



Effect of Inhomogeneous Nugget on Weld Performance in Resistance Spot Welding of HPDC AlSi7MnMg — Part 1: Material Characterization

The effect of welding process parameters and microstructural inhomogeneity of base material on nugget microstructure

BY Y. WANG, Z. TENG, Z. LI, Y. XIA, H. LIU, Z. CHEN, C. LIU, J. BROWN, AND Y. LI

Abstract

High-pressure die-cast (HPDC) aluminum alloys are widely regarded as a promising material for next-generation lightweight automotive structures. Compared to large, integrated die-cast bodies, adopting a modular design in which multiple small castings are joined by resistance spot welding can significantly reduce both manufacturing complexity and maintenance costs. However, the base material (BM) of HPDC aluminum alloys exhibits microstructural inhomogeneity because of the random distribution of eutectic Si networks and α -Al dendrites. This inhomogeneity leads to the formation of partially melted zones (PMZ) and fully melted zones (FMZ) with varying thicknesses under different welding thermal cycles, resulting in inhomogeneous nuggets. To clarify the nugget formation mechanism and microstructural characteristics under the coupled influence of BM inhomogeneity and welding thermal cycles, this study compares two typical processes: multi-pulse (MP) and single-pulse (SP), and systematically analyzes the nugget morphology, microstructure, and growth mechanism under each condition. The results show that the PMZ exhibits only slight differences from the BM. In contrast, the FMZ differs from the BM in that it develops new columnar grain zones and equiaxed grain zones. At the same nugget diameter, the continuous heat input from the SP process can reduce PMZ formation and promote greater FMZ development compared with the MP process. However, it also increases the likelihood of

crack formation. This study examines the weldability of the HPDC aluminum alloy and provides theoretical guidance for its application in large-scale structural castings for automotive bodies.

Keywords

- High-Pressure Die Casting
- Resistance Spot Welding
- Microstructural Inhomogeneity
- Partially Melted Zones
- Multi-Pulse Current
- Single-Pulse Current

Introduction

As the automotive industry continues to pursue low-carbon and high-efficiency development, the lightweighting of vehicle body structures has become a key approach to improving overall energy efficiency and extending driving range (Ref. 1). Aluminum alloys, due to their low density, high specific strength, and excellent corrosion resistance, have emerged as the preferred materials for the next generation of lightweight body structures (Ref. 2). In recent years, with the rise of significant integrated die cast concepts such as Tesla's "Giga-casting," the application of Al-Si high-pressure die casting (HPDC) aluminum alloys in automotive structural components has further accelerated (Ref. 3). However, although integrated die cast bodies can significantly reduce the number of parts, they also face practical limitations such as high mold costs, long development cycles, size constraints, and expensive post repair procedures (Ref. 4). In addition, large HPDC aluminum alloy structural components require high-capacity casting equipment. They are limited by current casting processes, often exhibiting microstructural

inhomogeneity and defects such as porosity and shrinkage cavities (Ref. 5). Therefore, to balance manufacturing cost and vehicle body quality, the industry is gradually shifting toward an approach in which castings are produced in separate modules and subsequently assembled using joining techniques. This strategy improves manufacturing quality, flexibility, and serviceability (Ref. 6).

In current automotive body joining schemes, HPDC aluminum alloys are still primarily joined using mechanical methods such as self-piercing riveting (SPR) (Ref. 7). However, inherent issues within HPDC, including shrinkage porosity and brittle eutectic Si networks, often lead to crack initiation or even fracture during rivet penetration (Ref. 8), significantly compromising joint strength and fatigue performance (Ref. 9). Furthermore, the SPR process imposes strict constraints on sheet thickness, stack-up sequence, and die accessibility, thereby limiting the degree of part integration and the feasibility of complex geometries (Ref. 10). The presence of rivets also inevitably increases local mass and material cost, which conflicts with the lightweighting goals of modern vehicle design (Ref. 11). Therefore, relying solely on SPR is insufficient to meet the comprehensive requirements of future automotive bodies for high strength, joint quality, and structural integration. There is an urgent need to explore alternative joining strategies that are better suited to HPDC aluminum alloys (Ref. 12).

Resistance spot welding (RSW) is one of the core joining processes in automotive manufacturing due to its high efficiency, low cost, and ease of automation (Ref. 13). Compared to SPR, RSW does not introduce additional structural weight, making it a promising candidate for joining HPDC aluminum alloys (Ref. 14). However, in contrast to steels, the high thermal conductivity, low electrical resistivity, and dense oxide film of aluminum alloys significantly reduce welding thermal efficiency and accelerate electrode degradation. As a result, conventional single-pulse (SP) welding processes often yield unsatisfactory outcomes, posing substantial challenges for RSW (Ref. 15). To address these issues, General Motors Co. (GM) has developed a multi-pulse (MP) RSW strategy based on the conditioning, shaping, sizing waveform (Ref. 16). This approach enables stable nugget growth through a three-stage current mode consisting of preheating, forming, and final shaping. Concurrently, GM has introduced the multi-ring domed (MRD) electrode, which features annular protrusions capable of breaking through the surface oxide film (Ref. 17). This design suppresses electrode sticking, thereby significantly improving weld quality in aluminum RSW joints (Ref. 18).

However, HPDC aluminum alloys inherently exhibit pronounced microstructural inhomogeneity and casting defects. The random distribution of α -Al dendrites and eutectic Si networks with inconsistent melting points, coupled with inevitable shrinkage porosity and voids formed during HPDC, results in poor microstructural consistency of the base material (BM) (Ref. 19). When subjected to different welding procedures, these inhomogeneities tend to generate less favorable welding nuggets, thereby posing further critical challenges to the application of the RSW process. Existing studies have primarily focused on the effects of nugget size and fracture modes on mechanical performance (Ref. 20).

However, investigations into the microstructural evolution of nuggets under different thermal cycles and the correlation between nugget microstructure and mechanical performance remain significantly limited.

This study focuses on the formation mechanisms of the nugget in HPDC aluminum alloy RSW, under various welding thermal cycles, as well as the relationship between the nugget microstructure and the mechanical performance of the joint. In two complementary papers, the typical MP and SP processes are systematically characterized, detailing the differences in nugget microstructures, their formation mechanisms, and their correlation with mechanical properties. In this study, a comprehensive analysis is conducted of the macro-morphology, microstructure, and formation mechanisms of nuggets. Our further research will thoroughly investigate the fracture behavior and mechanical performance of the corresponding joints. This research aims to bridge the current knowledge gap regarding the influence of BM microstructure on joint performance under different welding processes for HPDC aluminum alloy RSW, providing new theoretical insights to support the application of advanced casting materials.

Experimental Procedures

Materials

The study used 2.5-mm HPDC aluminum alloy AlSi7MnMg sheets with the chemical compositions listed in Table 1. The chemical composition was determined using direct-reading optical emission spectroscopy (OES) with an electrical spark excitation source. This aluminum alloy is a typical hypoeutectic alloy with approximately 7 wt-% silicon. All workpieces were manufactured with dimensions of 120 × 40 mm and underwent alcohol cleaning before welding. The overlap width between the two sheets was 40 mm.

