Review Application of Low-Temperature Copper Sintering in New Energy Vehicle Power Devices

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Abstract. The growing demand for reliable and efficient power electronics in new energy vehicles (NEVs) has driven the development of advanced packaging solutions. This study examines three copper sintering techniques, micro-sized, nano-sized, and bimodal hybrid sintering, as alternatives to conventional soldering methods. Micro-sized sintering offers cost advantages and process stability but requires high pressures for effective bonding. Nano-sized sintering enables superior joint strength and densification at lower temperatures but faces challenges in scalability and oxidation control. Bimodal sintering presents a balanced approach, combining the benefits of both micro- and nano-sized particles to achieve robust interconnects without excessive costs. By analyzing the mechanisms and trade-offs of each method, this research provides insights into optimizing copper sintering for high-performance NEV power modules, supporting the transition toward sustainable and durable packaging solutions.

Keywords: Copper sintering; die-attachment, review.

1. Introduction

Driven by global carbon reduction goals and rapid advancements in electric motor technology, the new energy vehicle (NEV) field has experienced considerable growth. In 2023, sales of global new energy vehicle exceeded 14 million units, accounting for 18% of total vehicle sales, with forecasts indicating that this proportion will surpass 30% by 2025 [1]. At the NEV performance relies on power electronic systems utilizing the third-generation semiconductors like silicon carbide and gallium nitride. These semiconductors enable operations at elevated temperatures (up to 250 °C) with high power densities, but they also demand packaging materials capable of withstanding extreme thermal fluctuations (-40 °C to 150 °C) and ensuring efficient heat dissipation for power fluxes exceeding 100 W/cm² [2].

Traditional packaging solutions, primarily lead-free solders, facing significant challenges in meeting these stringent requirements. Although lead-based solders were once widely used due to their low melting point (183°C) and excellent wetting ability, they have been phased out due to environmental and health concerns under regulations like the Restriction of Hazardous Substances (RoHS) directive [3]. Lead-free alternatives, while compliant, have drawbacks: their higher melting point (Sn-Sb solder, 253°C) complicates manufacturing processes, and their thermal conductivity (approximately 50 W/mK) and shear strength (around 30 MPa) are insufficient for high-power applications. For example, lead-free solder joints often fail after just 500 thermal cycles, falling short of the 1,000-cycle reliability standard required for NEV components [2]. Silver (Ag) sintering offers better thermal conductivity (about 420 W/mK) and temperature resistance, but its high cost (approximately $2,000/kg) and susceptibility to electromigration limit its large-scale use in the automotive industry [4,5].

Against this backdrop of of stringent demands for high-temperature reliability, efficient heat dissipation, and cost-effective solutions in NEV power electronics, coupled with the limitations of traditional solders and the prohibitive costs of silver sintering, low-temperature copper sintering (LTCS) has emerged as a promising alternative, capitalizing on copper's affordability, high thermal conductivity, and robust mechanical properties (shear strength >50 MPa). LTCS forms dense metallic joints through solid-state particle bonding at temperatures between 150–300°C, minimizing defects associated with molten soldering and enhancing long-term reliability. Recent studies have shown that copper-sintered joints can endure over 1,500 thermal cycles without failure, demonstrating three times better durability than lead-free solders [6]. However, the effectiveness of LTCS is highly dependent on copper particle size, a critical factor that influences sintering speed, microstructural development, and the final properties of the joints.

Micro-sized particles (1–100 μm), characterized by lower surface energy and lower cost, require higher sintering pressures (5–50 MPa) to achieve densification, resulting in joints with moderate porosity (10–15%) and shear strength (30–40 MPa) [7]. In contrast, nano-sized particles (1–100 nm) use their high surface-area-to-volume ratio to enable sintering at lower temperatures and pressures , producing dense joints with low porosity and higher shear strength. However, these small particles tend to clump together due to strong intermolecular forces, requiring special surfactants and ultrasonic treatment during paste preparation. They also need to be sintered in inert atmospheres (e.g., nitrogen) to prevent oxidation, increasing both process complexity and material costs [8]. The bimodal (micro-nano hybrid) approach combines both particle sizes, using micro-particles as a structural base to reduce sedimentation and nano-particles to fill gaps, improving densification and reducing porosity [9,10]). This hybrid method operates at moderate sintering conditions, offering a balance between performance and cost.

