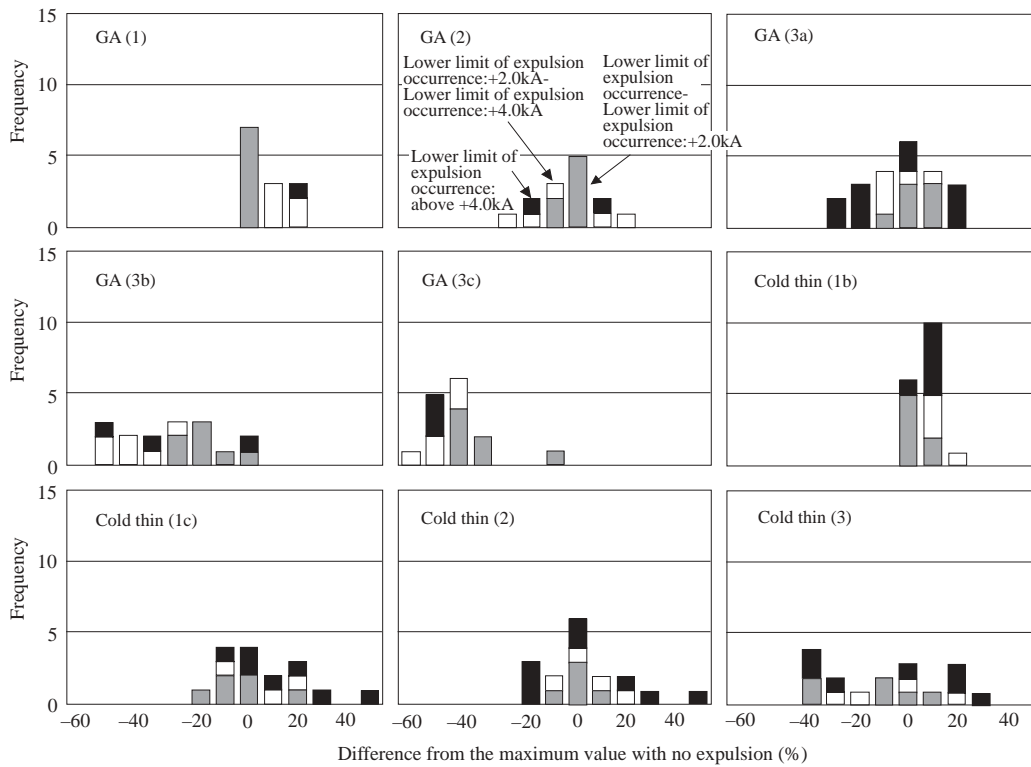


Fig. 7 Changes in TSS due to expulsion occurrence

amount of additive elements should be selected, rolling conditions and temperature conditions for annealing or hot galvanizing should be controlled, and a steel sheet should be designed in a manner that will satisfy the functions necessary for auto body members, including the process-ability into auto parts and strength. Based on this guideline, Nippon Steel has developed high strength steel sheets excellent in weld strength characteristics fit for auto body skeletal structure.

Fig. 8 gives the examples of GA steel sheets. A series of steel sheets are prepared ranging from the ones fit for those parts strict in workability, including side members, front and rear, and center pillars, low in yield strength (YP), and high in elongation, to the ones high in YP though low in elongation and at a level up to 980 MPa by assuming the application to members durable enough for use as sills

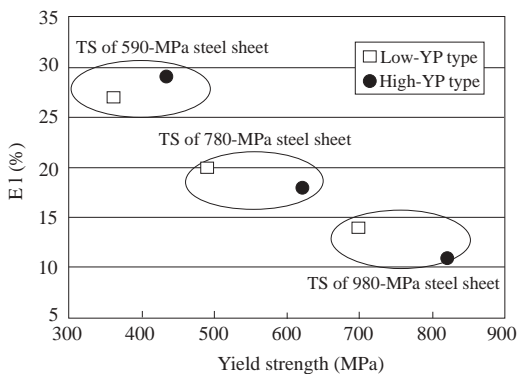


Fig. 8 Examples of high strength steel sheets excellent in weld strength characteristics (2.0-mm-thick GA steel sheets)

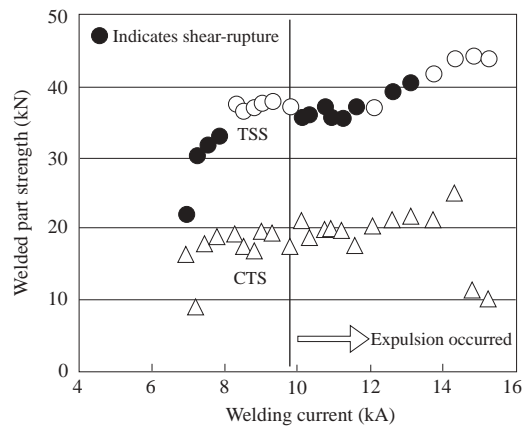


Fig. 9 Changes in strength of spot-welded parts due to welding current of 2.0-mm-thick low-YP-type 980-MPa GA steel sheets

and roof rails though low in strain when processing. Fig. 9 shows the changes in weld strength due to welding current when 2.0-mm-thick low-YP-type GA steel sheets at a level of 980 MPa were welded with an electrode force of 6.45 kN and a weld time of 19 cycles. At the time of measuring TSS, the steel sheets were tear-ruptured, making it possible to obtain a weld with a ductility ratio also exceeding 0.5.

4. Conclusion

High strength steel sheets developed, with a high weld strength stably secured, can contribute to the realization of auto bodies compatible in both crashworthiness and light weight without betraying

our trust. However, it is prerequisite for the achievement of this objective to ensure that large expulsion is not allowed to occur. It is also necessary to computerize welding work and incorporate various techniques, for example, to improve form stability during parts processing so that insufficient contact between an electrode and a steel sheet can be avoided. Undoubtedly, steel sheets should be improved further and innovated, at which time development should be proceeded as well with their basic performances, including weldability and weld strength, taken into consideration.

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