Effect of formation and state of interface on joint strength in friction stir spot welding for advanced high strength steel sheets

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Abstract. The tensile shear strength and cross tension strength of friction stir spot welded joints were evaluated in the cases of lap joints of 270 N/mm² grade and 980 N/mm² grade cold rolled steel sheets with respect to the stir zone area, hardness distribution, and interface condition between the sheets. The results suggested that both the tensile shear strength and cross tension strength were based on the stir zone area and its hardness in both grades of steel. The “hook” shape of the interface also affected the joint strength. However, the joining that occurred across the interfaces had a significant influence on the value of the joint strength in the case of the 270 N/mm² grade steel.

1. Introduction
Because it is a solid state joining process, friction stir spot welding (FSSW) is expected to overcome the welding issues for advanced high-strength steel (AHSS) found in conventional fusion welding processes. However, its implementation requires further assurance of the mechanical properties based on a detailed understanding of the welding phenomena.

Studies on the mechanical properties have shown that the factors influencing the joint strength are the stir zone (SZ) area, microhardness of the joint weld, and shape of the interface in the case of a lapped weld joint of two sheets of an identical aluminum alloy [1–3]. Among these, the most influential factor for the joint strength was found to be the SZ area, with a larger SZ area producing a higher joint strength [1]. As a characteristic phenomenon in FSSW, the shape of the interface was deformed by the plastic flow around the tool, which had a significant influence on the joint strength. With the formation of the SZ, the interface was supposed to rise up toward the upper sheet, extend around the SZ, reach the area of the probe, and end up in the form of a hook. This “hook” shape was supposed to cause a failure along its direction and lower the joint strength.

In contrast, sufficient investigations have not yet been performed to determine the factors influencing the joint strength of a lapped friction stir spot weld joint of two sheets of an identical automotive steel, especially AHSS above the 980 N/mm² grade. However, some reports have shown that the SZ area and hardness of the joint have effects on the joint strength, just as when using FSSW for aluminum alloys [4–6]. Besides these effects, the influence of the hardness distribution, or the localized strength within the weld, on the joint strength during FSSW should be considered in the case of AHSS, analogous to the trend seen in resistance spot welding (RSW). The higher microhardness of the weld basically increases the joint strength. However, when the microhardness of the weld is unfavorably high, and the joint is loaded in the direction to open the lap sheets, the joint strength may decrease. This is considered to be because the high microhardness in the weld is related to a brittle
microstructure, which results in brittle fracture, and the high microstructure in the heat affected zone (HAZ) prevents the plastic deformation, which results in a stress concentration at the weld [7–10].

However, there have been no reports on the influence of the shape and state of the interface on the joint strength with a comparison between conventional mild steel and AHSS up to a grade of 980 N/mm². Therefore, the mechanical properties of friction stir spot welds of 270 N/mm² grade steel and 980 N/mm² grade steel were evaluated, and the influence of the shape and state of the interface on the joint strength was investigated.

2. Experimental procedure

FSSW was used to form lapped weld joints in two sets of 1.2-mm-thick identical steel sheets, as listed in table 1, where TS270 and TS980 represent 270 N/mm² grade steel and 980 N/mm² grade steel sheets, respectively. A Si₃N₄ ceramic tool was used, which consisted of a flat shoulder with a diameter of 10 mm and a threaded probe with a diameter of 3.8 mm and a height of 1.7 mm. The weld time was 0.5–3.0 s, the plunge force was 6 kN, and the rotation speed was 3000 rpm. During the FSSW, Ar gas was used for shielding the weld.

The cross-sectional microstructures were observed using optical microscopy after etching with a saturated picric acid solution or 3% nital reagent. The projected cross-sectional SZ area, which represented $S$, was estimated using Eq.(1).

$$S = \pi \cdot \left( \frac{Ds}{2} \right)^2 - \left( \frac{Dp}{2} \right)^2$$  \hspace{1cm} (1)

where $Ds$ is the diameter of the SZ, and $Dp$ is that of the plunged area measured by cross-sectional metallography, as shown in Figure 1.

A tensile shear test and cross tension test were conducted for the obtained weld joints, and the fracture patterns were evaluated by the cross-sectional metallography of the fractured specimens.