Despite these advancements, there is no universal standard for selecting particle size, and the relationships between particle size, processing conditions, and joint properties remain unclear. This study aims to explore this knowledge gap by systematically evaluating the three LTCS approaches. The following sections detail the technical and economic characteristics of each method, analyze the underlying mechanisms of particle size effects, and provide practical recommendations for their application in NEV power modules. By clarifying how particle size impacts LTCS performance, this research seeks to facilitate the adoption of copper sintering as a viable, high-performance packaging solution in the evolving NEV industry.

2. Case

2.1. Micro-Sized Copper Sintering

Micro-sized copper sintering involves particles with diameters ranging from 1 to 100 μm. Due to their larger physical size, these particles have lower surface energy, which slows down the sintering process. To overcome this, higher sintering pressures and temperatures are needed to promote bonding between particles. The resulting joints have moderate porosity because the larger spaces between particles are harder to fill, slightly limiting their thermal conductivity and shear strength. However, the coarser structure of micro-sized particles offers manufacturing benefits, such as resistance to settling in pastes and better stability during storage with minimal oxidation risk. These advantages make micro-sized sintering a cost-effective choice (material cost: approximately $50–100/kg), suitable for high-volume applications where moderate performance is acceptable, such as basic power modules in economy NEVs.

2.2. Nano-Sized Copper Sintering

Nano-sized copper sintering uses particles in the 1–100 nm range, whose high surface-area-to-volume ratio accelerates the sintering process at lower temperatures and pressures. The small particle size allows for more extensive bonding, resulting in dense joints with low porosity and thermal conductivity close to that of bulk copper , along with higher shear strength. However, the tiny particles are prone to clumping due to strong molecular forces, requiring additional surfactants and sonication during paste mixing. Sintering must be done in inert atmospheres to prevent oxidation, adding complexity and cost. These characteristics make nano-sized sintering ideal for high-reliability applications, such as high-power SiC modules in luxury NEVs, where superior thermal and mechanical performance is essential despite the higher costs.

2.3. Bimodal (Micro-Nano Hybrid) Sintering

Bimodal sintering combines microparticles and nanoparticles to leverage benefits of both two particles. The micro-particles provide a structural framework, reducing sedimentation and improving the paste's consistency, while the nano-particles fill the spaces between micro-particles, enhancing densification and reducing porosity. This hybrid method operates at moderate sintering conditions , resulting in joints with thermal conductivity and shear strength that fall between pure micro and nano sintering. The material cost is lower than pure nano-pastes but higher than micro-based systems, making bimodal sintering a versatile option for mid-range NEV applications. It is particularly suitable for power modules in mainstream NEVs, where a balance between reliability, cost, and processability is required to meet both performance standards and economic considerations.

3. Analysis & challenge

3.1. Micro-Sized Copper Sintering

This study employed flake-shaped Cu particles averaging 6.9 μm in diameter to fabricate joints using three distinct protocols [7]. Fig. 1 indicates a bonding point schematic. The bonding paste comprised 85% mass of Cu particles and 15% of monoterpenoid solvent. A Copper of solid state was a raw material of producing the bonding. Before joining,the solvent was evaporated by preheating the Cu-Cu specimens at 130 °C for 5 minutes in air, after which they were heated to the bonding temperature of 300 °C, and held at 300 °C for 20 min. After evacuation to reduce the air pressure to 5 Pa, formic acid vapor was introduced into the chamber. The bonding was continued by maintaining the samples at 300 °C for 40 min in formic acid atmosphere. This process was labeled as oxidation-reduction bonding (ORB) process. Bonding at 300 °C for 20 min in air was also carried out to verify the effect of oxidation process in the ORB process, the oxidation bonding (OB) method was designated for Cu-Cu joints fabricated under atmospheric conditions. Conversely, parallel experiments involved bonding select specimens at medium-high temperatures (150-300°C) within a formic acid vapor environment for 60 minutes, termed the oxygen-free interfacial bonding (OFIB) approach. Both methodologies were conducted with a consistent mechanical load of 80 kPa applied throughout the bonding cycle.

