Relationship between cross tension strength and carbon content of lower sheet in friction element welded steel joints

Sho Matsui\textsuperscript{a}, Kohsaku Ushioda\textsuperscript{b} and Hidetoshi Fujii\textsuperscript{b}

\textsuperscript{a}Nippon Steel Corporation, Tokyo, Japan; \textsuperscript{b}Joining and Welding Research Institute, Osaka University, Osaka, Japan

ABSTRACT

High-strength steels (HSSs) have been increasingly used in car bodies to simultaneously achieve the weight reduction and high collision safety of vehicles. In resistance spot welding, which is widely used for joining car bodies, low cross tension strength (CTS) of joints using HSSs is a problem. In this study, we focused on friction element welding (FEW) to enhance the CTS. To investigate the joint strength of steel sheets jointed by FEW, a pre-hole was provided in the upper sheets, and the element was passed through the pre-hole to joint with a lower sheet, and then cross tension tests of the joints were conducted. In addition, the microstructures of the joints were observed to investigate the fracture positions. In the cross tension test, three types of fracture modes were observed. When the carbon content of the lower sheet was as low as 0.07 – 0.15 mass\%, the joint broke at the head of the element. However, when the carbon content was increased to 0.20 mass\%, the joints were fractured at the softened area of heat affected zone in the thickness direction of lower sheets. While the carbon content was further increased to 0.30 mass\% (C30), the cracks propagated inside the area quenched from the two-phase temperature region (inter-critically quenched area) of the lower sheets and then fractured in the lower sheet thickness direction. Consequently, the CTS was decreased. To clarify the mechanism of the decrease in CTS, the fracture surface was observed together with the hardness difference measurement between ferrite and martensite by the nanoindentation method. As a result, it was clarified that the hardness difference between the two phases was significantly large, leading to the ductile fracture. Based on these findings, the low CTS of C30 was inferred to be caused by the poor local ductility in the inter-critically quenched area.

KEYWORDS

Friction element welding; solid state joining; microstructure; cross tension strength; high strength steel

1. Introduction

In recent years, higher environmental and safety performance has been demanded of automobiles. For example, with regard to environmental performance, fuel efficiency is being improved to reduce CO\textsubscript{2} emissions, and new fuel efficiency standards have been established to promote a 32.4\% improvement in fuel efficiency from the FY2016 results, targeting FY2030. With regard to safety performance, in the collision safety performance evaluation published by the Ministry of Land, Infrastructure, Transport and Tourism and the National Agency for Automotive Safety and Victim’s Aid, the occupant protection performance, is evaluated by colliding the vehicle body with a barrier, has increased in percentage since FY 2018 [1]. For this reason, reductions in sheet thickness are being promoted by applying high-strength steel sheets, which enable both weight reduction of car bodies for improved fuel economy and collision safety. Resistance spot welding is an important joining method in the assembly of automobile bodies since resistance spot welding is widely used as a joining method for automobile bodies, with 3000–6000 welding points per automobile. On the other hand, resistance spot welds are subject to a decrease in cross tension strength (CTS), which indicates the peel strength of the joint caused by the increase in the strength of the steel sheet [2]. This decrease in CTS has been reported to be caused by a decrease in the toughness of the weld zone due to an increase in the strength of the steel sheet, i.e. an increase in carbon content [3,4]. It has also been reported that P solidification segregation, which occurs when the weld solidifies, also reduces the toughness of the weld and lowers the CTS [3–6]. To solve these causes, modification of the weld microstructure by post-current application, in
which the weld is heat-treated after welding, has been investigated in resistance spot welding. Examples include post-current application [7] to temper the weld zone, post-current application [3–6] to alleviate solidification segregation of P, HAZ auto-tempering-promoting post-current application [8] to improve the toughness of the Heat Affected Zone (HAZ) of the weld, and post-current application [9] to alleviate P segregation and relax stress concentration due to heat affected zone expansion by conducting multiple short-time energizing cycles. However, in these methods, the increase in joining time and the variation in joint strength compared to welding with a single current flow are considered to be problems.