Microhardness testing of the weld was carried out using a 1.9-N load and a holding time of 10 s with a 0.2-mm grid spacing in both the through-thickness and transverse directions. The hardness distribution of the welds was plotted as either a contour map or transverse hardness profile for the upper sheet side at 0.3 mm from the surface lapped with the lower sheet.

| Steel   | C     | Si   | Mn   | YP(N/mm²) | TS(N/mm²) | El(%) |
|---------|-------|------|------|-----------|-----------|-------|
| TS270   | 0.002 | 0.003| 0.13 | 160       | 300       | 51    |
| TS980   | 0.12  | 1.4  | 1.9  | 810       | 990       | 18    |

Figure 1. Schematic drawing of parameters for estimation of SZ area.
3. Results

The cross-sectional macrostructures at each weld time are shown in Figure 2. For TS270, the SZ was already formed and two sheets were completely in contact at 1.0 s, and the SZ area gradually increased with the weld time. For TS980, the SZ was formed in 1.0 s despite the lack of full contact between the sheets and increased in area with the weld time. The relationship between the SZ area estimated by Eq.(1) and the weld time is shown in Figure 3. The SZ area basically increased with the weld time in similar ways for both grades. However, that of TS980 was less than that of TS270 at 1.0 s, while that of TS270 was less than that of TS980 after 2.0 s or longer.

The hardened area and its increase were limited to the area around the SZ in TS270, whereas a broad area as wide as the microstructure change showed a large increase in microhardness in TS980. Figure 4 shows the cross-sectional macrostructures etched by the natal reagent and the microhardness distribution based on the values derived from the 0.2-mm grid spacing with a weld time of 3.0 s. In the case of TS270, the hardened area was limited to the area around the SZ, and the values around the interface close to the probe (A1) were almost equal to those of the base metal (BM). However, in the case of TS980, the hardened area extended from the area around the interface close to the probe (B1) to an area at a distance of 0.8 mm (B2). Figure 5 shows the cross-sectional hardness distribution in the weld, measured at the upper sheet side at 0.1 mm from the interface. The highest hardnesses were observed in the SZ areas for both steels, with values reaching Hv195 in TS270 and Hv464 in TS980.

![Figure 2. Cross-sectional macrostructures etched by saturated picric acid with respect to weld time, where interface shapes are drawn with curves on left sides.](image.png)

![Figure 3. SZ areas of TS270 and TS980 with weld times.](image.png)
Figure 4. Comparison of cross-sectional microstructure etched by natal regent and microhardness distribution with 0.2-mm grid spacing at weld time of 3 s, where dashed lines represent interfaces in (a2) and (b2).

Figure 5. Hardness distributions of TS270 and TS980 on upper sheet side at 0.1 mm from interface with weld time of 3 s, where SZ, HAZ, and BM represent average hardnesses of SZ, HAZ, and BM, respectively.

The value of the average hardness of the HAZ in TS980 was close to that for the SZ. However, that of the HAZ in TS270 showed a low value and was relatively close to that of the BM.

Figure 2 also shows that the interface rose up toward the upper sheets in both cases within 2.0 s or less, which is called the “rising-up” shape in this paper. The interface of TS270 at 3.0 s was also the “rising-up” shape and extended to the surface of the upper sheet. However, the interface of TS980 at 3.0 s was extended around the SZ through the upper sheet and reached the probe, which showed a “hook” shape.

These shape transitions in the interface from “rising-up” to a “hook” were assumed to be caused by the extent of the metal flow, which dragged the lower sheet surface into the upper sheet, formed the “rising-up” shape of the interface, and subsequently drove the “rising-up” interface inward toward the
direction of the probe when it was extended close to the shoulder, forming the “hook” shape [11]. Because of the transition, the interface inside the upper sheet was supposed to expand the surfaces of the sheets containing oxides and other inclusions, which resulted in a weak interface between the sheets [2].

The joining across the “rising-up” interface could be seen in TS270, whereas the interface was completely separated in TS980, even in the similar “rising-up” shape. The detailed cross-sectional microstructures around the interface with a weld time of 2.0 s are shown in Figure 6 and Figure 7. The interfaces for the two grades seem to have similar “rising-up” shapes in a comparison between (a) and

Figure 6. Cross-sectional microstructures of TS270 with weld time of 2 s, where distances from probe are (a1) 0.6 mm, (a2) 1.1 mm, and (a3) 2.0 mm, as shown in (a).