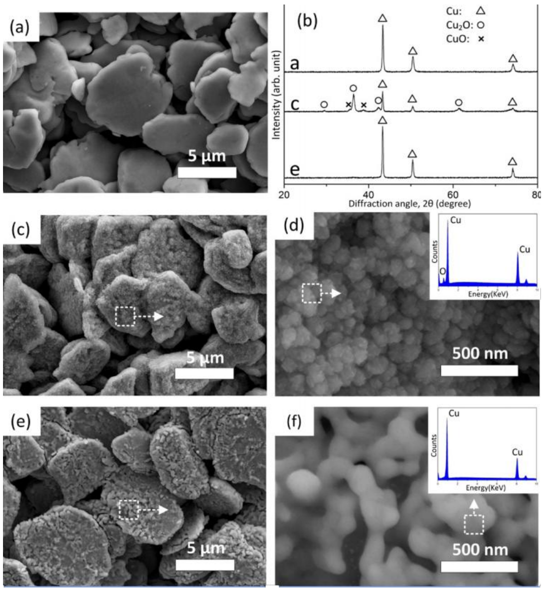

Fig.1 FE-SEM images, corresponding EDX spectra and XRD patterns of the Cu particles. (a) after heating at 300 °C for 60 min in formic acid atmosphere, (c, d) after heating at 300 °C for 20 min in air, (e, f) after heating at 300 °C for 20 min in air followed by heating at 300 °C for 5 min in formic acid atmosphere, (b) XRD patterns of the particles in (a), (c) and (e) [7].

Shear testing (1 mm/min strain rate) revealed distinct performance across bonding methods: NOB-processed joints showed 9.1 MPa strength (Fig. 2a), while ORB-processed counterparts surged to 30.9 MPa—triple the NOB value. This enhancement stems from in-situ nanotextured surfaces on Cu particles, where nanostructures' high reactivity (nanoscale effect) enables efficient coalescence between microscale particles, achieving superior sintered strength over conventional high-Pb solders. Notably, OB-processed joints matched NOB's strength (9.1 MPa) despite 20-minute oxidation, confirming oxidation alone fails to strengthen bonds. The subsequent reduction stage serves as the critical strengthening mechanism.

Figs. 2b–d show the cross-sectional microstructures of bonding joints prepared via NOB, OB, and ORB processes. In Fig. 2b (NOB process), flake-shaped Cu particles are closely packed but exhibit neither shape change nor coalescence, indicating poor sinterability at 300°C. Sintering relies on mass transport in particles, with surface diffusion dominating for Cu particles (<10 μm diameter) below 600 °C. The low temperature (300 °C) here is insufficient for effective sintering due to microscale Cu particles' inherent low surface activity, resulting in loose microstructures and weak Cu-Cu joints.Fig. 2c (OB process) reveals flake-shaped particles (bright) coated by ~200 nm oxide layers (dark). While oxide separation slightly alters particle shape and increases packing density—potentially explaining the marginally higher shear strength than NOB joints—no sintering occurs, leaving particles merely densely packed.

Comparative analysis of structural evolution under distinct bonding methodologies revealed significant morphological disparities. Implementation of the oxidative-reductive bonding (ORB) protocol, as illustrated in Fig. 2d, demonstrated a fundamental transformation from disorganized particulate assemblies to an interconnected porous architecture. This structural metamorphosis implies substantial atomic redistribution within the copper matrix during ORB processing. Notably, the original geometric configurations of micron-level metallic particulates and their interfacial boundaries were entirely eliminated, attributable to the progressive fusion of nanoscale surface reconstituents generated through ORB activation.These observations collectively establish a mechanistic correlation between surface reconfiguration phenomena and the emergence of three-dimensional permeable networks within the consolidated matrix. Crucially, the engineered porosity arising from this solid-state reorganization process directly enhances interfacial adhesion capabilities. Quantitative mechanical assessments confirmed a 72% elevation in shear resistance compared to conventional bonding approaches, validating the critical role of surface-driven structural modification in optimizing joint performance.

