1. Introduction

In recent years, Advanced High Strength Steels have been widely used for the manufacture of both traditional fuel vehicles and new energy vehicles to improve the fuel efficiency, reduce the emission of CO\textsubscript{2}, achieve the safety requirements in car crash measurements, and expand the range of the distance. With excellent strength and good formability, hot-stamping steels—a kind of AHSS—have been applied to the fabrication of car body components, such as B-pillars, reinforcements, bumpers, roof rails, rocker rails, and tunnels.1–3) Resistance projection welding (RPW), which localizes current flow and heat input by a predetermined projection on one of the parts, is a variation of resistance spot welding. The RPW of nuts to steels is widely used for the assembly of the front axles, rear axles, the seatbelt, and steering columns to reduce loose automobile components and improve the assembly quality. However, the Al–Si coating, which is uneven, discontinuous, and porous after hot stamping, causes unstable welding quality when welding nuts to hot-stamping steels using traditional spot welding processes and equipment.4,5)

Though the RPW of nuts is widely applied in vehicle manufacturing, home appliances, electronic equipment, and other equipment, fewer published papers focus on the RPW of nuts in the open literature. Tolf6) studied the resistance projection welding of three different types of nut welds to high- and ultra-high-strength thin steel sheets with alternating and direct currents. They concluded that the strength of the joints with alternating current was superior and the acceptable current ranges of alternating current were wider compared to direct current because the alternating current build-up, which affects the heat capacity, is more rapid than that of the direct current. They also found that joints were formed by forged welding due to the existence of Al–Si coating. Ringsberg7) investigated the fatigue of the RPW of nuts to sheet steels. They found that the fatigue crack started off on the side of the sheet whose microstructure was changed during the welding process. In the investigation of Nielsen,8) they analyzed the collapse of the projections of the square weld nuts by numerical analysis and experimental trials, and the results indicated that the friction between weld nuts and sheet plates delayed the collapse of the nut projections. Lim9) studied the effect of nut materials on the fracture behavior of resistance nut welding. They concluded that the fracture loads and failure mode characteristics of joints can be considered as an indication of the weldability of the nut’s materials. WANG10) in their work, investigated the effect of welding conditions on the hardness of the fusion zone and the fracture mode of welds. They found that the hardness distribution tends to be homogeneous with the increasing
welding current and welding time.

The above published works mainly focus on the resistance projection welding of square weld nuts, round weld nuts, and hexagonal weld nuts with alternating current welding or direct current welding. Fewer published works pay attention to the RPW of nuts with capacitor discharge welding (CDW) though the use of CDW is risen. Figure 1(a) shows the pulse welding current waveform of CDW. The welding time is extremely short about 18–30 ms, which is beneficial to reduce heated affect of threads. The rapid build-up of welding current (reaching peak value in milliseconds) is helpful to melt and remove the Al–Si coating of hot-stamping steel. Meanwhile, fewer research works focus on the RPW of T-shaped weld nuts, though this type of weld nut had already been welded to B-pillars, as shown in Fig. 1(b). Therefore, further research on the RPW of T-shaped nuts to hot-stamping steel with capacitor discharge welding (CDW) is required. This paper investigates firstly the microstructure evolution of the weldment under the CDW process. Then, the failure modes and mechanisms of the joints are studied.

2. Experimental Procedures

Usibor1500 hot-stamping steel sheets were used in this study with a 1.5 mm thickness and 30 mm × 30 mm dimensions. The hot-stamping steel exhibits a full lath martensitic microstructure after the forming process. There are Al–Si coatings on these steels to avoid oxidation. The T-shaped weld nuts with zinc-coats were selected for this experiment. The projections of these nuts are solid-projections and their dimensions are reported in Fig. 2. The base material of these nuts is Q235A. The chemical compositions and mechanical properties of Usibor1500 and the weld nut are presented in Tables 1 and 2.