Figure 7. Cross-sectional microstructures of TS980 at weld time of 2 s, where distances from probe are (b1) 0.6 mm, (b2) 1.1 mm, and (b3) 2.0 mm, as shown in (b).
(b). However, at the tip of the “rising-up” interface at 0.6 mm from the probe, the interface seems to be joined as fine ferrite grains in TS270, as seen in (a1) and (a4), whereas an obvious separation can be observed in TS980 at (b1) and (b4). In TS270, the ferrite grains were joined between the upper and lower sheet at 1.1 mm, as seen in (a2) and (a5), and some of them were similarly joined at 2.0 mm, as seen in (a3) and (a6). In contrast, as shown in (b2) and (b5) or in (b3) and (b6), the interface was clearly visible and the microstructures were different across the interface, which indicated that the joining was incomplete in these regions in TS980.

The tensile shear strength (TSS) increased with the weld time in both steels, as shown in Figure 8. Figure 9 shows the cross-sectional microstructure of a fractured specimen after the tensile shear test. At 1.0 s, both steels were fractured across the SZ, as shown in (a1) and (b1). At 2.0 s, the joint of TS270 was also fractured across the SZ, as seen (a2), whereas one side transitioned from the “rising-up” shape of the interface and propagated vertically through the upper sheet in the case of TS980, as seen in (b2). At 3.0 s, in the case of TS270, one side was fractured through the SZ, and the other side was fractured along the “rising-up” interface, as seen in (a3). In the case of TS980, one side was also fractured through the SZ, and the other side was fractured leaving the SZ with a “hook” shape for the interface, as seen in (b3).
The cross tension strength (CTS) of TS270 increased with the weld time, whereas the CTS of TS980 showed a peak at 2.0 s and subsequently decreased as shown in Figure 10. It should also be noted that it showed a lower value than that of TS270, even though a higher value was expected. Figure 11 shows the cross-sectional microstructures of the failed samples after the cross-tension test. Similar to the TSS results, both grades at 1.0 s and the TS270 joint at 2.0 s were fractured across the SZ. The TS980 joint at 2.0 s and the TS270 joint at 3.0 s were fractured along the “rising-up” shape of the interface toward the surface of the upper sheet on both sides. However, at 3.0 s, both sides of the TS980 joint were fractured along the “hook” shape of the interface.

Figure 12 shows the TSS plotted by the SZ area, and it reveals that the TSS values of both grades increase with the SZ area, whereas the TSS values of TS270 are lower than those of TS980 at the same SZ area.

The CTS of TS270 also increased with the SZ area, as shown in Figure 13. The CTS of TS980 also increased with the weld time for the SZ area. However, it showed a peak at 7.8 mm² and subsequently decreased. In contrast to the TSS results, the CTS values for TS270 were higher than those of TS980 for the same SZ area.

4. Discussion
Both the TSS and CTS values were supposed to increase with the SZ area in both grades. The results shown in Figure 12 reveal that the TSS increased almost linearly with the SZ area in both grades, which agrees with previous reports [5]. It is supposed that if the fracture passes across the SZ of TS980, in which the microhardness is higher than that of TS270, the TSS value of TS980 will be higher than that of TS270, just as in the case of RSW [7].

To evaluate the influences of the SZ area and microhardness in the SZ on the resulting TSS, the prediction formula developed for RSW, as given in Eq.(2), was applied [12].

$$TSS = \frac{\pi d^2}{4} \cdot \frac{H_{vn}}{3\sqrt{3}},$$  \hspace{1cm} (2)

where \(d\) is the diameter of a nugget, and \(H_{vn}\) is its Vickers hardness. In FSSW, the center of the joint is open because of the plunge of the probe. Therefore, the equation was modified using the SZ area, which represents \(S\), as shown in Eq.(3).

$$TSS = S \cdot \frac{H_{vn}}{3\sqrt{3}},$$ \hspace{1cm} (3)