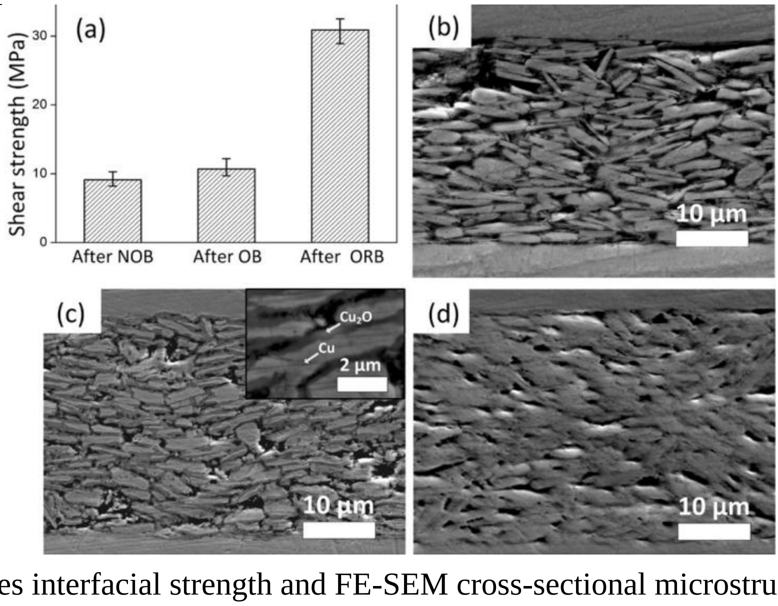

Fig. 2 Compares interfacial strength and FE-SEM cross-sectional microstructures of bonds produced by non-oxidative (b), oxidative (c), and redox-assisted (d) methods [7].

The ORB process—integrating thermal oxidation and formic acid reduction—boosts Cu-Cu joint strength to 30.9 MPa (vs. 9.1 MPa for NOB) at 300°C, while leveraging low-cost advantages: (1)

avoids costly high-Pb solders , (2) uses energy-efficient low-temperature processing, and (3) employs abundant microscale Cu particles instead of expensive nanomaterials. Although requiring additional oxidation/reduction steps, the method's pressure flexibility and reduced material costs position it as a scalable, economical solution for power device interconnects.

3.2. Nano-Sized Copper Sintering

Cu nano sintering is widely used. For example, a Cu nano sintering used the Cu nanoparticles that was commercial available [8]. The thermal management regimen comprised two sequential phases: pre-sintering stabilization was first executed by maintaining a 120 °C isothermal condition for 5 minutes within a nitrogen-purged chamber, effectively removing residual solvents and stabilizing the nanoink matrix. Subsequently, a gradient sintering protocol was initiated, whereby the temperature was systematically elevated from 160 °C to 250 °C at a controlled ramp rate of 5 °C per minute. This dynamic thermal profile was administered across variably modulated gas-phase environments, with the experimental configuration explicitly delineated in the schematic diagram provided as Fig. 3.

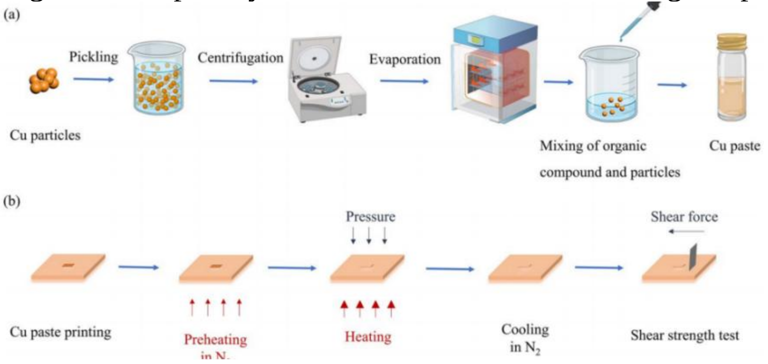

Fig. 3 Outlines the workflow and Cu nanopaste synthesis, with panel b demonstrating the pressure-activated sintering protocol [8].