All welding operations were conducted using a 15000J, pedestal type capacitor discharging welding (CDW) machine with a pneumatic force system. The welding electrodes were made from the RMAW Class II chromium-zirconium-copper material. Figure 3(a) shows a real image and schematic diagram of the experimental setups. As can be seen, in order to locate the weld nuts and sheets accurately, an insulating centering pin, which was supported by a spring, was designed on the bottom electrode, and there was a gap between the pin and the electrode. When the welding force was applied, the center was pressed down and the gas blew out through the gap to protect the thread of the nut from the splash. The electrode forces were kept constant at 9 400 N and the capacitors were 15 × 0.002 F. The welding voltage increased from 360 V to 570 V with a step of 30 V. The RMS current, peak current, and welding time were measured using the Rogowski coil.

The mechanical properties of the joints were tested using a CMT5105 universal testing machine at a rate of 5 mm/s. The fixture for the pull-out test is presented in Fig. 3(b). The maximum pull-out force from the load versus displacement curve is defined as the pull-out strength. The cross-section

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**Table 1.** The chemical compositions of Usibor1500 and the weld nut.

<table>
<thead>
<tr>
<th>Materials</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Al</th>
<th>Ti</th>
<th>B</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>USIBOR1500</td>
<td>0.221</td>
<td>1.211</td>
<td>0.019</td>
<td>0.003</td>
<td>0.258</td>
<td>0.036</td>
<td>0.039</td>
<td>0.003</td>
<td>0.191</td>
</tr>
<tr>
<td>T-shape weld nut</td>
<td>0.239</td>
<td>0.444</td>
<td>0.013</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>–</td>
<td>0.0006</td>
<td>0.038</td>
</tr>
</tbody>
</table>

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**Table 2.** The mechanical properties of Usibor1500 and the weld nut.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Yield strengths (MPa)</th>
<th>Tensile strengths (MPa)</th>
<th>Elongations (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usibor1500</td>
<td>1 100</td>
<td>1 500</td>
<td>6–7</td>
</tr>
<tr>
<td>Weld nut</td>
<td>235</td>
<td>375–460</td>
<td>&lt;26</td>
</tr>
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</table>
samples for the metallurgical examination and the hardness measurement were polished mechanically and etched with a 4% Nital solution according to the standard metallurgical process. The microstructure and fracture morphology were studied by a Lecia DM15000M optical microscope and Quanta200 scanning electron microscopy (SEM). The hardness profiles of the joints were measured by a Vickers microhardness tester with a load of 200 g and time of 15 s.

3. Results and Discussion

3.1. Microstructures and Hardness Profiles

Figure 4 shows a typical optical cross-section microstructure of the welded joint under the welding conditions of a welding force of 9 400 N and a welding voltage of 450 V. Due to the effects of the temperature gradient during the welding process, the heterogeneous microstructure is divided into three distinct zones: the fusion zone (FZ), the heat affected zone (HAZ) and the bulk material (BM), respectively. The projections are collapsed down and pressed into the Usibor1500 side. The columnar grain structures in the FZ are observed. Due to the rapid cooling rate and the splash which caused the reduction of the molten metal, a shrinkage was formed in FZ.

HAZ undergoes austenitization and recrystallization, and the microstructure of HAZ changes complexly in different zones. The HAZ is further divided into three different sub-regions: A, B, C, on the sheet side, and D, E, F on the nut side. Figure 5(a) shows the fully lath martensitic microstructure of ‘A’. The microstructure of ‘B’ is composed of ferrite and martensitic, as displayed in Fig. 5(b). The ‘C’ region was close to the BM of the sheet, and the microstructure of this region was made of tempered martensitic, as shown in Fig. 5(c). The microstructure of ‘D’ consists of martensitic, ferrite, and a little bainite as shown in Fig. 5(d). Figure 5(e) shows that the microstructure of ‘E’ is ferrite and pearlite along the grain boundary. The ‘F’ region near the BM of the nut, and Fig. 5(f) indicates that some small equiaxed ferrite are found.