On the other hand, multi-materialization is also underway, in which non-ferrous metals and resins are used as materials applied to automobiles to achieve a weight reduction of the car body, and a variety of joining methods are used to join them. For example, Self-Pierce Riveting [10] and Friction Element Welding (FEW) [11], blind rivets, etc. Most of the joining methods for multi-material joining are solid-phase joining methods, which join without melting the base metal, and do not cause solidification segregation of P, which is one of the causes of CTS reduction in resistance spot welding as mentioned above. In addition, since the shape of the joint edge, which is a stress concentration area, is different from that of resistance spot welding, there is a possibility that the stress concentration can be relaxed. Therefore, if these solid-phase joining methods can be applied to the joining of high-strength steel sheets, high CTS can be expected. We focused on FEW among the solid-phase joining methods used for multi-material joining. This method has been studied mainly as a joining method for aluminum and steel. In this joining method, the upper sheet is aluminum and the lower sheet is steel. A connecting piece made of steel, called an element, is pressurized from the aluminum side, rotated, penetrated through the aluminum, and friction-welded to the element and the lower sheet. The joining is accomplished by pinching the aluminum of the upper sheet between the head of the element and the lower sheet. FEW is difficult to join high-strength steel sheets because the element must penetrate the upper sheet, even if the upper sheet is steel. However, it is considered that steel sheets can be joined by making a through-hole in the upper sheet and friction-welding the element to the lower sheet through the hole in the upper sheet. Although similar FEW technologies had been reported [12] in the past, EJOWELD CFF®, a FEW developed by EJOT, attracted attention when it was applied to Audi’s Q7 [13]. Several studies on FEW have been reported [11,14–20]. For example, Absar et al. attempted to measure the temperature at the aluminum/steel sheet interface during joining by FEW using film thermocouples [16]. Varma reported on the analysis of temperature and plastic deformation behavior during the joining process of FEW by numerical simulation [17]. Ruszkiewicz et al. reported on the relationship between joining parameters and the time required for joining aluminum alloy sheets and 1500 MPa-class hot-stamped steel sheets [18]. Thus, although various studies of FEW have been conducted on the joining of aluminum and steel sheets, there are no reports on the detailed observation of the microstructure of the joint or on the joining of steel sheets to each other.

The joint between the element and the lower sheet is considered to be a friction stud welding. Compared to FEW, friction stud welding has been studied in various ways from ancient times to the present [21–23]. However, there are no reports on friction stud welding of high-strength steel sheets or detailed observation of the microstructure of the joints.

In this study, we conducted a cross-tension test using steel sheets with through holes in the upper sheet to evaluate the joint strength when FEW is applied to steel sheet joints. The relationship between joint strength and microstructure was investigated by observing the microstructure and fracture morphology of the joints.

2. Experimental method

2.1. Specimen and joining conditions

For the upper sheet, a 980 MPa-grade dual phase steel sheet of 0.15 mass% carbon consisting of ferrite (α) and martensite (M) with a thickness of 1.6 mm and a through-hole of 7 mm in diameter was used at the point to be joined. As mentioned above, in FEW, the upper sheet is joined by pinching it between the head
of the element and the lower sheet. On the other hand, since the lower sheet is friction-welded to the element, the joint strength is assumed to be affected by the composition of the lower sheet. Table 1 shows the carbon content, carbon equivalent, and tensile strength of the steel sheets used for the lower sheet. For the lower sheet, we focused on carbon, which is essential for high strength of steel sheets, and used six types of steel sheets with different carbon contents ranging from 0.07 to 0.30 mass%. All sheets are 1.6 mm thick. The joints made from each steel sheet are referred to as C07, C12, C14, C15, C20, and C30. After cold rolling, both steel sheets were furnace heated to the 2-phase region and quenched to obtain a 2-phase structure consisting of $\alpha$ and M. The joining equipment used was an EJOWELD CFF manufactured by EJOT. A schematic diagram of the element geometry used in this study is shown in Figure 1. The elements were steel elements with a diameter of 4.5 mm and a length of 5 mm from the bottom of the head to the tip of the shaft. The Vickers hardness at the shaft of the element is about 350 HV.