Welding Process

The welding apparatus employed in this study comprised a Fanuc 2000iA robotic arm integrated with a HERON servo-driven welding gun and a medium-frequency direct current (MFDC) controller provided by Welding Technology Corp., as illustrated in Fig. 1A. As shown in Fig. 1B, the RSW process typically consists of three stages: squeezing, welding, and holding. During welding, a GM-patented MRD electrode was employed to effectively disrupt the oxide film on the aluminum sheet surface, thereby significantly reducing contact resistance at the electrode-workpiece interface. The nominal electrode diameter used in all experiments was 19 mm.

As shown in Fig. 1C, both MP and SP RSW processes were conducted under a constant electrode force of 4.9 kN (1100 lb). In the MP process, the welding sequence consisted of an 8kA root-mean-square (RMS) preheating pulse for 0.05 s to promote oxide film disruption, followed by a shaping pulse of 32 kA RMS for 0.05 s, and then a 31 kA RMS sizing stage maintained for 0.30 s. This multi-stage current strategy provides controlled heat input and intermittent cooling,

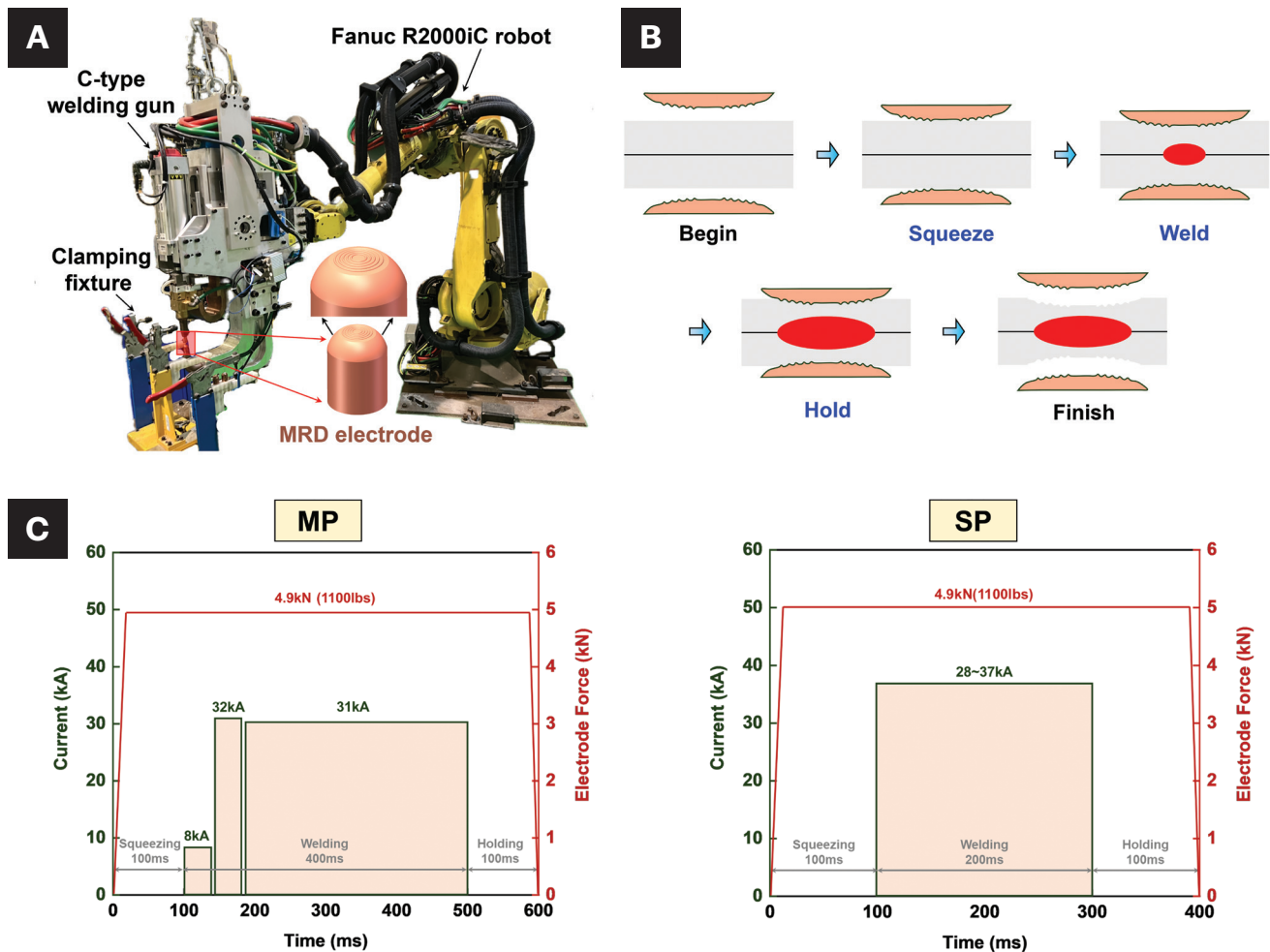


Fig. 1 — Welding system, process, and schedule: A — Welding system; B — welding process; C — RMS value of MP and SP schedules.

Table 1 — Chemical Compositions (wt-%) of C611

Si	Mn	Mg	Fe	Cr	Ni	Cu	Al
≈ 7.2	≈ 0.55	≈ 0.24	≈ 0.11	≈ 0.0044	≈ 0.0045	≈ 0.06	Bal.

enabling gradual nugget growth while minimizing expulsion and defects. In contrast, the SP process applied a single welding pulse of 28–37 kA RMS for 0.20 s. This parameter set is specifically selected to produce a nugget size comparable to that of the MP process, enabling a direct comparison of the effects of heat input on nugget microstructure.

Characterization and Testing

The welded specimens were first hot-mounted in Bakelite. Specimens were prepared using standard metallographic practices, finishing with 1 μm silica suspension. For electron backscatter diffraction (EBSD) analysis, a final polishing stage was performed using a 0.05 μm silica suspension and vibratory polishing to achieve a deformation-free surface suitable

for high-resolution microstructural characterization. Keller's reagent was used to etch the nugget for observation of both macrostructure and microstructure. Macrostructure and microstructure characterizations were performed using a Wilson VH3100 microhardness system and a Leica DFC495 optical microscope (OM). Metallographic cross-sectional images were quantified in ImageJ to determine nugget areas. Scanning electron microscope (SEM) and EBSD analyses were conducted on a TESCAN MIRA3. The EBSD datasets were subsequently processed using AZtecCrystal software. Time-of-flight secondary ion mass spectrometry (TOF-SIMS) analyses were performed on a TESCAN GAIA3.

