UDK 631.824:621.791.763
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

RESEARCH ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF DISSIMILAR MAGNESIUM ALLOYS USING RESISTANCE SPOT WELDING METHOD

MIKROSTRUKTURA IN MEHANSKE LASTNOSTI TOČKOVNO ZVARJENIH SPOJEV IZ RAZLIČNIH MAGNEZIJEVIH ZLITIN

Wanqi Hou[1], Zheng Jia[1,2*], Qiuli Chen[1], Xiaowei Niu[2]

[1]College of Mechanical Engineering, Shenyang University, Shenyang 110044

[2]College of Environment, Liaoning Province Environmental Pollution Remediation Professional Technology Innovation Center & Shenyang Key Laboratory of Collaborative Technology Innovation for Industrial Pollution Reduction and Carbon Reduction, Shenyang University, Shenyang 110044, China

Prejem rokopisa – received: 2025-02-20; sprejem za objavo – accepted for publication: 2025-07-02

doi:10.17222/mit.2025.1399

The mechanical behavior of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys under tensile loading and evaluates the impact of resistance-spot-welding parameters on joint microstructure, nugget size, and tensile strength were investigated. Through XRD, SEM, and Vickers hardness analysis, the microstructural evolution, hardness profiles, and fracture features of welded joints were characterized. Results demonstrate that optimized parameters (0.6 kN electrode force, 0.4 s welding time, 16 kA current) yield a peak joint strength of 1.001 kN, offering insights for refining magnesium-alloy welding processes.

Keywords: resistance spot welding, Mg-Sn alloys; tensile strength, microhardness profile

Avtorji v članku opisujejo raziskavo mehanskega obnašanja uporovno točkovno zvarjenih spojev med tankima pločevinama iz magnezijevh zlitin tipa Mg-1Sn-1Ca in Mg-2Sn-0,5Ca. Ocenili so vpliv parametrov uporovnega točkovnega varjenja na mikrostrukturo spoja, velikost spojev in natezno trdnost. Z rentgensko difrakcijo fazno analizo (XRD), vrstično elektronsko mikroskopijo (SEM) in merjenjem Vickersove trdote po preseku zvarnega spoja so okarakterizirali razvoj mikrostrukture, profil trdote in značilnosti loma zvarnih spojev. Rezultati kažejo, da so z optimiziranjem parametrov varjenja (sila elektrode 0,6 kN, čas varjenja 0,4 s, tok 16 kA) dosegli največjo trdnost spoja 1001 kN. Raziskava je na ta način pokazala možnosti izboljšanja postopkov medsebojnega točkovnega uporovnega varjenja različnih magnezijevih zlitin.

Ključne besede: uporovno točkovno varjenje, zlitine na osnovi Mg-Sn, natezna trdnost, profil mikrotrdote, mikrostruktura

1 INTRODUCTION

Magnesium alloys have garnered widespread attention in various industries, such as automotive, aerospace, and electronics, due to their low density, high specific strength, and excellent machinability. Among these alloys, the Mg-Sn system is particularly favored for its outstanding mechanical properties and potential corrosion resistance. The addition of elements such as calcium (Ca) further enhances the alloy's performance, improving its microstructure and increasing its overall strength.

Resistance spot welding (RSW) is an efficient welding technique, particularly suitable for welding thin sheet-metal parts and automated welding in mass production. It is especially useful in industries such as automotive and aerospace, where large-scale welding is required, and it is one of the most widely used joining methods in automotive-body manufacturing. This technique passes current through two electrodes and the contact points between the materials to be welded, utilizing the heat generated by electrical resistance to heat the metal to a molten state. Pressure is then applied to solidify the molten area, thus achieving the weld. Compared to other welding methods, resistance spot welding has a smaller heating area, enabling precise control of the welding process. The welding points are concentrated in small areas, which helps to improve the strength and consistency of the welds.

In recent years, to reduce vehicle weight, improve fuel efficiency, and decrease CO_2 emissions in order to minimize the environmental pollution, the automotive industry has shifted its focus to magnesium alloys.[1] Magnesium and magnesium alloys, with their unique advantages such as low density, high specific strength, high specific stiffness, and high damping capacity, have become the best alternatives to aluminum alloys and steel.[2] This makes magnesium alloys an ideal choice for various structural and functional components. However, the high thermal conductivity and low melting point of magnesium alloys make them prone to overheating and oxidation during the welding process. On the other hand, resistance spot welding offers advantages such as high efficiency, a high degree of automation, and high weld strength. It provides precise temperature control and lo-

*Corresponding author's e-mail:
jz140@163.com (Zheng Jia)

calized heating, which better regulates the temperature and heat distribution during the welding process, thus reducing damage to the magnesium alloy.

Despite the excellent performance of resistance spot welding (RSW) technology in many applications, the widespread use of magnesium alloys is still hindered by challenges in welding technology, particularly in the RSW process.[3,4] Magnesium alloys exhibit low ductility at high temperatures, making them prone to hot cracking and other welding defects, which further affect the performance and reliability of the welded joints. The changes in microstructure during welding, especially the formation of the weld-nugget zone, directly influence the final mechanical properties of the welded joints. Therefore, understanding the relationship between welding parameters (such as welding current, pressure, and time) and the mechanical behavior of the welded joint is crucial for optimizing the welding process and improving the performance of magnesium alloy structures.

