

Effects of Electrode Combinations on RSW of 5182-O/AlSi10MnMg Aluminum

The weld nugget size, weld morphology, and weld performance during RSW of dissimilar aluminum alloys were studied

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Abstract

Aluminum is a key lightweight material for reducing vehicle weight and improving fuel efficiency and is used in wrought, extruded, and cast forms. There is little research on resistance spot welding (RSW) of wrought-to-cast dissimilar aluminum alloys. For this paper, two types of electrodes were developed, and 2.3-mm 5182-O wrought and 4-mm AlSi10MnMg die cast sheets were welded by RSW with different electrode combinations. The results demonstrate that electrode geometry significantly influences the weld nugget morphology, weld performance, and failure mode. The proprietary Newton ring electrode produces the largest weld nugget size and consistent weld performance. Through the optimized electrode combination, severe weld nugget migration problems can be addressed for RSW of dissimilar aluminum alloys. Furthermore, the fracture crack under the tensile shear load always starts from the AlSi10MnMg side but not on the 5182-O side due to work hardening and concentration of stress regardless of whether the welds failed in the interfacial failure or pullout failure modes.

Keywords

- Resistance Spot Welding
- Tensile Shear Strength
- Microstructure
- Failure Mode
- Sheet Aluminum
- Casting Aluminum

Introduction

Intensified global warming has forced countries around the world to place stringent regulations on the automotive industry to reduce carbon dioxide emissions and improve vehicle fuel efficiency. This is being done, in part, by introducing a large amount of lightweight material into vehicles to reduce their weight (Ref. 1). With respect to excellent strength-to-weight ratio and excellent corrosion resistance, aluminum alloys, which are present in wrought, extruded, and cast forms, play a key role in lightweighting car bodies (Refs. 2–4). Among various aluminum alloys, the Al-Si casting alloy is widely used because of its good casting performance, corrosion resistance, air tightness, and sufficient mechanical properties (Ref. 5). Its weldability has been studied in different welding processes, including gas tungsten arc welding (Ref. 6), gas metal arc welding (Ref. 7), laser beam welding (Refs. 8, 9), and friction stir welding (Refs. 10, 11).

Resistance spot welding (RSW) is one of the main joining solutions in the automotive industry due to its low cost, reliability, high speed, ease of operation and automation, and suitability for high-volume production (Ref. 12). In the past, many efforts were made to study RSW's process parameter effects on the mechanical properties and failure modes of wrought aluminum welds, and the results showed that the weld nugget size had a significant impact on failure modes (Refs. 13–15). However, there are few studies on RSW of cast aluminum alloys. General Motors studied the fatigue behaviors of Aural-2 die casting sheet with a proprietary multi-ring domed (MRD) electrode. The results indicated that the nugget size corresponded to fatigue life (Refs. 16, 17). To the best of our knowledge, a clear relationship between joint microstructure and static performance has not been proven. Furthermore, a dissimilar material combination with unequal thickness is frequently used in actual automotive production. Compared to a similar material combination with equal thickness, performing RSW on a dissimilar material combination having unequal thick-

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Fig. 1 — The welding conditions and structure of the three types of electrode combinations.

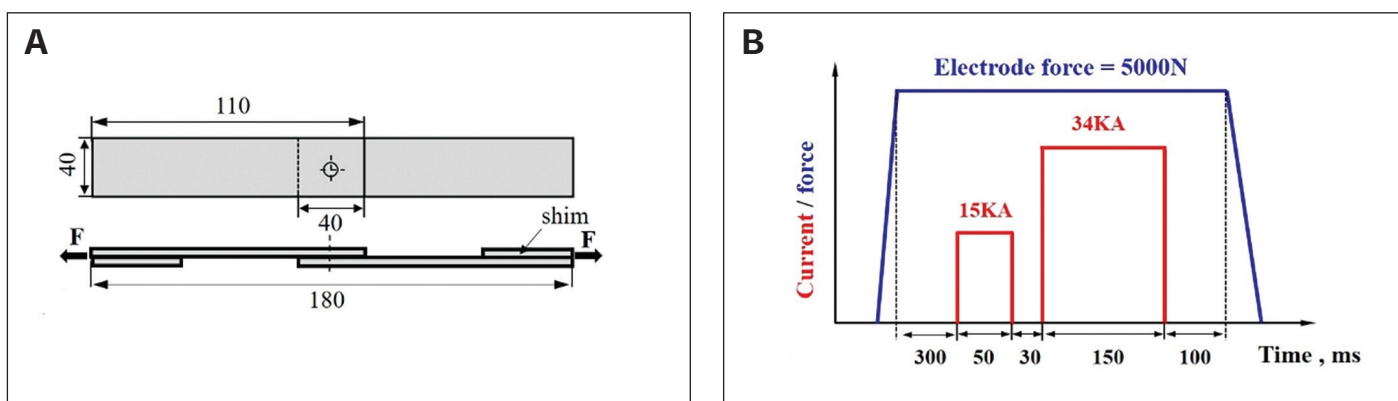


Fig. 2 — A — Schematics of the tested specimen geometries and dimensions for the tensile shear test; B — the welding schedule.

ness is more complicated. And the joints are expected to show different failure behaviors due to the large difference in physical, chemical, and mechanical properties and the microstructure of various types of materials. Therefore, it is important to study the effects of welding parameters on the weld nugget size and solve the problem of the weld nugget migration for RSW of dissimilar materials (Refs. 18–20). Electrode geometry has a huge impact on micromorphology and mechanical properties of the joints (Refs. 21–23) and provides a potential way to solve the weld nugget migration challenge for RSW of dissimilar material combinations.

The purpose of this study was to investigate the effect of various electrode combinations on the weld nugget size, weld morphology, and weld performance during RSW of dissimilar aluminum alloys. Two types of electrodes were developed. One was the proprietary Newton ring (NTR) electrode having a concave center, and the other was a dome-shaped electrode having a 100 mm radius (R100). The 2.3-mm 5182-O wrought and 4-mm AlSi10MnMg cast aluminum alloys were welded with NTR/NTR, R100/R100, and R100/NTR electrode combinations. The microstructures, mechanical properties, and failure behaviors of the joints were investigated.

Experimental Procedure

Materials and Welding Processes

Both 2.3-mm 5182-O wrought and 4-mm AlSi10MnMg cast aluminum alloy sheets were selected. The nominal chemical compositions and mechanical properties are given in Table 1. A RSW machine with a servo gun was used to weld the sheets. It provided a stable direct current (DC) with a frequency of 1000 Hz. The welding conditions and the electrode morphologies and combinations are shown in Fig. 1. The composition of the electrode was Cu-Cr-Zr alloy. Aluminum alloy sheets were cut into dimensions of 110 × 40 mm, and the overlap length was set to 40 mm in accordance with Japanese Standards Association JIS Z 3136, *Specimen Dimensions and Procedure for Shear Testing Resistance Spot and Embossed Projection Welded Joints*. The tensile shear test specimen geometry is shown in Fig. 2A. Prior to welding, acetone was used to clean oils and dirt off the sheet surfaces. The 5182-O aluminum alloy was located on the positive side of the welding power source. The weld schedule was set as shown in Fig. 2B. A preheat pulse current was applied before the main welding current to improve welding process stability (Ref.