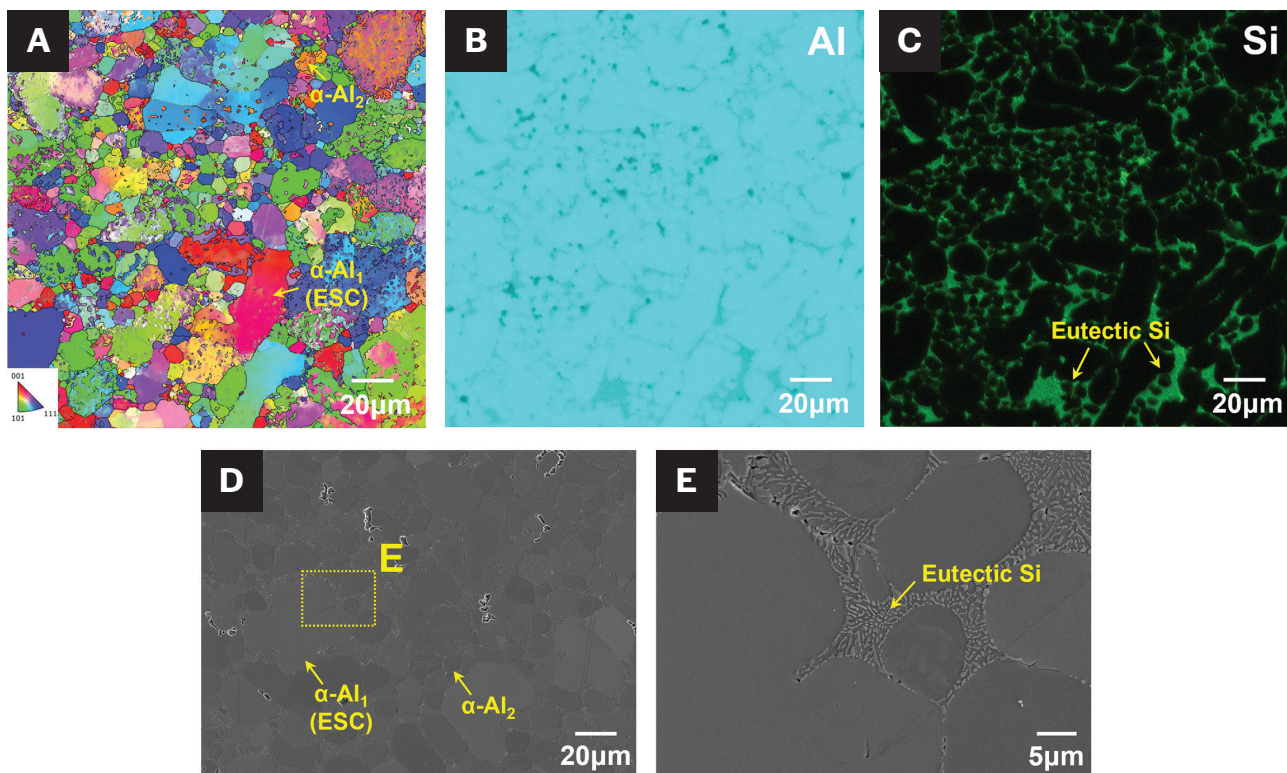


Fig. 2 — SEM, EDS, and EBSD results of BM: A — EBSD results of α -Al dendrites and eutectic Si networks; B and C — EDS results corresponding to region A; D — SEM results of α -Al dendrites and eutectic Si networks; E — microstructures corresponding to regions E in D.

Results

BM Microstructure

Figure 2 presents the BM microstructure obtained through SEM analysis. The microstructure exhibits significant inhomogeneity, consisting of coarse primary Type I α -Al dendrites, finer Type II α -Al dendrites, and eutectic Si networks, all randomly distributed. Type I α -Al dendrites are believed to form under relatively slow-cooling conditions before molten aluminum is injected into the mold cavity. They are therefore referred to as “externally solidified crystals” (ESC) (Ref. 21). In contrast, the Type II α -Al dendrites form within the mold at higher cooling rates. Additionally, eutectic Si networks form during solidification around both types of primary aluminum phases. These characteristic features are also further evidenced by EBSD and EDS analyses. As a result, the BM exhibits microstructural inhomogeneity due to the coexistence and random distribution of α -Al dendrites and eutectic Si networks with differing melting points, which profoundly influences subsequent welding behavior.

Nugget Appearance

Figure 3 shows the macrostructure of the MP and SP nuggets. To eliminate the influence of welding parameters on nugget diameter, nuggets with identical diameters obtained from MP and SP were selected, as shown in Figs. 3A and B.

Due to the application of the MRD electrode cap, serrated indentation marks can be observed above and below the nugget. In terms of visible defects, the nugget formed under the SP process exhibits more cracks and pores, while the one formed under the MP process shows no obvious nugget defects. However, small pores still exist in the BM and nugget regions for both processes. Further observations from Figs. 3C and D indicate that the nugget microstructures from both methods consist of two zones: partially melted zones (PMZ) and fully melted zones (FMZ). FMZ includes columnar grain zones (CGZ) and equiaxed grain zones (EGZ). Macroscopically, the nugget formed by the SP process shows a larger dark area corresponding to the FMZ and a smaller PMZ. The microstructure details of each zone will be discussed in the next section.

Figure 4 presents the quantitative analysis of the cross-sectional area of FMZ (FMZ area) for MP and SP nuggets. Under the same nugget diameter, the FMZ area of the MP nuggets is approximately 99 mm², while that of the SP nuggets reaches 128.5 mm², which represents an increase of 30%. To further analyze the FMZ size while excluding the influence of nugget diameter, the equivalent FMZ thickness was calculated by dividing the FMZ area by the nugget diameter. The values are 1.69 mm for MP and 2.02 mm for SP, showing a 20% increase for the SP nugget relative to the MP nugget. These results demonstrate that the SP process promotes the formation of a larger FMZ.