In prior examinations, joints were made under various joining conditions, and the joining conditions that did not cause fracture at the weld interface were selected when the chisel test was conducted in reference to JIS Z 3144. Joining conditions are shown in Table 2. Since there is a through-hole in the upper sheet, the penetration process in the upper sheet, which is generally used for joining steel and aluminum, is not included in this test condition. In STEP 1, impurities, such as rust-preventive oil adhering to the surface of the lower sheet are cleaned while deforming the tip of the element, in STEP 2, the element and the lower sheet are friction-welded, and in STEP 3, the joint is cooled by stopping rotation and holding pressure to achieve joining. Upset length indicates the amount of element indentation in each process. Therefore, under these joining conditions, a total of 3.4 mm is pushed in during STEP1 and STEP2 from the time the tip of the element contacts the top surface of the lower sheet until the joining is completed.

2.2. Strength evaluation and microstructural observation of joints

The cross tension test (JIS Z 3137), which is generally used to evaluate the peel strength of resistance spot welds, was used to evaluate the strength of the joint. The tensile speed was 10 mm/min. The CTS of the maximum load obtained from the test was used as the strength index of the joint, and the relationship between the carbon content of the lower sheet and the CTS was investigated.

The cross-sectional microstructure of the joints was observed using an optical microscope (OM) and a scanning electron microscope (SEM). The joint cross-sections were polished and corroded with Nital before each observation. For C20 and C30, the Vickers hardness distribution of the cross-section of the joint was measured. The measurement points were 0.2 mm inside the lower sheet from the mating surface of the steel sheets and ±4 mm from the center of the joint. The measurement load was 0.98 N and the measurement interval was 0.1 mm.

Of the joints that fractured in the cross-tension test, C12, C20, and C30, which have different fracture modes, were Nital corroded after polishing the cross sections and observed using an OM. For C30, fracture surface observation and cross-sectional observation using SEM were also performed to confirm the details of the fracture path.

3. Experimental results

3.1. Cross-sectional observation of joints

Since similar microstructural changes, deformation, and weld interface conditions were observed in the joints of all material combinations, only micrographs of C30 are shown in

| Table 1. Carbon content, Ceq, and tensile strength of lower sheets used. |
|-----------------|-----------------|-----------------|
| Carbon content (mass %) | Ceq (WES) | Tensile strength (MPa) |
|-----------------|-----------------|-----------------|-----------------|
| C07 0.07 | 0.42 | 600 |
| C12 0.12 | 0.56 | 985 |
| C14 0.14 | 0.58 | 1210 |
| C15 0.15 | 0.56 | 990 |
| C20 0.20 | 0.53 | 1270 |
| C30 0.30 | 0.63 | 1560 |

Ceq (WES) = C + Si/24 + Mn/8 + Ni/40 + Cr/5 + Mo/4 + V/14.

Figure 1. Schematic of the element.
Figure 2. The element passes through a through-hole in the upper sheet and was friction-welded to the lower sheet. It can be seen that the elements and the lower sheet have undergone significant plastic deformation as well as microstructural changes due to the thermal effects during joining. There were no joining defects at or around the weld interface, and good joining was achieved. Heat-affected microstructural changes were not observed in the upper sheets, which were mechanically joined by being pressed by the heads of the elements.

Figure 3 shows the results of SEM observation of the microstructures of the joints at B and C in Figure 2(b) and the base metal microstructure of C30. Note that only Figure 3(c) has a different magnification. This observation point is HAZ created by heating and cooling during joining inside the lower sheet. The base metal microstructure of the lower sheet used for C30 is a two-phase microstructure consisting of \( \alpha \) and M (Figure 3(a)). In region B, where the edge of the joint and its surrounding area are observed, it can be seen that the plastically deformed lower sheet is extruded above the surface of the lower sheet, forming the edge of the joint (Figure 3(b)). The area near the edge of the joint exhibited a microstructure consisting of M and \( \alpha \), which appeared to have been quenched from the two-phase region. C is the area where significant microstructural changes due to heat effects were observed by OM (Figure 3(c)).