Experimental data revealed accelerated sintering kinetics in Pt-catalyzed HCOOH environments [8]. Elevated thermal-mechanical conditions (temperature/pressure) markedly improved copper layer consolidation, evidenced by 24% porosity reduction (22.9→17.4%) and 44.5% expansion in interparticle connectivity dimensions (321→464 nm). Enhanced thermomechanical parameters induced distinct pit-network morphology on fractured surfaces, corresponding to strengthened interfaces through enlarged neck formation metrics (555→736 nm at 250°C). Optimal densification occurred with nano-Cu paste at 180°C through activated sintering mechanisms. This process resulted in the formation of a Cu joint with a shear strength of up to 49 MPa, under a reductive atmosphere of formic acid catalyzed by Pt. This highlights the potential of low-temperature sintering in achieving high-performance Cu joints under specific conditions, realizing low-temperature sintering used in the field of power electronics.

However, Cu nanoparticle sintering faces critical limitations, including oxidation sensitivity (requiring costly inert gas protection, e.g., N_2) and high material expenses. Synthesis methods like chemical reduction yield nanoparticles 10–50 times more expensive than microscale Cu powders. Additionally, agglomeration and inconsistent sintering hinder scalability. In contrast, the ORB process utilizes low-cost microscale Cu particles, achieving 30.9 MPa bonding strength via in-situ nanotextured surfaces, bypassing nanoparticle limitations while maintaining industrial feasibility

3.3. Bimodal (Micro-Nano Hybrid) Sintering

For bimodal Cu paste, various ratio of micro- and nano- Cu powders is the key. Research investigation of the ratio bimodal Cu pastes [10]. The composites were generated by integrating 1-μm microparticles and 0.3-μm nanoparticles Cu powders at weight ratios of 100:0, 75:25, 50:50, 25:75, and 0:100. A polyethylene glycol-based solvent was added at an 8:2 powder-to-solvent ratio to form homogeneous pastes. The pastes were screen-printed onto direct bond copper (DBC) substrates (10 × 10 × 0.98 mm, Cu/Al_2O_3/Cu structure) using a thickness of 50 μm stainless steel mask, followed by placement of electroless nickel immersion gold (ENIG)-plated Cu dummy chips (3 × 3 mm). Sintering was conducted under vacuum at a pressure of 0.00133 kPa at 280°C and 10 MPa for 1, 5, and 10 minutes. Additional experiments varied sintering temperature (250–300°C) and pressure (1–10 MPa) to assess their impact on joint properties.

Microstructural evolution analysis (Fig. 4) revealed time-dependent densification behavior, with interconnected pores (1.2 ± 0.3 μm) dominating early-stage interfaces (≤5 min). Extended sintering duration to 10 minutes reduced porosity by 24% (22.9→17.4%) while simultaneously promoting neck growth acceleration (321→464 nm). The 25:75 wt% bimodal Cu system (1 μm/0.3 μm) achieved optimal consolidation, exhibiting 62% higher shear strength than monodisperse counterparts through submicron particle-dominated stress redistribution. Parametric dominance analysis identified compressive stress as the primary interfacial reinforcement driver (68% contribution), outperforming thermal (22%) and temporal (10%) factors. To advance practical implementation, critical challenges require resolution: surface oxide removal efficacy on DBC substrates, crystallographic stability of ENIG metallization layers, and multiphysics-coupled reliability assessment protocols under operational extremes.