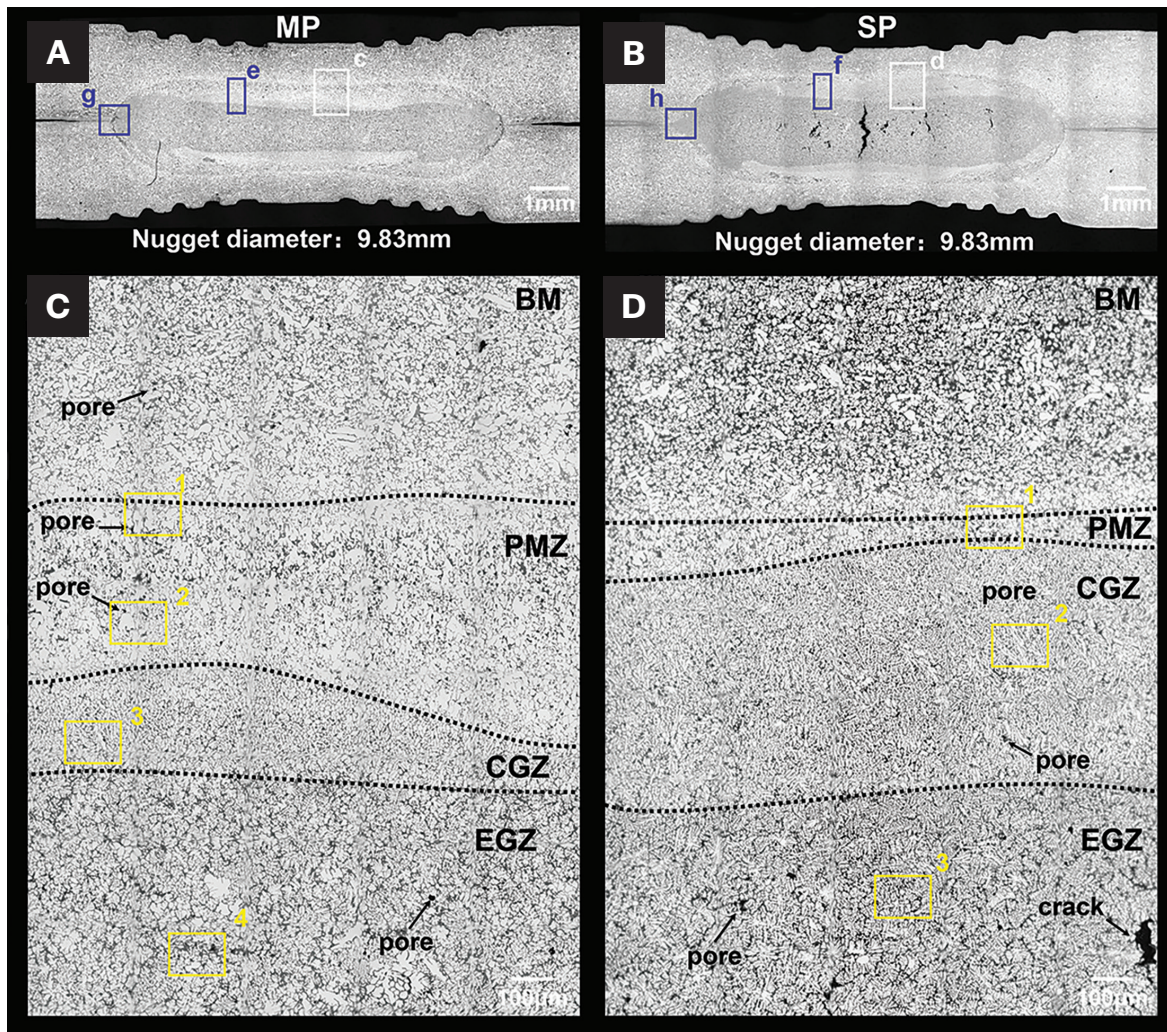


Fig. 3 — Nugget profile and microstructure of MP and SP nuggets: A — MP nugget profile; B — SP nugget profile; C and D — microstructures corresponding to regions C and D within A and B.

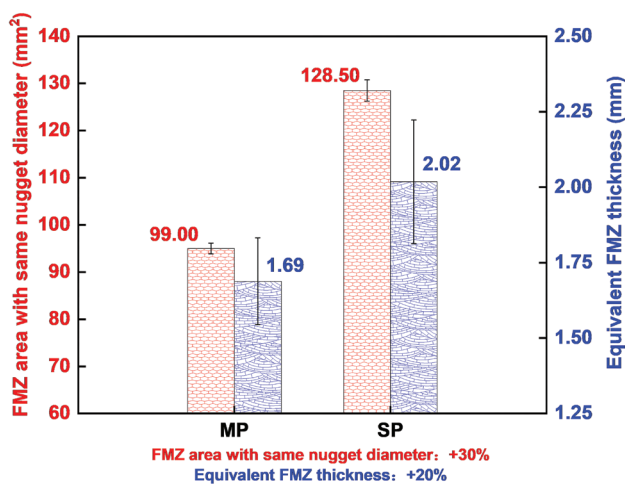


Fig. 4 — Comparison of the FMZ size in MP and SP nuggets.

Nugget Microstructure

Figure 5 presents the microstructures from BM to FMZ for MP and SP nuggets, observed under higher-magnification optical microscopy. In the MP nugget, the PMZ is significantly wider, where melting of eutectic Si networks occurs while the α -Al dendrites remain largely unmelted. Moreover, closer to the FMZ, the eutectic network appears increasingly dissolved, leaving behind a higher fraction of α -Al. This is attributed to repeated cooling during the MP process, in which the PMZ temperature fails to reach the melting point of the α -Al dendrites, leading to a thicker PMZ transition layer. In contrast, the SP process, with a higher peak temperature, results in a larger FMZ and a very narrow PMZ. Compared with the PMZ, the FMZ has undergone complete melting and resolidification. Typical columnar grains with strong orientation preference are observed in the CGZ, indicating directional solidification. In the EGZ, under more uniform cooling conditions and lower thermal gradients, equiaxed grains nucleate freely, leading to a more homogeneous and refined microstructure.

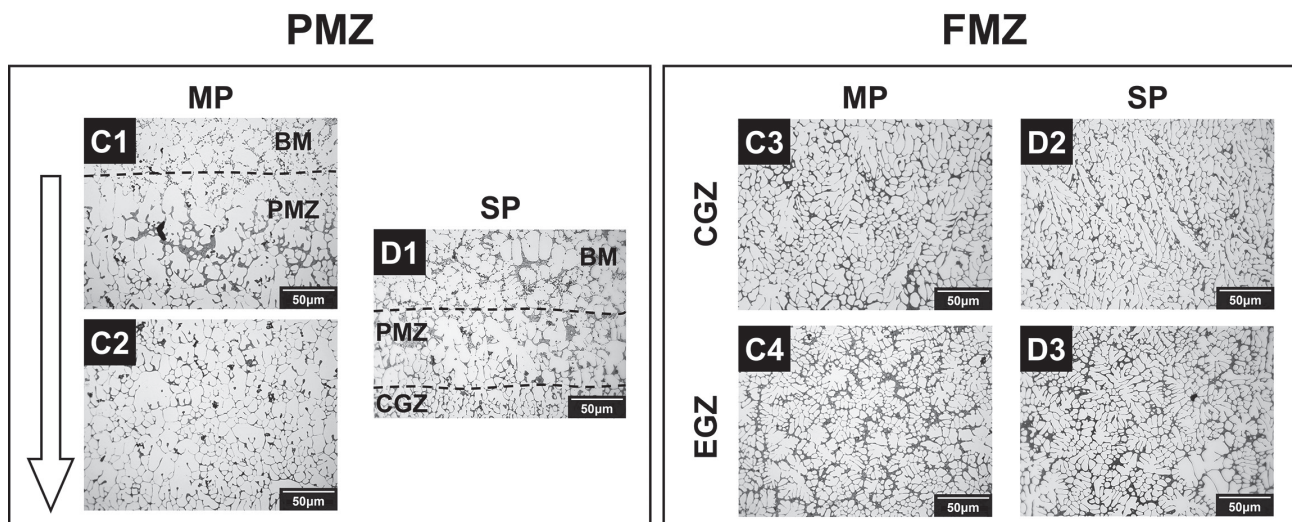


Fig. 5 — Enlarged OM photographs of MP and SP nuggets: C1 – C4 — correspond to the region 1–4 marked in Fig. 3C; D1–D3 — correspond to the region 1–3 marked in Fig. 3D.