The upper left of the C (Figure 3(c)) was in the direction of the weld interface and the
maximum temperature was higher, the temperature was lower toward the lower right. In the region D shown in Figure 3(c), where the maximum temperature in the C was considered to be high, a microstructure consisting mostly of a single phase M was observed, suggesting that austenite (γ) transformation was induced by heating to a temperature above AC$_3$ and then the alloy was quenched (Figure 3d). Next, in region E shown in Figure 3(c), a microstructure composed of M and α was observed, which was considered to be quenched after partially transformation to γ by heating to temperatures between AC$_1$ and AC$_3$ (Figure 3(e)). In region F shown in Figure 3(c), where the maximum temperature in C was considered to be low, tempered martensite (tM) and α in which the base metal was tempered were observed. It was considered that this region was heated to a temperature below AC$_1$. From this difference in microstructure, the maximum temperature during joining in region C can be written as a dotted line using AC$_1$ and AC$_3$ (Figure 3(c)). The lower sheets joined by FEW showed a large gradient of the maximum temperature and a variety of microstructures distributed over a narrow area. Hereinafter, the area where the maximum temperature is less than AC$_1$ and the microstructure-like region F is called a tempered area. The area where the maximum temperature is between AC$_1$ and AC$_3$ and the microstructure-like region E is called the intercritically quenched area. The area where the maximum temperature is AC$_3$ or higher and the microstructure like region D is called a quenched area.

3.2. Cross tension test results

Micrographs of C12, C20, and C30 after cross-tension tests are shown in Figure 4. The arrows in Figure 4 indicate the direction of crack propagation leading to fracture. Three types of fracture modes were observed in this study. The first type breaks at the head of the rivet as shown in Figure 4(a) (hereinafter referred to as Type A). Next, as shown in Figure 4(b), the joint is broken in the direction of the thickness of the lower sheet from the edge of the joint, similar to a plug failure in resistance spot welding (hereinafter referred to as Type B). Finally, as shown in Figure 4(c), the crack propagates along the inter-critically quenched area of the lower sheet and then breaks in the thickness direction, similar to a partial plug failure in resistance spot welding (hereinafter referred to as Type C). There was no fracture of the weld interface in any joints. It indicated that friction welding between the element and the lower sheet was performed well.

Figure 5 shows the relationship between CTS obtained by the cross-tension test and the carbon content of the lower sheet. The CTS of the joints with lower sheets which is relatively low carbon content (<0.20 mass %) was constant at 7.5–8.5 kN. The fracture mode was Type A. Compared to these joints, C20, which has a higher carbon content (0.20 mass %) in the lower sheet, showed a Type B fracture mode, but there was almost no decrease in CTS. At C30, which has the highest carbon content in

![Figure 4. Micrographs after cross tension test. (a) C12, (b) C20, and (c) C30.](image)

![Figure 5. Relationship between CTS and the carbon content of the lower sheets.](image)
this study (0.30 mass %), the fracture mode became Type C and the CTS decreased.

The load-displacement curves for each fracture mode in the cross tension tests are shown in Figure 6. When the fracture mode was Type A, load drop did not occur until the maximum load was reached. On the other hand, in the case of Type B, the load drop (green arrows) was observed just before the maximum load. The load drop indicated that a crack had initiated or propagated. In the case of Type C, several load drops were observed before the maximum load was reached, possibly due to crack initiation or propagation (red arrows). This result suggested that in the case of Type C, the load increased with repeated initiation, propagation, and cessation of cracks, leading to fracture as soon as the maximum load was reached.

The results of Vickers hardness tests on C20 and C30 joints are shown in Figure 7. Figure 7 also shows the fracture position in a cross-tension test of a joint made of the same steel sheet. In both joints, HAZ softened areas occurred. And the Vickers hardness increased toward the center of the joint. The reason was considered the increase in the M fraction due to the maximum temperature exceeding AC1. The Vickers hardness inside the element increased from an initial hardness of 350 HV to about 500 HV due to the heat effect during joining. The results of the correspondence between Vickers hardness and fracture location (arrows in Figure 7) showed that the C20 fractured in the tempered area, where the Vickers hardness was lower than that of the base metal. The C30 fractured in the inter-critically quenched area, where the Vickers hardness increased rather than in the HAZ softened zone.