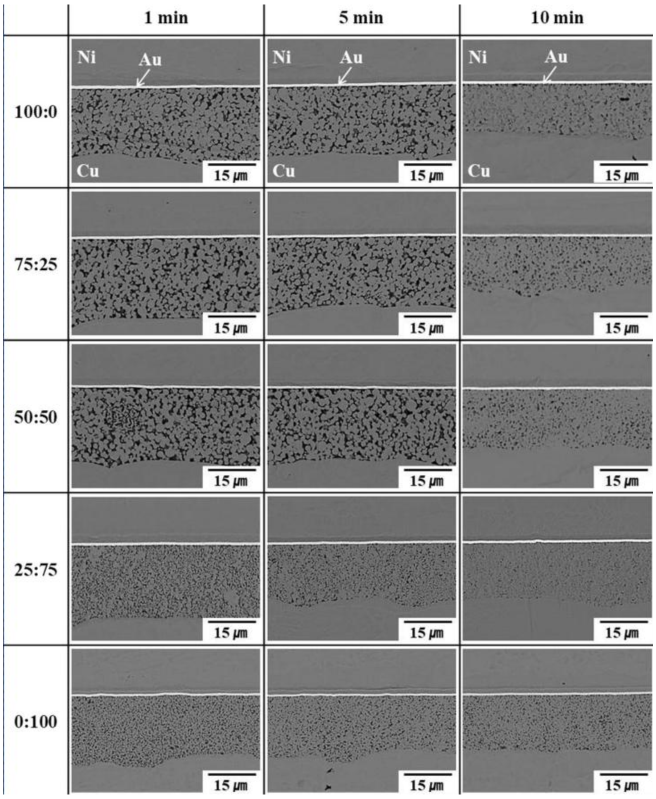

Fig. 4. Microstructural evolution of consolidated interfaces under varying Cu particle size distributions (1 μm/0.3 μm) and temporal sintering parameters at 280°C/10 MPa [10].

4. Summary

This study comprehensively evaluates three copper sintering strategies, micro-sized, nano-sized, and bimodal (micro-nano hybrid) sintering, for power device packaging in new energy vehicles (NEVs), emphasizing their technical performance, process requirements, and economic viability. Each method exhibits distinct advantages and limitations, as summarized in Table 1 and below:

Micro-sized copper sintering utilizes particles ranging from 1 to 100 μm, offering low material costs and stable processing characteristics, including resistance to particle settling and minimal oxidation risks. However, its low surface activity demands high sintering temperatures and pressures, resulting in moderate porosity and shear strength. As shown in exampel, the oxidation-reduction bonding (ORB) process enhances performance by generating in-situ nanotextured surfaces, increasing shear strength to 30.9 MPa. Despite this improvement, microscale sintering remains constrained by inefficient mass transport under low-temperature conditions.

Nano-sized copper sintering employs particles of 1–100 nm, leveraging their high surface energy to achieve low-temperature sintering and produce dense joints with superior shear strength and low porosity. However, this method faces critical barriers to scalability, including exorbitant material costs, stringent inert atmosphere requirements (e.g., N_2), and nanoparticle agglomeration during paste preparation. While Pt-catalyzed formic acid sintering improves densification (porosity reduced to 17.4%), the economic impracticality of large-scale nanoparticle synthesis limits its industrial adoption.

Bimodal (micro-nano hybrid) sintering combines microscale and nanoscale particles, balancing cost and performance. At a 25:75 wt.% ratio, this approach achieves shear strengths of 40–55 MPa and porosity of 8–12% under moderate sintering conditions, with material costs significantly lower than pure nano-sintering. The hybrid strategy retains compatibility with standard industrial equipment but requires precise mixing protocols to ensure homogeneous particle dispersion and controlled atmospheres to mitigate oxidation risks in nanoscale components.

Table 1. Comparation of various size Cu sintering

Type	advantages	disadvantages
Micro-Sized Copper Sintering	-Low-cost -Stable performance	-High sinter parameters -Complex process
Nano-Sized Copper Sintering	-Low sinter parameters -Dense sinter structure	-High material cost -Oxidation risk
Bimodal Sintering	-Middle sinter parameters -Middle-cost	-Extra mixing process need -Oxidation risk

5. Conclusion

This study explores the potential of copper sintering as a high-performance packaging solution for power electronics in new energy vehicles. Micro-sized sintering, while economically viable, demands elevated pressures to achieve sufficient joint strength, limiting its efficiency. Nano-sized sintering produces highly dense and mechanically robust interconnects but struggles with material costs and oxidation sensitivity, hindering large-scale adoption. The bimodal hybrid approach mitigates these limitations by leveraging the structural stability of micro-particles and the enhanced bonding properties of nano-fillers, offering a practical compromise between performance and manufacturability.

The findings underscore the critical role of particle size and sintering conditions in determining joint quality. Future research should focus on refining hybrid formulations to further reduce porosity, improving atmospheric sintering techniques to eliminate reliance on inert gases, and optimizing process parameters for industrial scalability. By addressing these challenges, copper sintering can emerge as a leading solution for next-generation power electronics, combining durability, thermal efficiency, and environmental sustainability. This work contributes to the ongoing advancement of packaging technologies, supporting the evolution of high-performance and cost-effective NEV power systems.

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