Figure 6 presents EBSD results for analyzing the grain morphology in the BM and nugget regions formed by MP and SP processes. The EBSD results first confirm the delineation of PMZ, CGZ, and EGZ. The grain morphology and orientation between the PMZ and BM are not significantly different, suggesting that although partial melting occurred in the PMZ during the welding thermal cycle, the subsequent solidification did not induce notable recrystallization or orientation selection. Further analysis reveals that columnar grains are more evident on both sides of the nuggets formed by MP and SP processes, which can be attributed to the combined effects of current density and cooling rate. Furthermore, the EGZ of the MP nugget shows a more refined grain structure compared to that of the SP nugget.

Figure 7 further compares the grain sizes in the EGZ obtained from the MP and SP nuggets. To accurately reflect the difference in grain size within the EGZ of the two types of nuggets, four distinct regions were selected from both MP and SP nuggets for grain size quantification. To minimize the influence of noise and post-processing artifacts, only grains with a diameter greater than 10 µm were included in the analysis. This allows a direct comparison of grain size trends in the EGZ between the two nuggets. In the EGZ of the MP nugget, the average grain size is approximately 19.48 µm with a standard deviation of 10.46 µm. In contrast, the SP nugget yields an average grain size of approximately 30.47 µm with a standard deviation of 17.73 µm. The average grain size and standard deviation increase by 56 and 70%, respectively. These results demonstrate that the MP process effectively promotes grain refinement in the nugget EGZ.

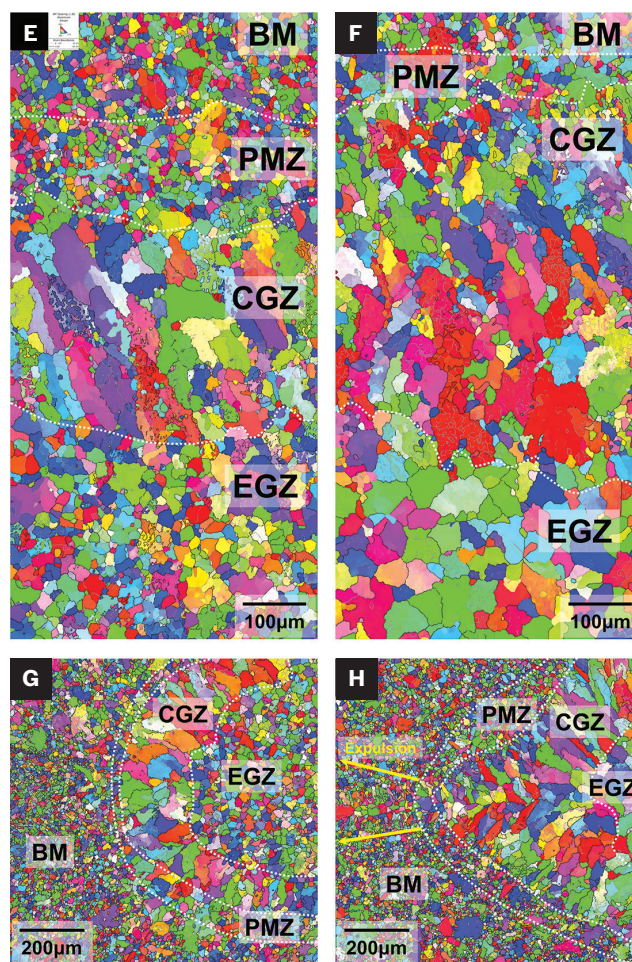


Fig. 6 — EBSD results of MP and SP nuggets: E and G — correspond to the regions E and G marked in Fig. 3A; F and H — correspond to the regions F and H marked in Fig. 3B.

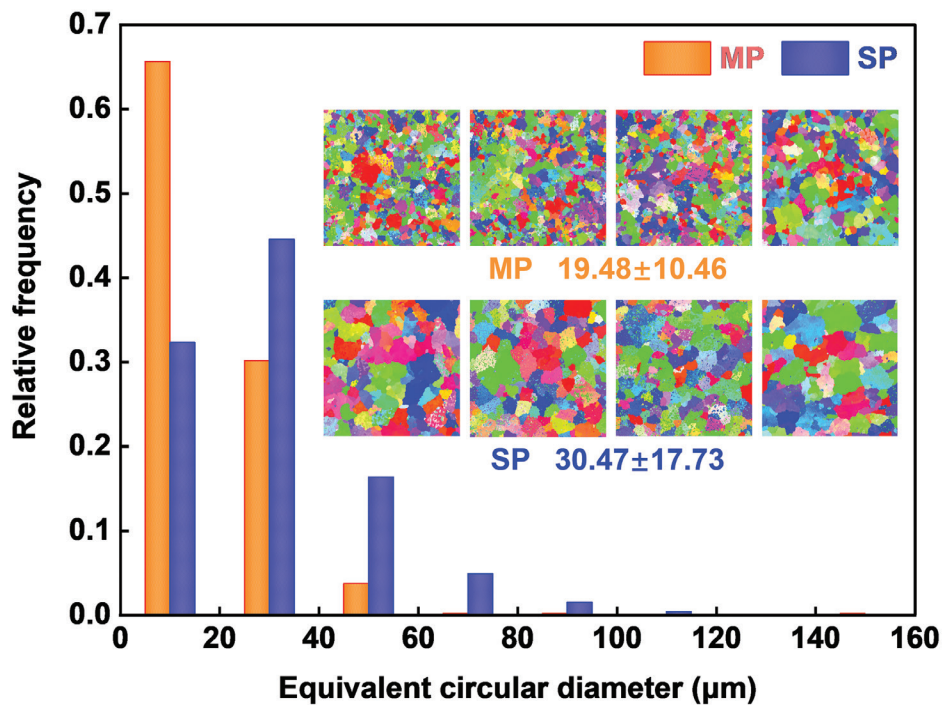


Fig. 7 — Comparison of the grain size in the EGZ of MP and SP nuggets.

Discussion

The Formation and Characteristics of the PMZ

In welding metallurgy, the PMZ is defined as a very narrow transitional region located between the fusion zones (FZ) and the adjacent solid-state region referred to as the true heat affected zones (HAZ) (Ref. 22). The peak temperature within the PMZ lies between the alloy's solidus (T_s) and liquidus (T_l), leading to localized melting and the formation of a transient semisolid structure consisting of coexisting solid and liquid phases (Ref. 23). As shown in Fig. 8, for the AlSi7MnMg alloy, the low-melting-point eutectic Si networks between α -Al dendrites in the as-cast microstructure preferentially melts in the PMZ. This leads to the formation of liquid phases along the grain boundaries of α -Al dendrites, particularly at those belonging to previously solidified coarse ESC grains, as well as along eutectic networks. In contrast, the α -Al dendrite trunks remain in the solid state due to their higher melting points. The melting behavior differs significantly between distinct initial microstructural constituents: the eutectic Si begins to melt extensively near 577°C, whereas the coarse ESC dendrites, which are compositionally close to pure aluminum, do not exhibit noticeable melting until approximately 660°C. This explains the observation in Fig. 5 that, within the PMZ, the fraction of dark-contrast eutectic Si networks decreases progressively toward the FMZ, eventually leaving only α -Al dendrites.