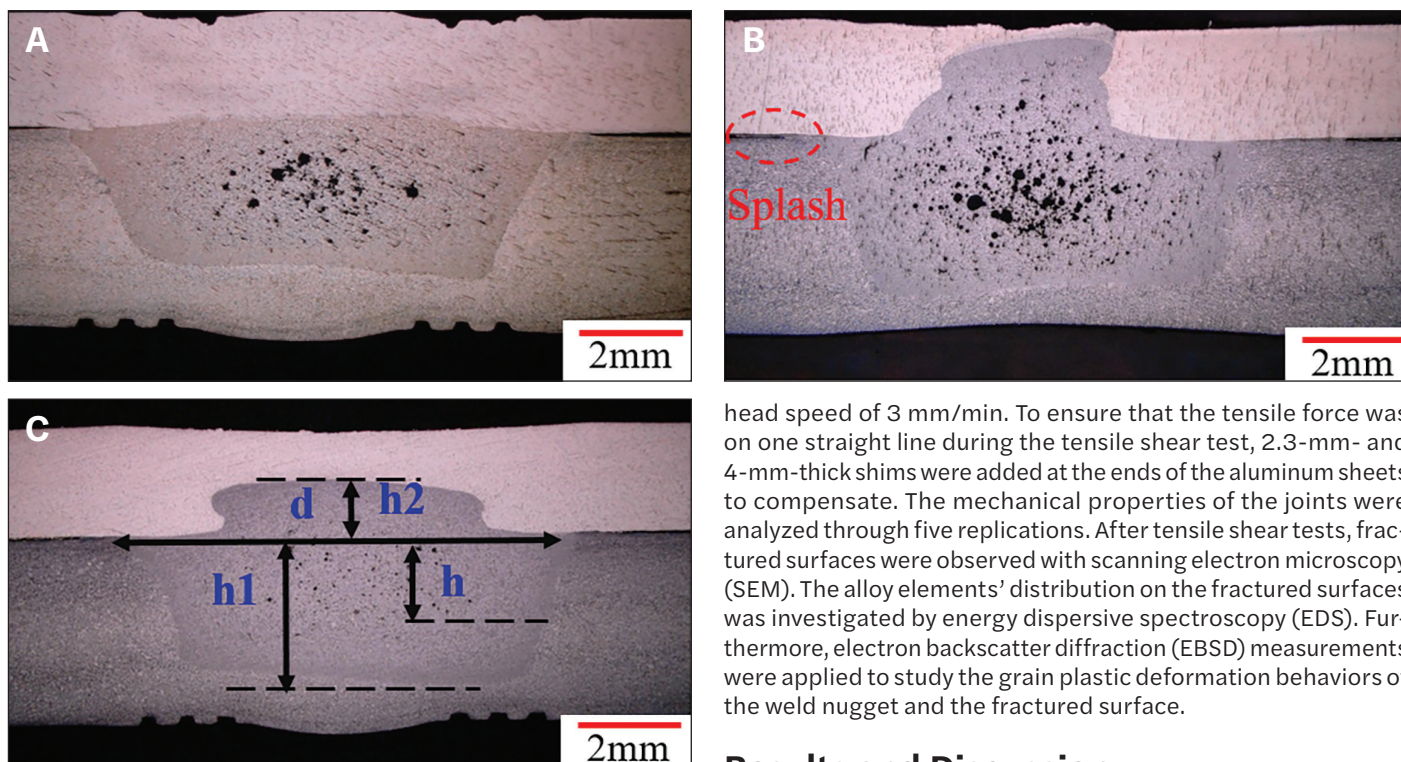


Fig. 3 — Cross-sectional views of the weld nuggets produced by different electrode combinations. A — NTR/NTR; B — R100/R100; C — R100/NTR.

24). The applied electrode force was 5000 N, squeeze time was 300 ms, preheat current was 15 kA for 50 ms, weld current was 34 kA, welding time was 150 ms, cool time was 30 ms, and hold time was 100 ms. Water was applied as a cooling agent at a flow rate of 4 L/min.

Microstructure and Tensile Shear Test

The metallographic specimens were made by transversely cutting the welded joint through the weld center. Then, they were mounted, ground, and polished in sequence. The etching with Keller's reagent (95 mL water, 2.5 mL HNO_3 , 1.5 mL HCl, and 1.0 mL HF) was successively used to reveal the microstructure of the welded joint. All samples were cleaned for 20 min in an ultrasonic bath using ethanol. Three replications were conducted with each combination and were used for microstructure study observed by standard optical and stereo microscopes (KEYENCE VHX-6000). A standard SUNS-UTM5105 tensile test machine with a 100-kN load capacity was used. All tests were carried out using a cross-

head speed of 3 mm/min. To ensure that the tensile force was on one straight line during the tensile shear test, 2.3-mm- and 4-mm-thick shims were added at the ends of the aluminum sheets to compensate. The mechanical properties of the joints were analyzed through five replications. After tensile shear tests, fractured surfaces were observed with scanning electron microscopy (SEM). The alloy elements' distribution on the fractured surfaces was investigated by energy dispersive spectroscopy (EDS). Furthermore, electron backscatter diffraction (EBSD) measurements were applied to study the grain plastic deformation behaviors of the weld nugget and the fractured surface.

Results and Discussion

Weld Morphology

Different electrode combinations produced various weld morphologies. Figure 3 shows the cross-sectional views of the typical welds obtained by NTR/NTR, R100/R100, and R100/NTR electrode combinations. As shown in Fig. 3A–C, the fusion zone in the weld was mainly concentrated on the AlSi10MnMg side. It was apparent that the NTR/NTR weld showed a severe weld nugget migration, and only shallow weld penetration was observed in the 5182-O side. By using the R100/R100 and R100/NTR electrode combinations, the weld nugget migration issue was suppressed. Compared to the R100/R100 electrode combination, the R100/NTR electrode combination generated more-uniform weld morphology in the 5182-O.

In conventional RSW, the weld nugget diameter (D) is at its maximum at the joint interface. The maximum weld penetration depth on the AlSi10MnMg side and 5182-O side are defined as h_1 and h_2 , respectively. Furthermore, the distance between the melting center and the joint interface is defined as h , which can be calculated as follows:

Table 1 — Chemical Composition of 5182-O Wrought and AlSi10MnMg Casting Aluminum Alloys (wt-%)

Element	Chemical Composition, wt-%									Mechanical Properties		
	Zn	Mg	Cr	Cu	Fe	Si	Ti	Mn	Al	YS, Mpa	UTS, Mpa	EL, %
5182-O	≤0.25	4–5	≤0.1	≤0.15	≤0.35	≤0.2	≤0.1	0.2–0.5	Bal.	110	255	12
AlSi10MnMg	<0.00	0.266	0.0052	<0.00	0.125	10.89	0.063	0.89	Bal.	147	312	8

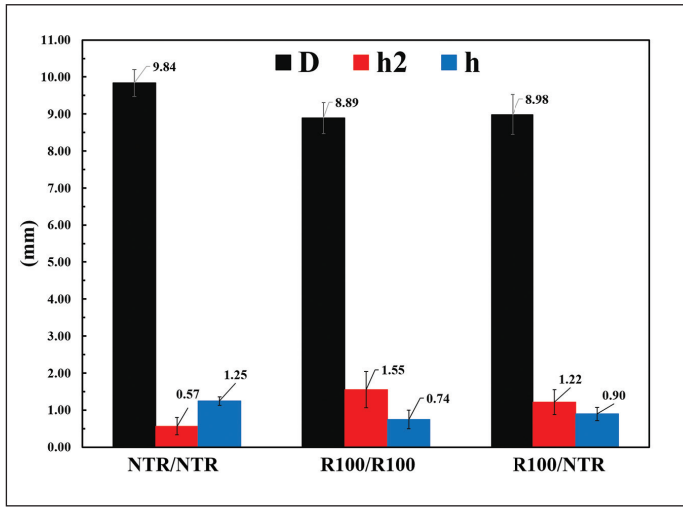


Fig. 4 – The weld nugget size measurements of D, h, and h2 with different electrode combinations.

$$h = h_1 - \frac{h_1 + h_2}{2} = \frac{h_1 - h_2}{2} \quad (1)$$

Figure 4 shows the measured value of the weld nugget size of D and h for different electrode combinations. The average maximum D of 9.84 mm was generated using the NTR/NTR electrode combination, and the minimum D of 8.89 mm was produced by the R100/R100 electrode combination. It can be clearly seen from Fig. 3B that expulsion was produced at the bonding interface when using the R100/R100 electrode combination. Due to the generation of expulsion, the weld nugget could not be fully grown. Therefore, D with the R100/R100 electrode combination was the smallest. This shows that the NTR electrode can help prevent the molten weld from expulsion and produce a larger weld nugget, which is consistent with the results of a previous study (Ref. 21). In addition, the volume of the melted metal on the 5182-O side was the largest, with h2 reaching up to 1.55 mm when the R100/R100 electrode combination was used. When using the NTR/NTR electrode, h2 was only 0.57 mm. This demonstrates that using different electrode combinations can control the weld nugget morphology and suppress the weld nugget migration issue when RSW materials with different thicknesses or different physical characteristics, such as wrought to cast aluminum alloys.

Nucleation Mechanism

During the RSW process, the heat of the molten metal (Q) is the heat generation (Q_1) minus the heat dissipation (Q_2), which can be expressed as

$$Q = Q_1 - Q_2 = I^2 R t - Q_2 \quad (2)$$

where Q is the heat of the molten metal, I is the welding current, R is the resistance of the weldment, and t is the duration of the current.