3.3. Detailed observation of post-break joints

We focused on C30, whose CTS decreased as the carbon content of the lower sheet increased, and the cross-sectional observation results after the cross-tension test at the joint are shown in Figure 8. The observation points are G and H shown in Figure 4(c). Arrows in Figures 8(a,c) indicate voids. The fracture path shown in Figure 8(b) indicates that the crack propagated inside the inter-critically quenched area, which was once heated up to the two-phase temperature region and then quenched by FEW. The voids observed near the fracture surface were mainly formed in the \(\alpha\) region near the boundary between the hard phase M, and the soft phase \(\alpha\), and were considered to have grown and coalesced.

A Micrograph illustrating the fracture surface observation points at the C30 after the cross-tension test and the results of the fracture surface observation on the lower sheet side are shown in Figure 9. The observed areas were the fracture surfaces in the inter-critically quenched area. Although some brittle fracture surfaces were observed, dimples were observed on the entire fracture surface, suggesting that the fracture was mainly ductile. Therefore, the low CTS at C30 is not likely due to brittle fracture.

4. Consideration

In consideration, the mechanism of the significant decrease in CTS of the joint with 0.30 mass % carbon in the lower sheet is discussed. As mentioned above, a decrease in CTS with an increase in the tensile strength of the steel sheet, i.e. with an increase in the carbon content of the steel sheet, has also been reported as a problem in resistance spot welding [2]. The main cause is
reported to be a decrease in nugget toughness due to an increase in the carbon content of the steel sheet [3,4]. The decrease in the toughness of welds due to solidification segregation of P has also been reported as a cause of the decrease in CTS [3–6]. This test confirmed that the CTS decreased with an increase in the carbon content of the steel sheet even in FEW, but dimples were observed on the entire fracture surface (Figure 9), suggesting that the cause is different from that of resistance spot welding [4] in which a cleavage fracture surface or intergranular fracture surface is observed on the fracture surface. Solidification segregation of P is also not expected to occur because FEW is a solid phase bonding method. It should be noted that in C30, which has particularly low CTS, the crack propagated inside the inter-critically quenched area and then fractured (Figures 4(c), 8). These results suggested that the stress concentration near the edge of the joint corresponds to the inter-critically quenched area (Figure 3(b)) and may be caused by the superposition of the stress concentration in this area and the two-phase microstructure consisting of α and M formed by inter-critically quenching. On the other hand, in resistance spot welding, the microstructure of the edge of the corona bond or nugget, which is the stress concentration area in the cross tension test, is M. As a result, in resistance spot welds with low CTS showing interface failure, the nugget consisting of M structure is the fracture path and the inter-critically quenched area cannot be the fracture path. In this respect, the cause of the decrease in CTS is considered to be different between FEW and resistance spot welding.

Based on the results obtained from the observations, it is considered that in C30, which has particularly low CTS, the crack propagated through the inter-critically quenched area with dimples in the cross-tension test and reached the maximum load, leading to fracture.
In particular, the C30 case is characterized by cracking at a low load compared to the C20 case (Figure 6). Furthermore, it is noteworthy that many voids were observed at the boundary between M and $\alpha$ in the C30 (Figure 8). In general, it has been reported that when an external force is applied to the two-phase structure of steel consisting of hard and soft phases, strain concentrates in the soft phase and a large strain gradient is generated at the interface between the soft and hard phases, which is the starting point for void formation [24–26]. It has also been reported that this strain concentration in the soft phase is more pronounced when the hardness difference from the hard phase is large [25]. For example, it is known that the hole-expandability of steel sheets with a two-phase microstructure with a large difference in hardness is prone to cracking due to strain concentration in the soft phase, resulting in low hole-expandability [26–28]. It has been reported that hole expandability is correlated with local ductility [29], and a large hardness difference reduces local ductility. Therefore, it is expected that the local ductility was low in the inter-critically quenched area of C30 in this study as well, and it was inferred that this is the cause of the low load cracking in the cross-tension test and the low CTS. However, it is difficult to directly evaluate the local ductility of the inter-critically quenched area because the area of C30 is narrow, with a width of $\sim$180 $\mu$m (Figure 3(c)), and the M fraction varies depending on the maximum temperature. Therefore, the hardness difference between the hard and soft phases, which affects local ductility, was measured by nanoindentation. The nanoindentation method can be used to evaluate the hardness of the soft and hard phases, respectively because the specimen surface can be observed with a scanning probe microscope (SPM) using the indenter that performs the indentation. A Bruker Hysitron Tribo Indenter (TI900) was used for nanoindentation. Measurements were taken at room temperature using a load-controlled method. A Berkovich-type diamond indenter was used, and the loading and unloading rates were 100 $\mu$N/s. The maximum load was set to 1000 $\mu$N to make the indentation size measurable for the nanohardness ($H_n$) in each of the soft and hard phases. The center of the joints C20 and C30 was cut and polished so that the center of the joint could be observed. The specimen surfaces were slightly corroded by electropolishing to make each phase easier to identify by SPM. A schematic of the $H_n$ measurement points is shown in Figure 10. $H_n$ was measured at a depth of 0.35 mm from the surface of the lower sheet, at the position where the M fraction was $\sim$60% in the inter-critically quenched area, and at the quenched area and tempered area 0.3 mm away from that point. $H_n$ measurements were made at more than 10 points for each phase in each region.