TOF-SIMS is a highly surface-sensitive qualitative chemical analysis method that reveals relative elemental concentrations across different regions (Ref. 25). As shown in Fig. 9, the overall Si content differs among the areas, which can be

attributed to the microstructural inhomogeneity of the BM. Furthermore, the relative Si signal in the PMZ of the nugget decreases continuously, indicating a reduction in eutectic Si-rich zones. Figure 9 shows that areas closer to the FMZ, which experience higher peak temperatures, exhibit more extensive melting of eutectic Si networks. A clear enrichment of Si is observed at the edges of the CGZ, which can be attributed to solute rejection during the columnar grain growth process. The microstructural characteristics of the PMZ and FMZ determine the microhardness distribution within the nugget, and these effects will be explored in detail in forthcoming research.

The Effect of Welding Process Parameters on the PMZ

In the PMZ, the alloy is in a solid-liquid coexistence state, and its thermophysical properties exhibit significant nonlinear variations with the solid fraction f_s . As f_s increases from 0 to 1, the effective thermal conductivity k_{eff} first decreases and then increases, while the thermal diffusivity decreases significantly (Refs. 26, 27). This results in hindered heat flow and a delayed local temperature rise within the PMZ, effectively forming a thermal resistance layer that slows heat transfer (Ref. 28). Meanwhile, the microstructural inhomogeneity of the BM amplifies this effect.

Figure 10 illustrates the mechanism of nugget growth under the MP and SP processes. Under the welding current of the SP process, the peak temperature continuously increases, and the nugget grows steadily with stable heat input, expanding toward both the notch and thickness directions. More adjacent regions are heated above the solidus temperature, and the previously formed PMZ is further heated and trans-

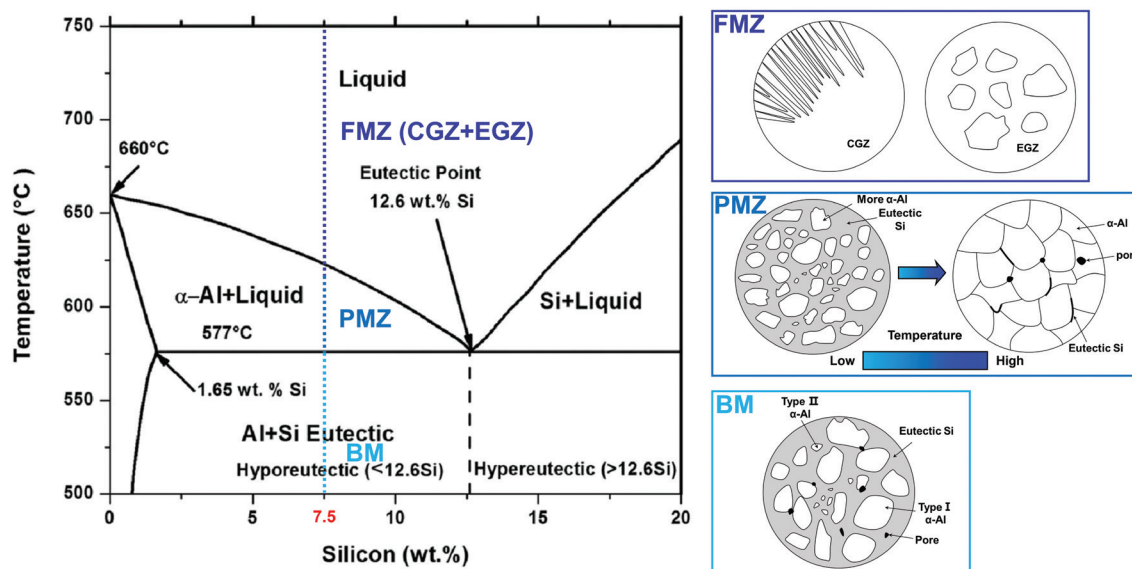


Fig. 8 — Al-Si phase diagram (Ref. 24) and schematic diagrams of phase composition when the maximum temperature is reached in different zones.

formed into FMZ. The nugget diameter gradually increases, while new outer regions at the nugget boundary enter the solid-liquid coexistence zone, forming a new PMZ. In contrast, the MP process segments the heat input by introducing cooling intervals between pulses, which prevents the peak temperature of each heating segment from continuously rising above the liquidus temperature. As a result, the nugget edge experiences repeated “solid-semi-molten-resolidified” cycles, leading to a layered accumulation of PMZ. Moreover, although the MP process provides a higher total heat input, multiple cooling intervals lead to heat loss, which is exacerbated by the microstructural inhomogeneity of the BM. In contrast, the SP process without cooling intervals ensures that most of the heat contributes directly to nugget melting and nucleation.

For HPDC aluminum alloys with a wide solidification range and inhomogeneous composition, the repeated melting-solidification mechanism in the MP process more readily promotes an increase in PMZ thickness. These results indicate that the coupling between the cooling interval and peak temperature is the key factor determining the PMZ thickness. When the pulse peak temperature exceeds the liquidus, the PMZ tends to thin. In contrast, if the peak temperature only approaches the solidus temperature, the MP process promotes layered accumulation and thickening of the PMZ.

Figure 11 compares the variation of the FMZ area with nugget diameter under MP and SP processes. It is evident that with increasing nugget diameter, the FMZ area in SP nuggets grows at a markedly higher rate compared to that in MP nuggets. In the SP process, the continuous increase in peak temperature during welding promotes more extensive melting and stable expansion of the FMZ, resulting in a larger increase in the FMZ area as the nugget expands. In contrast, the segmented heating and cooling intervals in the MP process limit FMZ growth, as repeated partial melting and resolidification cycles consume part of the thermal input without significantly contributing to FMZ enlargement.

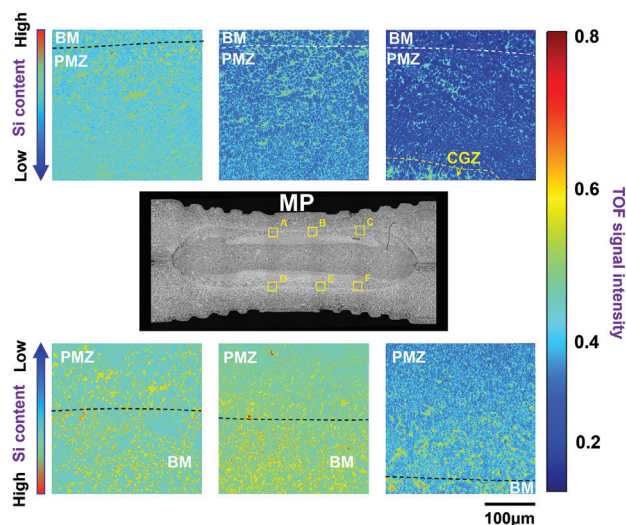


Fig. 9 — TOF-SIMS of Si content in the BM and PMZ of MP nugget.

Consequently, the SP process exhibits a more efficient conversion of heat input into FMZ growth, which is directly associated with improved joint strength and ductility.