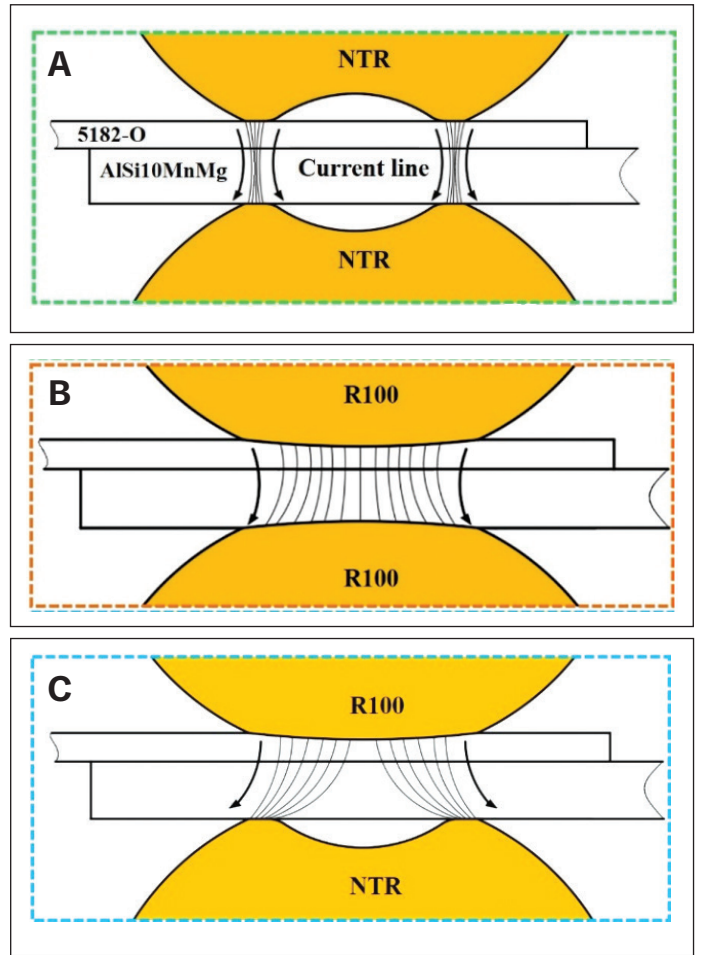


Fig. 5 – Schematics of the initial distribution of the current line. A – NTR/NTR; B – R100/R100; C – R100/NTR.

It should be mentioned that the resistance (R) is not constant during RSW of aluminum alloys; it varies with the temperature and aluminum sheet surface conditions. Here, the Q_1 was also approximately used to explain the morphology difference produced by various electrode combinations. Alloy 5182-O was thinner than AlSi10MnMg, so the Q_2 was higher. The R of AlSi10MnMg was higher than 5182-O (the resistivity was basically similar [Refs. 25, 26]), and so Q_1 in the AlSi10MnMg cast sheet was higher than in the 5182-O wrought sheet. Under these welding conditions, Q generated on the AlSi10MnMg side was higher than on the 5182-O side, and the fusion zone was larger. Therefore, the weld nugget was biased to the AlSi10MnMg side. As shown in Fig. 3, the distribution of the molten metal during solidification can be obtained by analyzing h. The larger h is, the closer the melting center is to the AlSi10MnMg side. When using the NTR/NTR electrode combination, D and h were larger, so the temperature field distribution was flatter. But the heat was more concentrated in the center when using the R100/R100 electrode combination. This is mainly determined by the nucleation process. The possible initial distribution of the current line is schematically shown in Fig. 5 according to Refs. 21, 23, which used high-speed cameras to monitor online the start of nucleation and the weld formation during RSW of similar aluminum alloys with NTR electrodes.

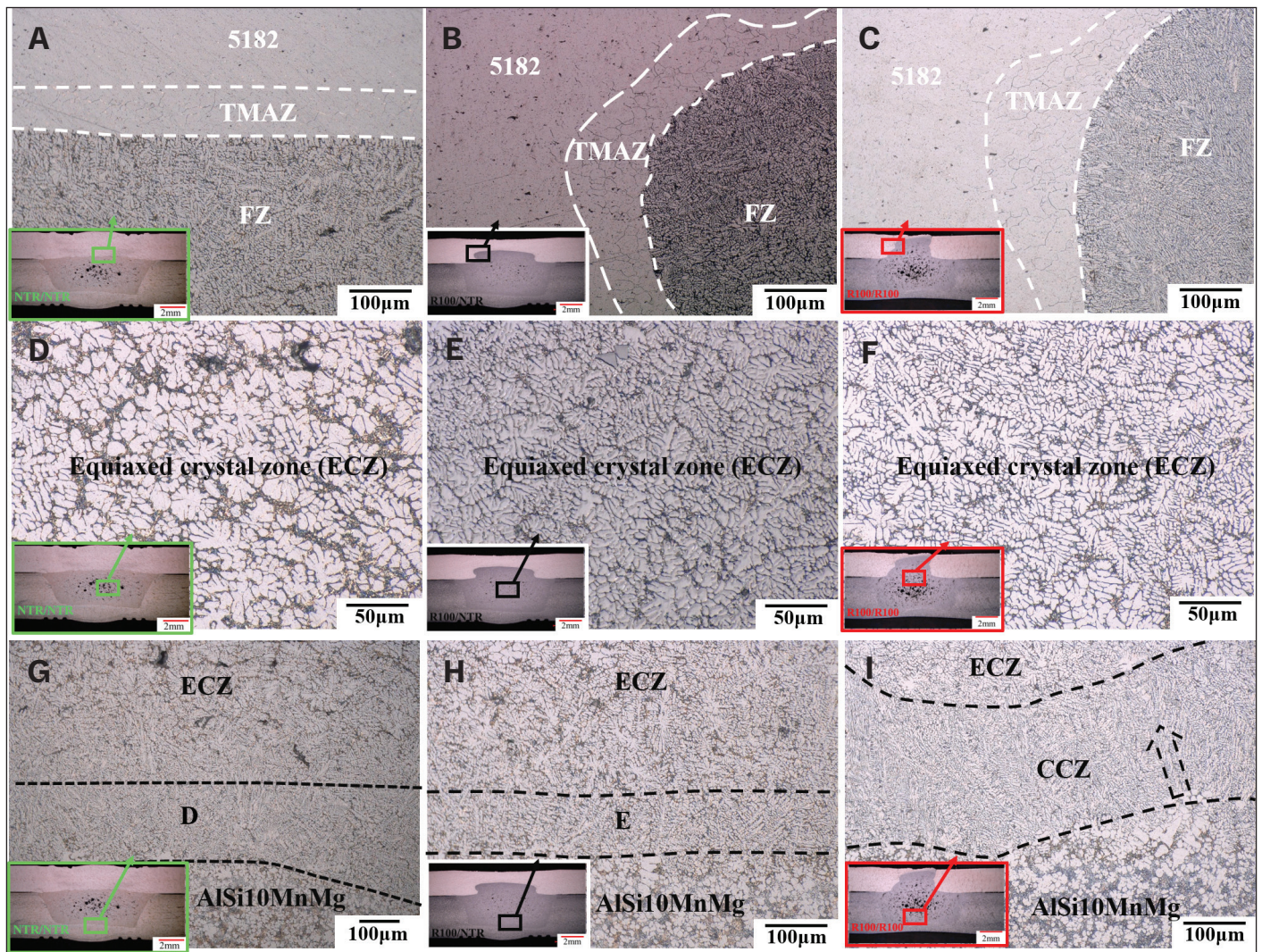


Fig. 6 — Microstructures of the weld obtained by different electrode combinations. A — TMAZ in the weld by NTR/NTR; B — TMAZ in the weld by R100/NTR; C — TMAZ in the weld by R100/R100; D — ECZ in the weld by NTR/NTR; E — ECZ in the weld by R100/NTR; F — ECZ in the weld by R100/R100; G — CCG in the weld by NTR/NTR; H — CCG in the weld by NTR/NTR; I — CCZ of the nugget by R100/R100.

When using NTR/NTR, the periphery of the electrode first contacted and melted the metal, and then the heat was gradually conducted toward the center to form a complete nugget. When using the R100/R100 electrode combination, the center of the electrode first contacted the aluminum sheets, and the weld formed at the center then expanded gradually toward the edge of the weld. Due to the heat concentrated in the center, the heat dissipation was slower than when the heat dissipated from the edge. As a result, the volume of the molten metal on the 5182 side was higher, resulting in smaller h compared to the R100/R100 electrode combination. When using R100/NTR, the heat on the AlSi10MnMg side was concentrated at the edge, and on the 5182 side, heat was concentrated in the center. Therefore, the R100/NTR electrode combination's h is greater than NTR/NTR's and less than R100/R100's, and its nugget morphology is like a nail, as shown in Fig. 3C.