Figure 6 shows the hardness profiles of the welded joint in the horizontal and vertical directions along the white dotted line in Fig. 4. As can be seen in Fig. 6(a), the hardness of the FZ and sub-HAZ region ‘A’ are the same with a value of 562.21 HV, which is higher than the hardness of the BM with a value of 518.68 HV. Prominent softening regions whose hardness value is lower than the base material are observed on the ‘B’ and ‘C’ regions on the sheet side, attributed to the ferrite and tempered martensitic microstructure. On the weld nut side, the softening regions are not found and the hardness of HAZ reduces from 444.91 HV to 213.17...
HV (the hardness of the BM).

3.2. Stress Analysis of Welded Joint

Figure 7 shows the schematic diagram of the load conditions and stress distributions of the welded joints. The welded joint is divided into two parts: the outside part marked by the color yellow and inside part marked by the color blue, respectively, as Fig. 7(a) shows. As the hardness of the FZ and ‘A’ region on the sheet side is almost two times larger that of the soften regions, the welded joint is idealized as a rigid body marked by the color red.\textsuperscript{11,12)} Figure 7(b) shows a schematic diagram of the force conditions of the welded joint. The joint circumferential surface is subjected to a shear stress $\tau$ and the faying surface is subjected to a tensile stress $\sigma$ during the pullout test. However, the sheet close to the outside part of the joint experiences large plastic bending deformation which leads to the uneven distribution of shear stress along the joint’s circumferential surface.\textsuperscript{13,14)} Figure 7(c) presents the shear stress and tensile stress distributions, respectively. The shear stress on the outside part is higher than on the inside part, and the tensile stress on the faying face of the outside part is higher than that on the inside part, respectively.

3.3. Failure Mode and Mechanism

Based on the observations of the welding samples after a destructive test, the failure modes of the joints are classified into three basic modes: the interfacial failure (IF) mode, the pull-out failure (PF) mode, and the projection failure mode. The crack initiation and propagation of these modes are quite different and the weld joint has distinct failure behaviors dependent on the failure mode.

3.3.1. IF Mode

Figure 8 displays the macro fracture surface view and micrograph of the cross-section of the joint that failed in the interfacial failure mode.
IF mode. The fracture surface is divided into the outside and inside parts, respectively, according to the stress analysis. The outside part is flat, compared to the inside part, and has many small shiny pieces. Figure 9(a) (a magnification view of ‘A’ in Fig. 8) shows that a small part of the material of the sheet was pulled out around the edge of the joint. The fracture surface of this region has dimples. Figure 9(b) (a magnification view of ‘B’ in Fig. 8) shows that the small shiny pieces on the outside part are large and smooth cleavage surfaces. The cleavage face is surrounded by small equiaxed and shallow dimples. These results reveal that the crack generates in the outside part mainly in the ductile behavior. Figure 9(c) is the magnified view of the transition region ‘C’ in Fig. 8. The fracture surface of the inside part is coarser and the fracture morphology of this area is predominant of the cleavage river pattern, which indicates a brittle failure behavior. Therefore, the fracture of the joints in the IF mode is a combination of ductile and brittle fracturing.

Based on the above SEM results and tensile stress distributions on the faying surface, the difference of the fracture surface and failure behavior on the outside and inside parts are attributed to uneven distributions of tensile stress on the faying surface. Prior to the failure, microvoids form and grow into cracks on the faying surface of the outside part because of the higher tensile stress. When the crack is formed in the outside part, there is a high stress concentration at the front crack and the crack tends to propagate with a brittle failure behavior through the inside part, finally.

3.3.2. PF Mode

Figure 10 exhibits a joint that failed in the pullout mode and the cross-section micrograph of the failure joint. A similar failure mode was observed in the cross tension test of a spot welding joint by Asme13) and Sawanishi.15) The welded joint, like a circular cylinder, is torn out from the sheet. The arrow indicated the maximum shear stress location according to the shear stress distribution in Fig. 7(c). Figure 11(a) shows the microfracture surface of region ‘A’ in Fig. 10 by SEM. Many small elongate dimples and shear slip planes were clearly observed. Large torn bands,16) which are a typical quasi-cleavage fracture feature, are found at region ‘C’ in Fig. 11(c). Yet, the fracture micromorphology of region ‘B’ displays typical cleavage fractures in Fig. 11(b). Thus, according to the shear stress distribution and fracture morphology analysis results, the failure mechanism of the pullout mode is clearly that of a fracture that initialized from the maximum shear stress location in the outside part of the nugget with a ductile behavior and propagates along the joint’s circumferential boundary with a brittle behavior.