The Effect of Welding Process Parameters on the Crack

Cracks observed in the nugget metallography in Fig. 3 are generally attributed to their formation during the solidification stage of RSW under thermal stresses. Their occurrence is closely related to temperature gradient, solidification mode, and microstructure, among other factors (Ref. 29). The grain size in the EGZ is significantly influenced by the welding thermal cycle and the subsequent cooling process (Ref. 30). The

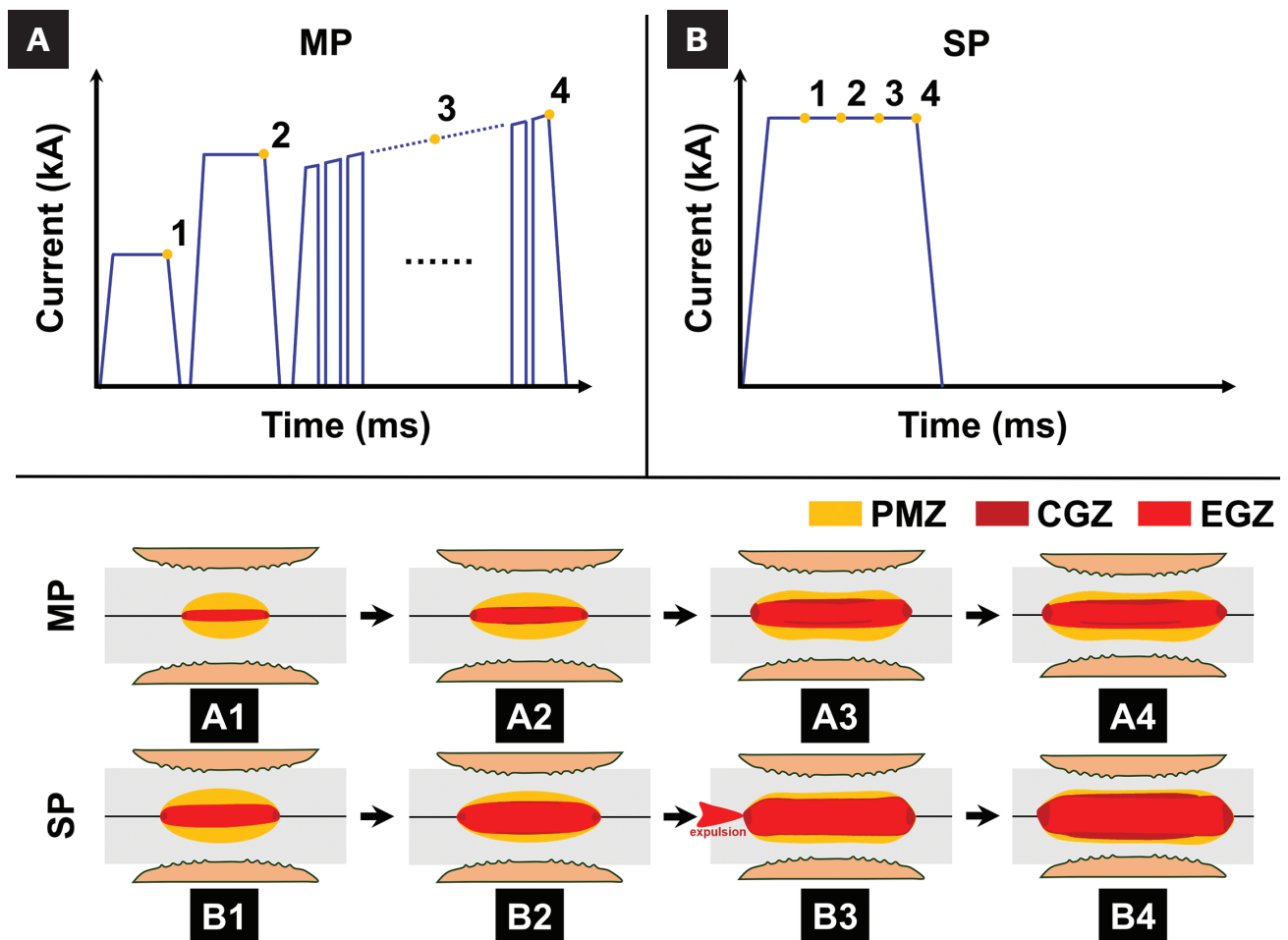


Fig. 10 — The process mechanism diagram of MP and SP nuggets growth: A — MP nugget; B — SP nugget; A1–A4 — schematic diagram of nugget growth mechanism during MP parameter welding, corresponding to points 1, 2, 3, 4 in A; B1–B4 — schematic diagram of nugget growth mechanism during SP parameter welding, corresponding to points 1, 2, 3, 4 in B.

MP process is followed by rapid cooling after each heating pulse, which significantly increases the instantaneous undercooling and thermal gradient in the EGZ, thereby promoting the nucleation of high-density equiaxed grains. Meanwhile, the repeated thermal cycles of heating and cooling limit the time available for grain growth, resulting in the formation of finer grains within the EGZ. In contrast, the SP process, lacking cooling intervals, produces fewer nucleation sites due to lower undercooling. The sustained high temperature near the liquidus line allows sufficient time for grain growth, thereby producing coarser grains in the EGZ (Ref. 31). Therefore, compared to the SP process, the fine grains in the EGZ formed by the MP process result in a significantly greater number of grain boundaries.

As shown in Fig. 12A, EBSD analysis reveals that although the MP nugget shows no macroscopic cracks, microcracks are still observed within the EGZ. These microcracks are significantly finer and more discontinuous than those in the SP nugget. In contrast, the SP nugget contains larger grains with fewer grain boundaries, leading to broader, more continuous crack paths. The refined grain structure produced by the MP process increases the number and density of grain bound-

aries, which promotes more frequent crack deflection and fragmentation of the crack front. As a result, crack propagation becomes more tortuous and energy-dissipated under MP conditions. In contrast, cracks in the SP nugget propagate along long, uninterrupted paths that promote the formation of large, macroscopic cracks. In addition, the formation of solidification cracks is strongly influenced by the temperature gradient and the solidification mode during welding (Ref. 32). It is well established that a steep temperature gradient promotes directional solidification and can increase susceptibility to cracking due to higher thermal stresses and localized strain accumulation. In contrast, a reduced temperature gradient promotes equiaxed growth and reduces stress concentrations during solidification. The MP process involves multiple pulse-heating and cooling cycles, which effectively reduce the instantaneous thermal gradient in the melt pool and modify the solidification conditions. This reduced thermal gradient under MP conditions favors a transition toward more equiaxed solidification and diminishes the propensity for large macroscopic cracks compared with the SP process.