Weld Microstructure and Hardness

Figure 6 shows the microstructure of the typical welds obtained by the NTR/NTR, R100/R100, and R100/NTR electrode combinations. The welds are divided into three distinct zones: the base metal (BM) zone, the fusion zone (FZ), and the thermo-mechanically-affected zone (TMAZ) located at the edge of the weld nugget. Figure 6A–C shows the TMAZs of the weld nuggets obtained by the NTR/NTR, R100/R100, and R100/NTR electrode combinations. The TMAZs are very narrow at only about 50–100 μm due to an extremely fast cooling rate during the RSW process and can only be observed near the 5182-O side. Figure 6D–F shows that the equiaxed crystal zone (ECZ) was formed in the center of the FZ obtained by the NTR/NTR, R100/R100, and R100/NTR electrode combinations. And there is a narrow columnar crystal zone (CCZ) observed near the BM of the AlSi10MnMg sheet, as shown in Fig. 6G (zone D), 6H (zone E), and 6I. During RSW, the solidification

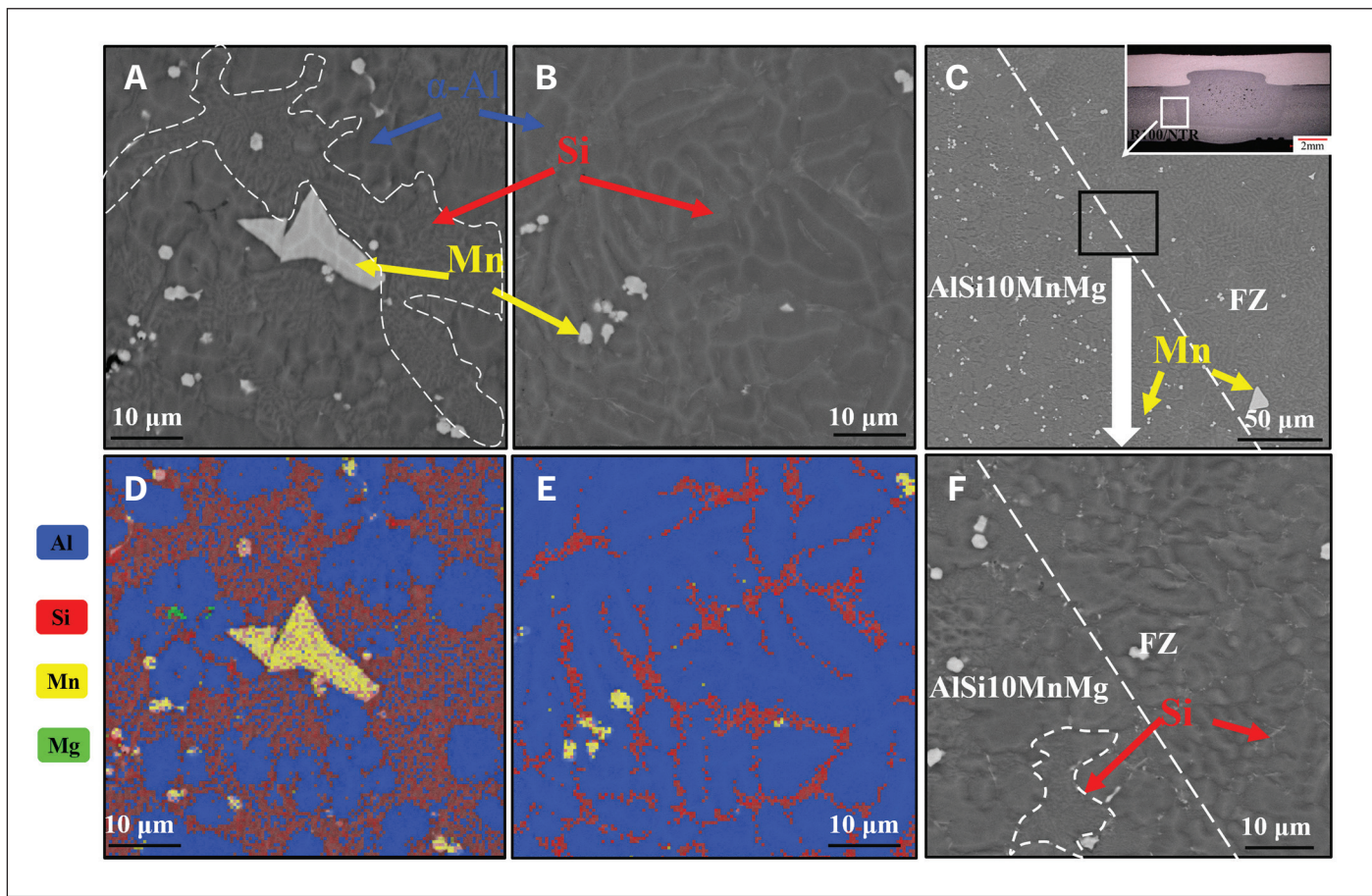


Fig. 7 — Microstructure and EDS analyses results of the BM, FZ, and near the FZ line of AlSi10MnMg casting aluminum with R100/NTR. A — Microstructure analysis of the BM; B — microstructure analysis of the FZ; C — microstructure analysis of the FZ line; D — map EDS analysis results of Fig. 7A; E — map EDS analysis results of Fig. 7B; F — enlarged view of the rectangular area marked in Fig. 7C.

rate at the edge of the weld nugget was faster than at the center of the weld nugget, and the nuclei formed first. Since the direction perpendicular to the weld nugget line had the largest temperature gradient, the columnar crystals formed first along this direction. In addition, the temperature gradient of the molten liquid tended to be closed in all directions. As the solidification proceeded and the crystal grains grew, the dendrites quickly contacted each other to stop the grain growth. Therefore, the ECZ was produced in the center of the FZ, and the CCZ formed near the BM of the AlSi10MnMg sheet.

Figure 7 shows the SEM and EDS mapping analyses results of the BM, TMAZ, and FZ of AlSi10MnMg casting aluminum alloy after RSW with the R100/NTR electrode combination. The BM of AlSi10MnMg consisted of α -Al and large Si and Mn phases, as shown in Fig. 7A and B. After welding, Si was supersaturated in the equiaxed α -Al, and the Si and Mn became smaller compared to the BM in Fig. 7B and E. This is mainly attributed to the short solidification time for the large melt Si and Mn, making it hard to grow during the solidification process. As shown in Fig. 7F, a significant size difference in the Si and Mn phases can be seen near the FZ line.

Figure 8 shows the microhardness of the weld nugget obtained by the NTR/NTR, R100/R100, and R100/NTR electrode combinations. Although the NTR/NTR, R100/R100, and R100/NTR electrode combinations produced various weld morphologies, they had similar hardness value distributions. The average hardness of 5182-O and AlSi10MnMg was approximately 60 HV and 95 HV, respectively. The hardness of the FZ was the highest, ranging between 110 and 120 HV, which was different from the RSW of wrought aluminum alloy (Ref. 13). In addition, the hardness value was lower and fluctuated in the center of the weld nugget due to the presence of porosities. Solution strengthening of smaller Si concentrations in the FZ led to the increased hardness of the FZ. In this study, the results were different from Sun's findings (Ref. 27), which reported that the hardness value of the TMAZ had been increased compared to the BM of the 5754 alloy owing to deformation hardening. Magnesium is the main alloying element of 5182-O and makes forming the precipitation phase nucleation difficult. As a consequence, the alloy cannot be strengthened by heat treatment, and its mechanical strength is usually improved by the work hardening effect. During RSW, the TMAZ experienced the combined action of mechanical and thermal effects. The deformation caused by mechanical effects resulted in work hardening, and

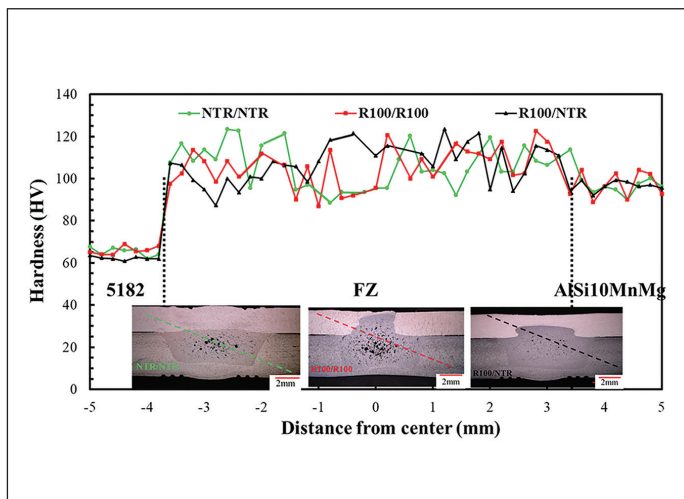


Fig. 8 — Microhardness value distributions of the weld obtained by NTR/NTR, R100/R100, and R100/NTR electrode combinations.