$H_n$ of C20 and C30 measured by nanoindentation is shown in Figure 11. The values in Figure 11 show the mean values, and the error bars show the maximum and minimum values. Regardless of the carbon content, the hard phase tM is tempered in the tempered area, so the hardness difference from the soft phase is small. On the other hand, the hardness of M which is the hard phase increases significantly in the inter-critically quenched area, and the hardness difference from $\alpha$ is evident. It is also noteworthy that $H_n$ in the quenched area without a soft phase was higher but lower than M in the inter-critically quenched area. The reason for this was considered to be the higher carbon
content of M in the inter-critically quenched area because of the partitioning of carbon to \( \gamma \) when heated to the two-phase region.

From these results, it can be inferred that the hardness difference in the inter-critically quenched area is significantly larger and the local ductility is reduced. Comparing the \( H_n \) in the inter-critically quenched area between C20 and C30, there is no difference in the \( H_n \) of \( \alpha \), but there is a large difference in the \( H_n \) of M between the two. It can be seen that the \( H_n \) of M in C30 is higher than that of C20. As the result, the difference in hardness of C30 is large. Specifically, the difference in hardness at C20 was 3.3 GPa, and at C30 it was 4.6 GPa. Since the hardness difference of C20 was small, the local ductility in the inter-critically quenched area was relatively high, and it is considered that the specimens fractured in the HAZ softening zone rather than in the inter-critically quenched area. In contrast, a large hardness difference exists in the inter-critically quenched area of C30, which is expected to indicate low local ductility in this area. As the result, it was considered that ductile cracks initiated and propagated at relatively low loads in the C30 inter-critically quenched area, and the CTS was decreased. In addition to this reason, since the C30 was harder than C20, it is possible that the edge of the joint was less plastically deformed than C20 during the cross-tension test, resulting in a relatively high-stress concentration.

5. Concluding remarks

In this study, we focused on FEW, a solid-phase bonding method, to improve the strength of the joints of high-strength steel sheets.

The CTS of upper steel sheets with through-holes and six types of lower steel sheets ranging from 0.07 to 0.30 mass % joints were evaluated. The relationship between joint strength and microstructure was discussed by investigating the microstructure and fracture morphology of the joints. The findings obtained are presented below.

1. In the HAZ of the lower sheet joined by FEW, the region where M single-phase was formed by quenching (quenched area), the region quenched from the two-phase temperature region (inter-critically quenched area), and the region tempered (tempered area) were observed.

2. In the cross-tension test, when the carbon content of the lower sheet was lower than 0.20 mass %, the joint fractured at the head of the element and the CTS was high. However, as the carbon content of the lower sheet increased, the fracture mode changed from the mode in which the HAZ softening zone mainly fractured in the thickness direction (0.20 mass %C) to the mode in which the crack propagated along the inside of the inter-critically quenched area and then fractured in the thickness direction (0.30 mass %C), resulting in a decrease in CTS.

3. When the carbon content of the lower sheet with low CTS was 0.30 mass %, the difference in hardness between \( \alpha \) and M in the inter-critically quenched area was significantly large, and voids formed at the interface between the two phases during the cross-tension test, causing crack growth with dimples in the inter-critically quenched area. In other words, the low
local ductility in the region was inferred to be the cause of the lower CTS.

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