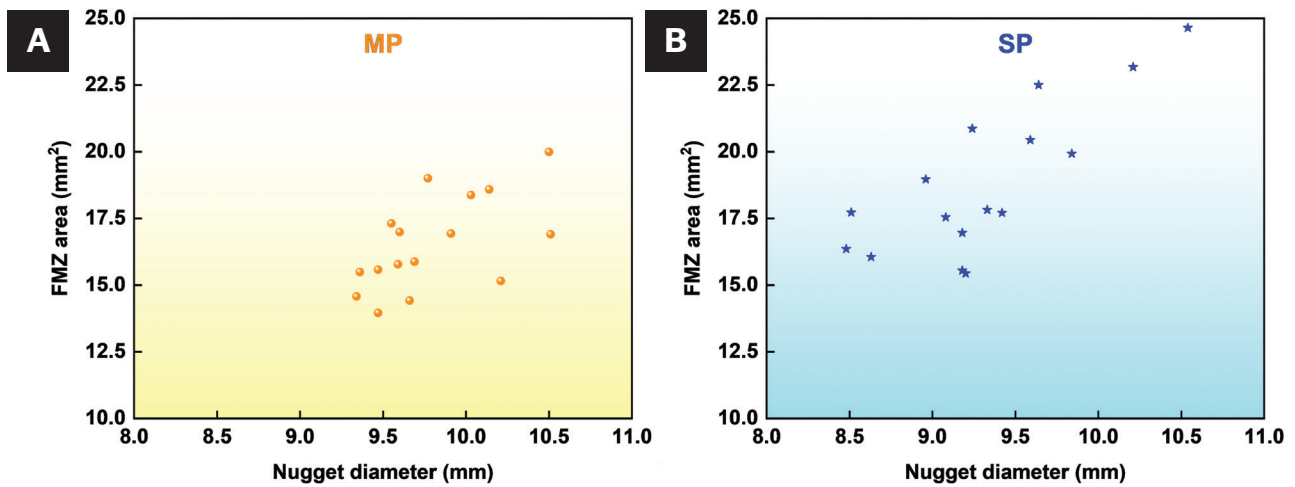


Fig. 11 — The variation trend of FMZ area with increasing nugget diameter for MP and SP nuggets: A — MP nuggets; B — SP nuggets.

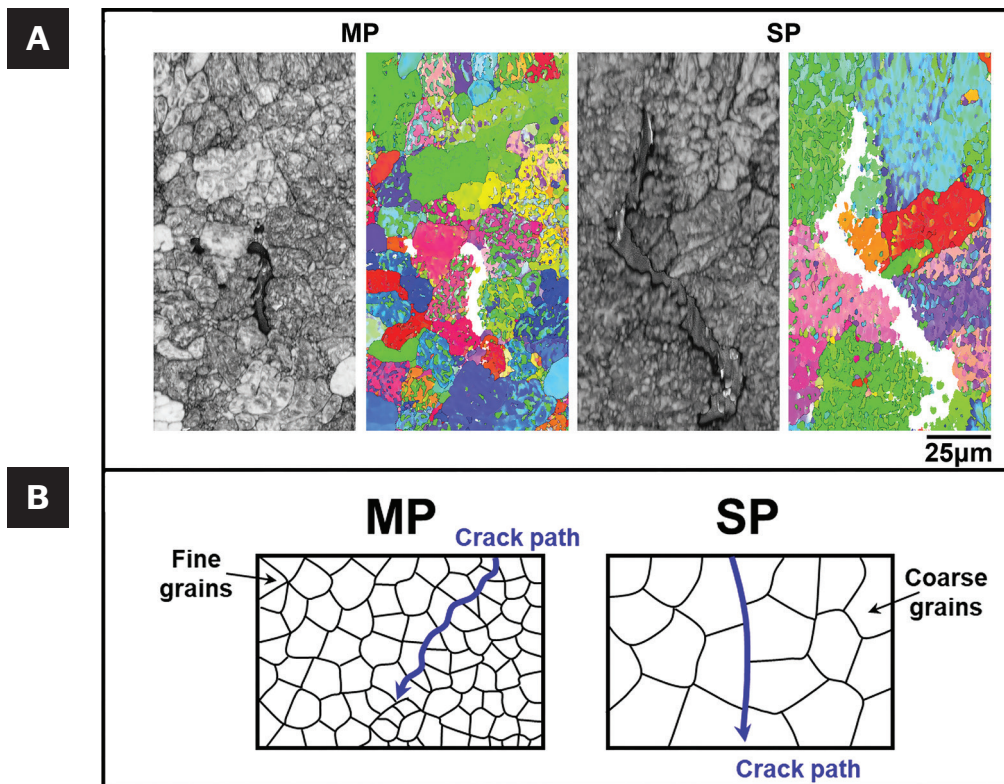


Fig. 12 — Comparison of hot crack features and crack resistance mechanisms in SP and MP nuggets: A — Hot cracks in MP and SP nuggets; B — mechanism of crack resistance enhancement by grain refinement.

Figure 12B further illustrates this mechanism: the MP process increases the number of grains in the EGZ, thereby increasing the number and density of grain boundaries, which enhances crack deflection and energy dissipation during crack propagation (Ref. 33). Consequently, the nugget formed by the MP process exhibits almost no macroscopic cracks compared to that formed by the SP process.

Conclusions

This study systematically compared the RSW nugget SP welding processes. Detailed analyses were conducted on the macroscopic morphology, microstructure, and formation mechanism of the nuggets. The key findings are:

- Both the MP and SP nugget regions can be divided into PMZ and FMZ. The FMZ consists of CGZ and EGZ. The PMZ exhibits a microstructure similar to that of the BM, while the FMZ is clearly formed through complete melting and

solidification. In the FMZ, the CGZ shows distinct directional solidification characteristics, whereas the EGZ exhibits features of simultaneous solidification.

■ The relatively thick PMZ observed in resistance spot welding of HPDC aluminum alloy can be attributed to the inherent microstructural inhomogeneity and melting point variation of the BM. Based on the observed microstructural features and known melting ranges of the constituent phases, it can be inferred that the PMZ experiences temperatures between the eutectic Si and α -Al dendrite melting ranges, resulting in a solid-liquid coexistence state. Therefore, after solidification, the microstructure observed in the PMZ is predominantly composed of α -Al.

■ In the SP process, continuous high-temperature input transforms the PMZ into FMZ, reducing the area of the PMZ. In contrast, the MP process involves heating-cooling cycles that prevent the temperature from rising further, resulting in a thicker PMZ. Consequently, the cross-sectional area of FMZ in SP nuggets is 30% larger than that in MP nuggets under the same nugget diameter, with an average increase in the equivalent FMZ thickness of 20%.

■ Based on EBSD measurements taken from four distinct regions within the EGZ for each welding condition, the MP nugget produces consistently smaller EGZ grain sizes compared with those in the SP nugget. The average EGZ grain size is reduced from $30.47 \pm 17.73 \mu\text{m}$ in the SP nugget to $19.48 \pm 10.46 \mu\text{m}$ in the MP nugget, accompanied by a marked increase in the fraction of fine grains. The heating-cooling thermal cycles of the MP process effectively refine the grain size in the EGZ and increase the number of grain boundaries, thereby hindering hot crack propagation and reducing the risk of crack formation.

Acknowledgments

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Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China. **ZHENKE TENG** and **JASON BROWN** are with Global Manufacturing Engineering at the General Motors Global Technical Center, Warren, Mich.

YUHAO WANG, ZHUORAN LI, YUJUN XIA, HUIHONG LIU, YONGBING LI (yongbinglee@sjtu.edu.cn), **ZIXUAN CHEN**, and **CHENG LIU** are with the Shanghai Key Laboratory of Digital Manufacture for Thin-walled Structures, State Key Laboratory of Mechanical System and Vibration, School of