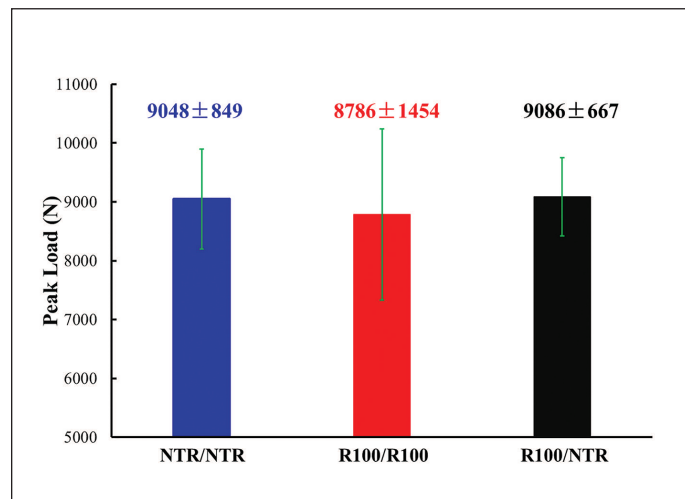


Fig. 9 — The peak load of tensile shear strength with different electrode combinations.

the thermal effect may have caused the maximum temperature in the BM to be higher than the recrystallization temperature. When the maximum temperature is higher than the recrystallization temperature, portions of the BM undergo recrystallization or grain growth, which decreases the hardness value (Ref. 28). Under the combined action of mechanical and thermal effects, the hardness values of the TMAZ almost remained constant. In addition, there was no obvious change of the hardness value near the FZ line on the AlSi10MnMg side. This is mainly because the Si in AlSi10MnMg is difficult to precipitate when the temperature is lower than the melting point and the heating time during RSW is short. Furthermore, the hardening ability is weak due to the low plasticity of cast aluminum alloy. Thus, there was no obvious change of the hardness on the cast aluminum side.

Tensile Shear Tests

Figure 9 shows the average tensile shear strength of the welds obtained with different electrode combinations. It can be seen that the average tensile shear strength of the welds produced with the NTR/NTR and R100/NTR electrode combinations were 9048N and 9086N, respectively. However, the average peak load of the welds with the R100/R100 electrode combination was only 8786N, less than those using the NTR/NTR and R100/NTR electrode combinations. Furthermore, the tensile shear strength of the welds produced with the R100/R100 electrode combination had greater fluctuations. There was little change in the average value of the peak load, but the error bars' ranges varied to a large degree. This may be due to a ring structure on the surface of the NTR electrode that can pierce the surface oxide film and provide more-stable contact resistance, as mentioned in Refs. 22 and 23. Generally, the tensile shear strength of the resistance spot welds are determined by the weld nugget size (Ref. 24). Even if the h_2 was the largest for the R100/R100 electrode combination, it did not improve the tensile shear strength. This demonstrated that the main factor affecting the tensile shear strength was the weld

size (D) at the bonding interface, and it had no direct relationship with h_2 . This is explained in more detail in the following section.

Figure 10 shows the top views of the typical fractured surface of the welds with different electrode combinations after the tensile shear tests. When using the NTR/NTR electrode combination, the welds cracked simultaneously along two paths under the tensile shear force, pulled out from the AlSi10MnMg side, and failed in a button pullout failure (PF) mode in the form of a boss. Figure 11A shows the failure curve during the tensile shear test with the NTR/NTR electrode combination. Figure 11B shows the cross-sectional views of the typical fractured surface of the welds with the NTR/NTR electrode combination. For the NTR/NTR electrode combination, the crack started to initiate at point A and propagated along the AlSi10MnMg sheet thickness direction when the load reached the maximum value. Then the second crack occurred at point B and propagated along the other side of the weld toward the weld surface until it was completely broken and failed in PF mode.

Figure 11C shows the failure curve during the tensile shear test with the R100/R100 electrode combination, and Fig. 11D shows the cross-sectional views of the typical fractured surface of the welds with the R100/R100 electrode combination after the tensile shear test. For the R100/R100 electrode combination, when the peak load reached the maximum value at point A, the crack initiated at point A, which first propagated along the AlSi10MnMg sheet thickness direction and then along the weld interface until the weld was suddenly and completely broken, and it failed in an interfacial failure (IF) mode. Figure 11E and F shows the load-displacement curve and the cross-sectional views of the typical fractured surface of the welded joints with the R100/NTR electrode combination. The fracture characteristic of the weld is similar to the R100/R100 electrode combination, which failed in an IF mode. Furthermore, the first crack initiated at point A and propagated along the AlSi10MnMg side. Then, the second crack initiated at point B and propagated along the interface of two aluminum sheets. Then, it switched its direction toward the FZ on the 5182-O side at about 135 deg with respect to the interface. Finally, the second crack stopped on the 5182-O side.

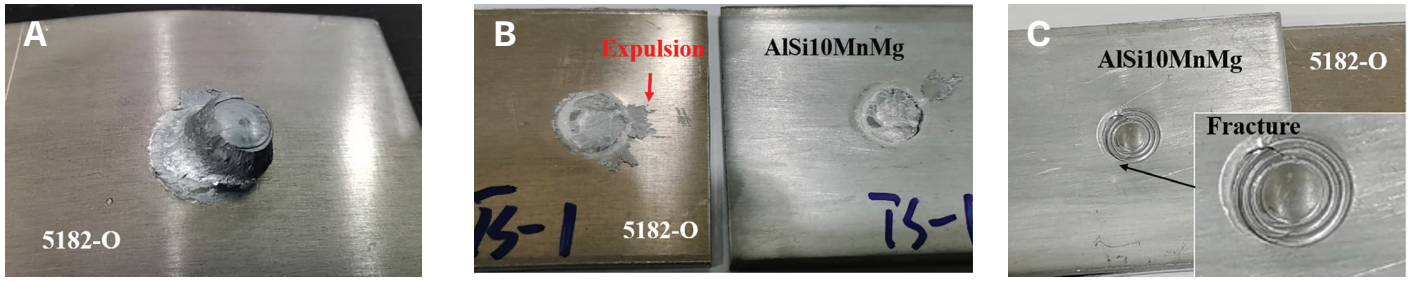


Fig. 10 — Fractured surface of the welds with different electrode combinations. A — NTR/NTR electrode combination; B — R100/R100 electrode combination; C — R100/NTR electrode combination.

Failure Analysis

Figure 12 shows the typical characteristic of the IF fractured surface, and a quasi-cleavage fracture was obviously exhibited in the center of the fractured face. Furthermore, the direction of the elongated dimples and cleavage surface deformities on the AlSi10MnMg side (Fig. 12E and F) suggested that shear stress dominated the whole failure process (Refs. 29, 30). Figure 13 shows the typical characteristics of the PF fractured surface. As shown in Fig. 13B, there were two different areas on the fractured surface. There were many circular dimples in the area close to the interface of two aluminum sheets, but many quasi-cleavage fractures were recognized in the area close to the surface of the AlSi10MnMg casting sheet. These phenomena indicated that part of the weld was mainly subject to tensile stress failure, and the other part was mainly subject to shear stress failure in the thickness direction (Refs. 29, 30).

At the beginning of the tensile shear test, the welded joints experienced the shear force F , which was parallel to the force direction, as shown in Fig. 14A. To align with the applied force direction, the weld nugget first rotated, then the bending moment led to the formation of tensile stress (Fig. 14B), which was perpendicular to the weld nugget. A cross-tension force $F_{\perp}$ was produced besides the shear tension force $F_{\parallel}$ because of the rotation. Many investigations indicated that the driving force of the IF is $F_{\parallel}$, and the driving force of the PF is $F_{\perp}$. And the failure mode of the resistance spot welds under tensile shear tests are determined by the weld nugget size (Refs. 13, 29–32),

$$F_{\parallel} = F \cdot \cos\theta \quad (3)$$

$$F_{\perp} = F \cdot \sin\theta \quad (4)$$

where F is the external force, $F_{\parallel}$ and $F_{\perp}$ are the force components parallel and normal to the joint face, and θ is the rotation angle.