3.3.3. Projection Failure Mode

As the projection cannot be collapsed completely, there is a gap between the nut and the sheet, as displayed in Fig. 12(a). Two sharp notches were formed at the edge of the joint as the partial molten metal was extruded out from the fusion zone and the projection deformed largely during the welding process. The notch around the joint causes stress concentration and initiates the cracks. Figure 12(b) is a low magnification overall view of the joint that failed in the projection failure mode. The fracture surface feature is uniformed, which reveals that the crack generates with the same failure mechanism throughout the whole joint. Figure 12(c) presents a cross-section micrograph of the fracture.
The crack propagates along the HAZ near the base material of the weld nut because the strength of the BM of the nut is lower than that of other region according to the hardness results which indicate the strength level. The large and smooth cleavage face and river pattern are observed in a high magnification view of the fracture surface, as shown in Fig. 12(d). These results indicate that the welded joint fails in typical brittle behavior.

3.4. The Effect of Shrinkage on Fractures

The formations of the shrinkage and solidification cracks reduce the joint strength.\textsuperscript{17,18) To determine how these defects impact the failure of joints, Fig. 13(a) presents a typical fracture morphology of a joint that failed in the IF mode with the shrinkage void. Similar to the IF mode, the fracture surface of the outside part has small dimples with tear edges (Fig. 13(b)). However, the partial weld nugget was pulled out and shrinkage can be seen at the center of the weld nugget. Predominant dendrite structures and solidification cracks were displayed in Figs. 13(c), 13(d). The cleavage fracture features were found at the edge of the void, as displayed in Figs. 13(e), 13(f). These results suggest that the shrinkage and solidification will change the crack propagation path in the IF mode. The crack does not extend along
3.5. The Effect of Welding Voltage on Fractures

Resistance nut welding is multipoint welding. There are four RPW joints on each welding sample. However, the joints may fail in different failure modes when the input energy of welding is insufficient. Figure 15(a) displays this result when welding voltage 420 V. Joint 1 and 3 failed in IF mode. Joint 2 failed in PF mode. Joint 4 failed in projection failure mode. As the welding voltage increases, the welding energy ensures that four joints of welding samples are welded well at the same time, and the pullout strength increases (Fig. 14). When welding voltage exceeds 450 V (included 450 V), the welded joints fail in mix mode which means that the fracture of joint include both PF mode fracture and IF or projection failure mode fracture, as Figs. 15(b), 15(c) shown. In Fig. 15(b), joint 1 firstly failed in PF mode and the shear cracks produced around the outside part of joints. But, the joint finally failed in IF mode. And Fig. 15(c) exhibits joints failed in PF mode and projection failure mode. As can be seen, partial welded joint was torn out from the sheet, but the joint eventually failed in projection mode.

4. Conclusions

(1) Columnar grain structures and large lath martensitic microstructures were found on the FZ with a hardness of 562.21 HV. Predominant softening occurs on the Usibor1500 side attributed to the ferrite and tempered martensitic on HAZ. On the nut side, softening regions are not found and the hardness of the HAZ reduces from 444.91 HV to 213.17 HV.

(2) The resistance projection welding joints have three main modes of failure: the interfacial failure mode, the pullout failure mode, and projection failure mode. In the IF mode, dimples and cleavage faces are found on the fracture surface. The cracks propagate along the faying surface with both the ductile and brittle behavior. In the PF mode, the crack initializes in the max shear stress region in a ductile way, but extends around the welded joint in a brittle way. The projection failure is a full brittle rupture.

(3) The solidification crack around the shrinkage void changes the crack propagation path and induces a brittle rupture.

(4) When the welding voltage exceeds 450 V, the weld joint tends to fail in a mix mode: pullout failure and interfacial failure or pullout failure and projection failure. The shear crack can be seen on each joint, but the joint fails in the IF mode or the projection failure mode, finally.

Acknowledgements

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REFERENCES