The relationship between the experimental and predicted TSS values is shown in Figure 14. The experimental TSS values are in good agreement with the predicted values, especially in the case of
TS980, which corresponds to the previous report [5]. The experimental TSS values for TS270 tended to be higher than those of the predicted TSS, and a possible factor for this is discussed later. This result suggests that the most influential factors for the TSS of an FSSW joint are the SZ area and microhardness in the SZ.

| Experimental TSS / kN | Predicted TSS / kN |
|----------------------|-------------------|
| ▲                    | ●                 |
| TS270                | TS980             |
| (thickness 1.2mm)    |                   |
| ▲ = 1                |                   |

**Figure 14.** Correlation between experimental and predicted TSS values for TS270 and TS980.

It is also supposed that the SZ area basically increases the CTS in both cases. However, the lower CTS values for TS980 compared to those for TS270 and the decrease in the CTS with an SZ area larger than 7.8 mm², as shown in Figure 13, cannot be explained using only the SZ area and the microhardness in the SZ. Therefore, the shape and state of the interface should be considered to understand this difference between TS270 and TS980.

It is suggested that the "hook" shape of the interface may cause the decrease in the CTS in spite of the increase in the SZ area. This "hook" shape is formed around the SZ and passes throughout the upper sheet, as seen in Figure 2(b3), and the shape of the interface is supposed to cause the fracture propagation along the interface under low stress in the direction to open the lapped sheets. This corresponds to the fracture along the "hook" shape shown in Figure 11(b3), and results in a decrease in the CTS. The "rising-up" shape is also considered to have a detrimental effect on the CTS, because the extension of the "rising-up" interface can be the initial crack inside the upper sheet, which can be seen in the correspondence between the shape of the interface in Figure 2(b2) and the crack direction, as shown by the arrow in Figure 11(b). However, the effect of the "rising-up" shape is considered to be relatively small compared to that of the "hook" shape because the "rising-up" shape does not reach the surface of the upper sheet, whereas the "hook" shape does. Therefore, the "rising-up" does not cause a large decrease in the CTS.

It is also supposed that the joining across the "rising-up" interface has a large influence on the value of the CTS. In the case of TS270, the interface beside the SZ was joined as shown in Figure 6(a4). In addition, it can be seen that the grains grew across the interface at the root of the "rising-up" shape, as shown in Figure 6(a5). It is believed that the joining can prevent the crack propagation along the interface and increase the CTS. In contrast to TS270, the interface of TS980 beside the SZ inside the upper sheet can be seen as a sharp edge in Figure 7(b4). The complete separation of the interface in the TS980 weld is considered to cause crack initiation under a lower stress in the direction to open the lapped sheets, which results in a lower CTS than that of TS270. Further investigation is needed to reveal the reasons for the joining across the "rising-up" interface and the difference in the states of the
joining between TS270 and TS980, although it is believed that diffusion joining affected the joining across the “rising-up” joining.

The crack initiation from the TS980 interface may also have been affected by the hardness distribution. The HAZ of TS980 was widely hardened, as shown in Figure 4(b2), compared to the case of TS270, in which the microhardness increase in the HAZ was relatively small, as shown in Figure 5. It is suggested that the harder plastic deformation in the HAZ of TS980 caused the higher stress concentration and fracture under a lower stress than the case of TS270, as mentioned in the case of RSW [9–10].

5. Conclusion
To ensure the mechanical properties during the FSSW of automotive steel, this study investigated the different factors influencing the joint strengths and failure modes of 270 N/mm² grade steel and 980 N/mm² grade steel, and the following conclusions were reached.

Both the TSS and CTS values of the FSSW joints of the 270 N/mm² and 980 N/mm² grade steels basically increased with the SZ area. A higher TSS corresponded to a higher microhardness value in the SZ in both grades.

The shape of the interface played a significant role in the CTS. A “hook” shape for the interface, which passed through the upper sheet, largely decreased the CTS because of the ease with which a fracture occurred along the interface, whereas a “rising-up” shape for the interface had a relatively small effect on the CTS.

The state of the interface had an influence on the CTS. When the “rising-up” interface was joined, as in the case of the 270-N/mm² grade steel, the crack propagation could be prevented and the CTS increased. However, when the joining across the “rising-up” interface was hard to achieve, as in the case of the 980 N/mm² grade steel, the CTS became relatively low.

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