With the rotation angle θ increased, $F_{\perp}$ increased. For the IF mode, the weld failure was completely driven by shear stress, as shown in Fig. 12. For the PF mode, the initial failure stage of the PF started with tensile stress, and the second stage was affected by

shear stress, as shown in Fig. 13. Brauser et al. (Ref. 29) found that the PF mode occurred due to different stresses in RSW of different materials. Furthermore, many researchers concluded that the tensile stress is the driving force for the PF mode (Refs. 13, 30, 31). In this study, experimental results showed that the occurrence of the PF mode in aluminum wrought-sheet-to-cast-sheet RSW joints was first driven by tensile stress (near the interface) then by shear stress (near the surface). This may be mainly related to the materials and thickness; $F_{\parallel}$ and $F_{\perp}$ may be affected by the thickness combination and deformation capacity of the material. The corresponding crack growth behavior and stress distribution under different failure modes need to be further studied.

Although AlSi10MnMg cast aluminum has a higher ultimate strength than 5182-O wrought aluminum, as shown in Table 1, it is worth mentioning the crack did not propagate along the 5182-O wrought aluminum side but on the AlSi10MnMg cast side. Similar to this study, this phenomenon was also observed in the spot welding of DP600–DP780 (Refs. 32–34), where the welds failed in the DP780 side.

The tensile stress of the weld nugget during the tensile shear test was not evenly distributed (Ref. 30). There was a concentrated stress at the nugget edge due to the maximum stress existing at the sheet/sheet interface, as shown in Fig. 15. The 5182-O wrought sheet experienced plastic deformation. Thus, the stress concentration level of the 5182-O sheet decreased, and the stress distribution tended to be uniform. At the same time, the AlSi10MnMg cast sheet had not undergone plastic deformation, and its stress distribution had not been changed. The AlSi10MnMg cast sheet stress concentration was more severe than in 5182-O. As a result, the cracks initiated on the AlSi10MnMg side.

During the tensile shear process, strain was transferred to the AlSi10MnMg side, and necking resulted from strain concentration due to the work hardening of 5182-O. It can be seen that there was a significant necking of 5182-O wrought aluminum sheet. After the tensile shear test, the hardness distribution and grain deformation of the aluminum sheets at the failure location were measured and are shown in Fig. 16. The hardness values at the failure location of 5182-O were higher than the BM and the area closer to the bonding interface, which is attributed to the work hardening effect during the tensile shear test. As the deformation was most severe at the area closer to the interface, the work hardening effect was more pronounced. Therefore, the hardness around the interface was higher compared with the other area far from the interface. The highest hardness of the area on the 5182-O side closer to the interface had reached 95HV compared

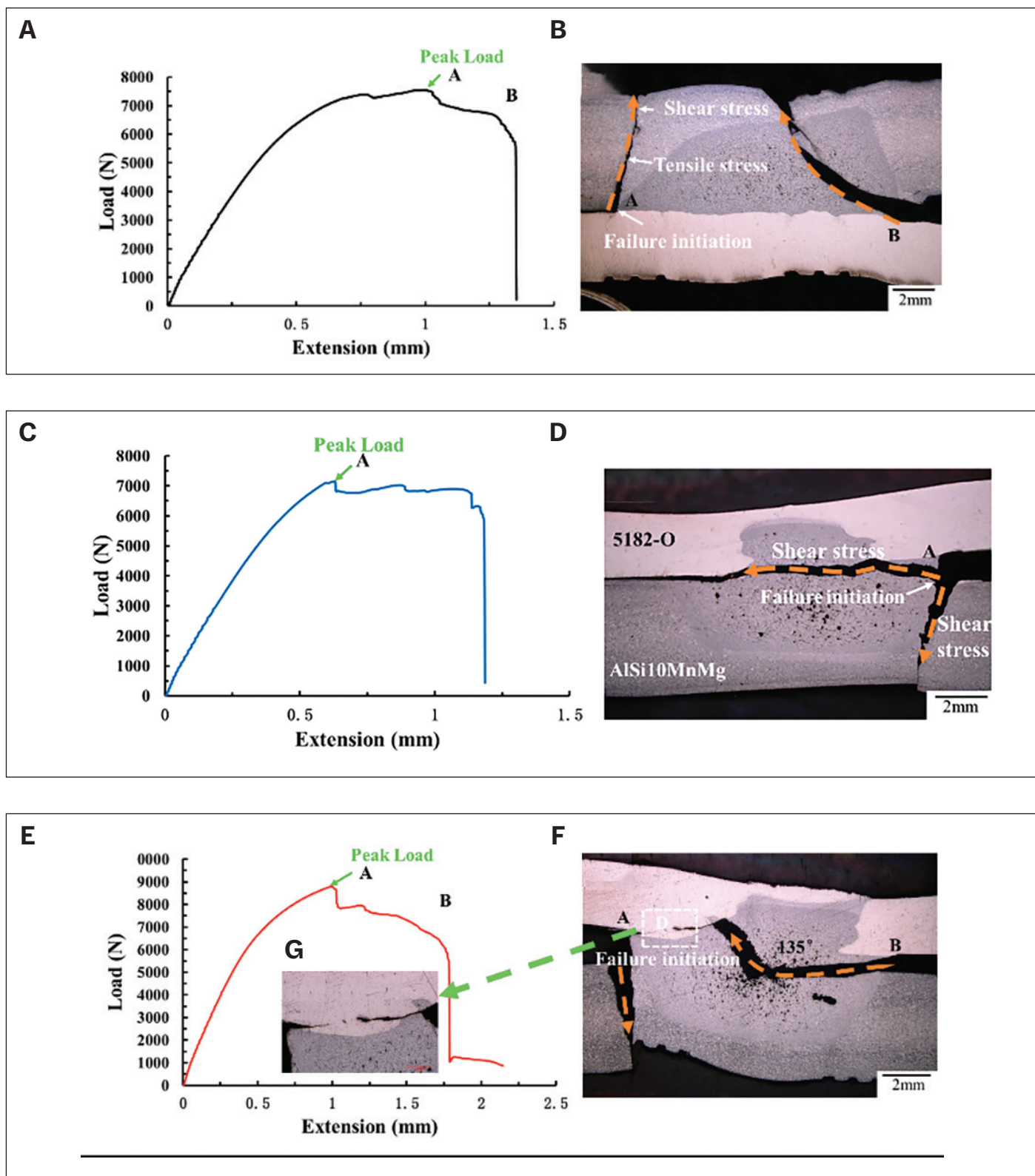


Fig. 11 — The load-displacement curves and cross-sectional views of the fractured welds taken from the fractured tensile shear samples. A — Load-displacement curve of the weld with the NTR/NTR electrode combination; B — pull-out failure; C — load-displacement curve of the weld with the R100/R100 electrode combination; D — interfacial failure; E — load-displacement curve of the weld with the R100/NTR electrode combination; F — interfacial failure; G — the magnified view of region D marked in Fig. 11F.

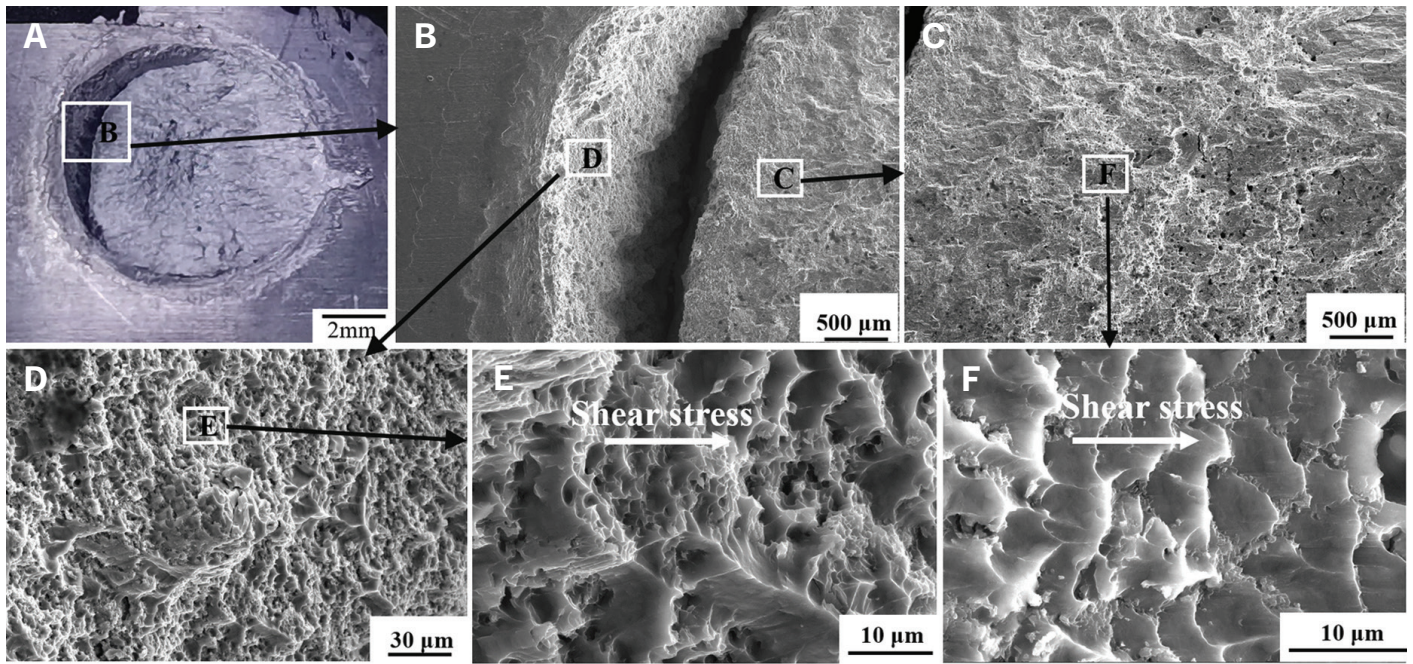


Fig. 12 — Typical microstructure characteristics of the IF fractured surface. A — Top view of the fractured surface; B — magnified view of region B marked in Fig. 12A; C — magnified view of region C marked in Fig. 12B; D — magnified view of region D marked in Fig. 12B; E — magnified view of region E marked in Fig. 12D; F — magnified view of region F marked in Fig. 12C.

to the 60HV of the BM, and the grain deformation can be clearly seen in Fig. 16D. But the highest hardness at the failure location on the AlSi10MnMg side was only raised from 95HV to 120HV. Although the hardness was still higher than that of the deformed 5182-O, the cracks were produced on the AlSi10MnMg side due to higher stress concentration whether the failure mode was IF or PF.

The work hardening effect also took place near the surface, as shown in Fig. 16 (position D). This is mainly because position D was subjected to greater shear stress, as analyzed above, but position C was under tensile stress. As the failure location was on the AlSi10MnMg side, $F_{\perp}$ became bigger and dominated with increased θ . Based on the above results, it could be concluded that the RSW joint strength of dissimilar materials with different thicknesses is not determined by the thickness of the thin plate side but by the combined effects of the undergone stress concentration and the work hardening degree of the welded materials. The degree of stress concentration caused by the deformability of the welded materials will affect the failure mode of the joints. The easier the material is to deform, the easier it is for PF failure to occur. In addition, the higher the ultimate strength and the lower the plasticity of the materials, the more likely it is to cause IF mode under the tensile shear test.

Conclusions

In this paper, the effects of various electrode structures on the RSW of 5182-O and AlSi10MnMg aluminum alloys were investigated. The microstructures, mechanical properties, and failure behaviors of the welds were discussed. The main conclusions were drawn as follows:

1) The electrode geometry has a significant influence on the weld nugget morphology and tensile shear strength. The weld produced by the NTR/NTR electrode combination had the smallest weld penetration on the 5182-O side, while using R100/R100 had the largest weld penetration and suppressed the weld penetration migration issue. Furthermore, the NTR/NTR electrode combination formed a larger weld nugget due to its special nucleation mechanism together with inhibiting expulsion occurrence. The welds produced by the NTR/NTR and R100/NTR electrode combinations generated higher and more-stable tensile shear strength than that with the R100/R100 electrode combination.

2) There was no significant difference in the weld nugget hardness distribution for the various electrode combinations. In addition, the hardness value of the TMAZ had no significant change. However, the hardness of the FZ increased compared to the BM due to solution strengthening effect.

3) The occurrence of the PF mode in aluminum wrought-sheet-to-cast-sheet RSW joints was first driven by tensile stress then by shear stress. However, the IF mode was completely driven by shear stress in different directions.

4) Under the tensile shear force, the cracks always started on the AlSi10MnMg side but not on the 5182-O side whether the failure mode of the welds was the IF or PF mode. The stress concentration degree of 5182-O was lower than AlSi10MnMg as 5182-O is easier to deform and has a higher work hardening degree.

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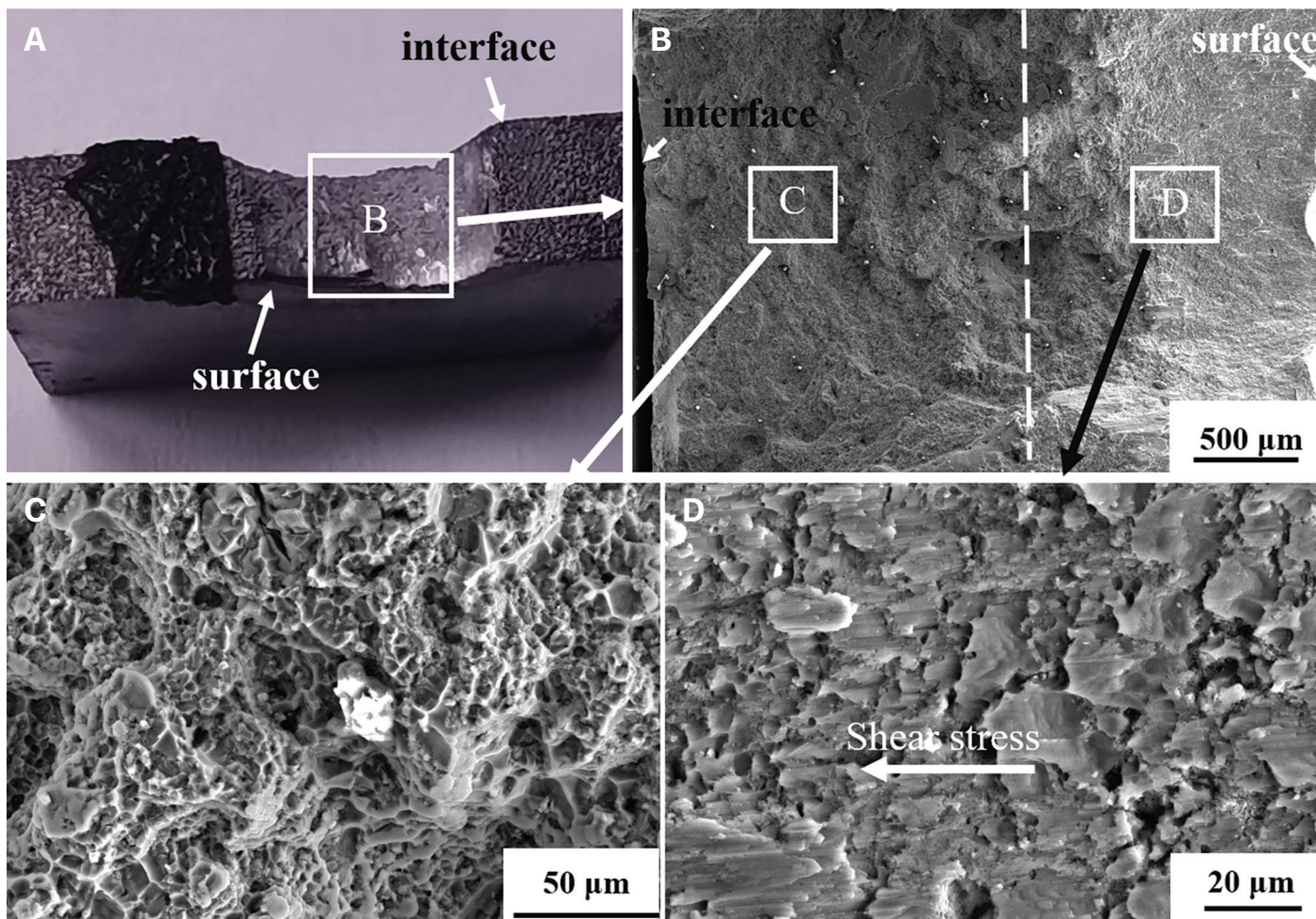


Fig. 13 — Typical microstructure characteristic of the PF fractured surface. A — Overview of the fractured surface on the AlSi10MnMg side; B — magnified view of region B marked in Fig. 13A; C — magnified view of region C marked in Fig. 13B; D — region D marked in Fig. 13B.

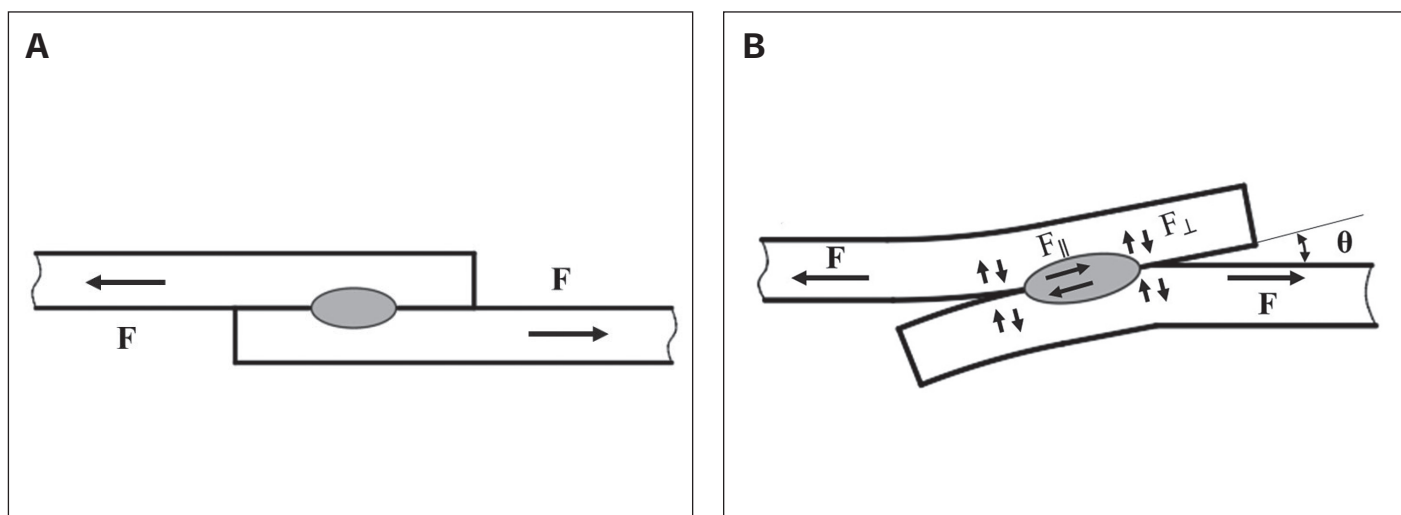


Fig. 14 — Schematics of the force of the welded joint during tensile shear testing. A — Initial configuration; B — nugget rotation.

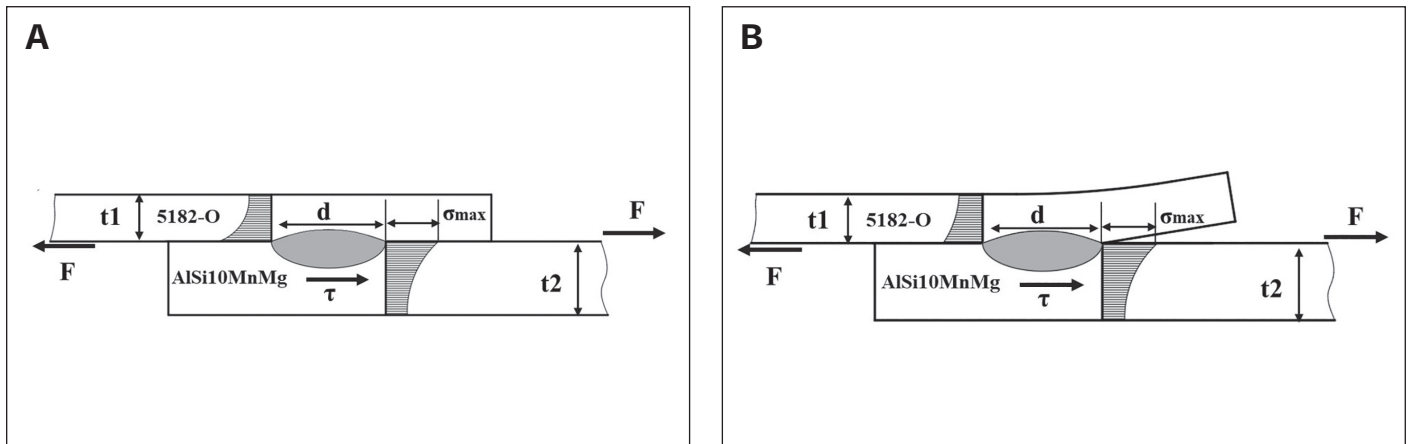


Fig. 15 – Schematics of stress distribution of the welded joint during tensile shear testing. A – Initial configuration; B – deformation.

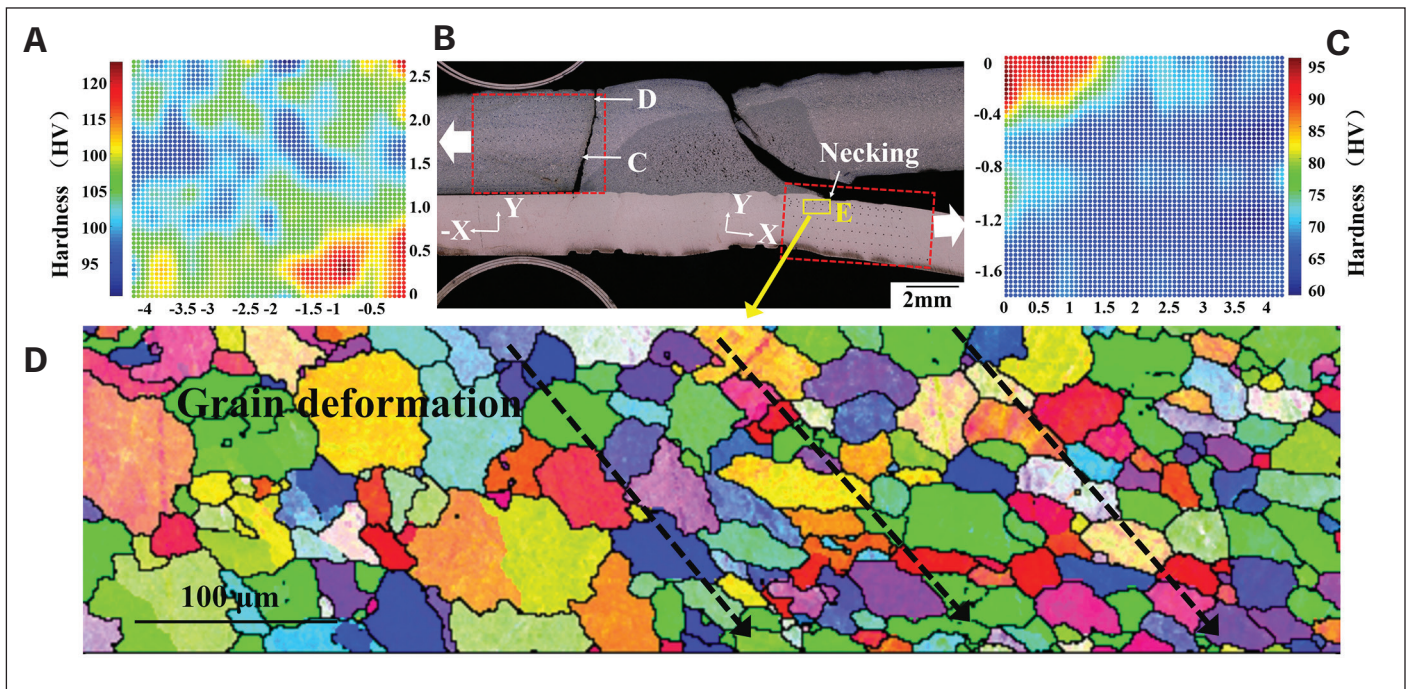


Fig. 16 – The hardness distribution and grain deformation of the aluminum sheets at the failure locations after the shear tensile test. A – Hardness distribution in the area marked in Fig. 16B; B – cross-sectional metallographic structure of the PF fracture; C – hardness distribution in the area marked in Fig. 16B; D – the EBSD mapping results of the grain size and orientation in E marked in Fig. 12B.

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