In response to the challenges of the RSW of magnesium alloys, researchers and engineers have proposed various improvements.[5–7] One effective approach involves optimizing welding process parameters such as current, pressure, and welding time. By better controlling the temperature during welding, these optimizations help reduce overheating and allow for process tailoring according to different magnesium alloy compositions and thicknesses, ultimately achieving optimal welding results. Therefore, studying the microstructure of RSW joints, welding defects, and optimizing the RSW process to overcome these challenges has become a key research topic in the field of magnesium alloy joining technology.

The aim of this article is to study the effects of different welding currents on the tensile strength, microhardness distribution, and microstructure of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca dissimilar magnesium alloy resistance spot welding joints using techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Vickers hardness testing. The research provides a theoretical basis for the optimization of the magnesium-alloy welding process and the enhancement of its performance.

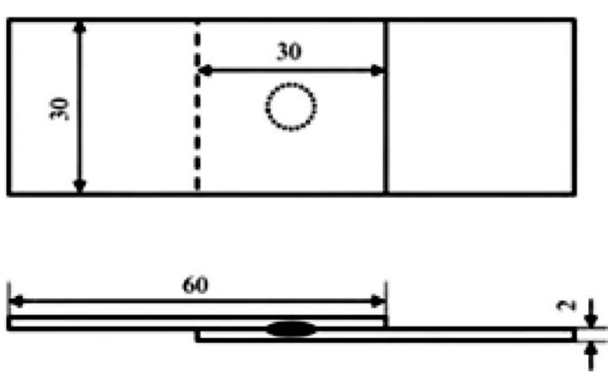

Figure 1: Schematic diagram of the resistance spot welding overlap configuration and tensile test specimen

2 MATERIALS AND METHODS

The materials used for preparing the experimental magnesium alloys (Mg-1Sn-1Ca, Mg-2Sn-0.5Ca) in this study were as follows: industrial pure magnesium (99.9 *w*/%), pure tin (99.9 *w*/%), and Mg-25%Ca master alloy. First, the materials were melted in an electric resistance furnace to prepare the required alloys. The chemical composition of the alloys is detailed in **Table 1.** The alloys were then processed into sheets with specific dimensions of 60 mm × 30 mm × 2 mm, and the sheets were overlapped by 30 mm along the length direction. The specific overlapping method is shown in **Figure 1.**

Table 1: Main chemical composition of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca magnesium alloys.

Alloy Composition	Actual Chemical Composition / *w*/%		
	Sn	Ca	Mg
Mg-1Sn-1Ca	0.88	0.79	Bal.
Mg-2Sn-0.5Ca	2.27	0.55	Bal.

Before the welding process, the plates must undergo thorough pre-welding cleaning, including removing oxide scales, oil stains, and other contaminants from the surface to ensure the cleanliness of the welding area.[8] Resistance spot welding technology generates resistive heat at the contact points of the welding workpieces through electric current. When the workpieces reach a state of thermoplastic deformation, pressure is applied to form a stable welding joint. In this process, the heat input required to form the welding joint, i.e., the resistive heat generated, is closely related to the welding parameters. The setting of the spot-welding parameters directly determines the magnitude of the heat input, which in turn affects the evolution of the nugget structure and the size of the nugget. In this experiment, a Yaskawa spot-welding robot was used for the resistance spot welding. During welding, the electrode pressure was maintained at 0.6 kN, and the welding time was 400 ms. Each welding composition was repeated for three sets of experiments under different currents. The parameters are shown in **Table 2.**

Table 2: Resistance spot welding process parameters.

Welded Samples	Welding Time (ms)	Welding Current (kA)	Electrode Pressure (kN)
Mg-1Sn-1Ca	400	12	0.6
		14	0.6
		16	0.6
Mg-2Sn-0.5Ca		12	0.6
		14	0.6
		16	0.6

The tensile-shear test was conducted on a WSM-100kN tensile testing machine with a tensile-shear rate of 1 mm/min. **Figure 2** is a schematic diagram of the tensile-shear test.

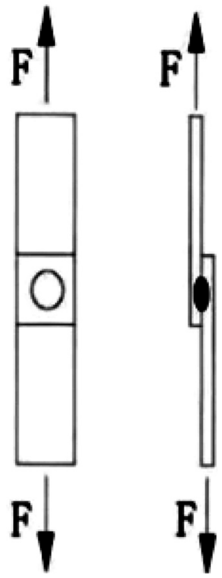

Figure 2: Tensile-Shear Test Diagram

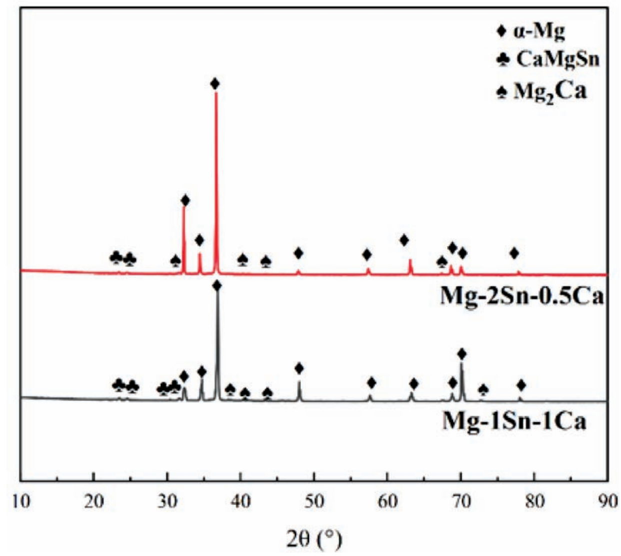

Figure 3: XRD of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca Magnesium Alloys

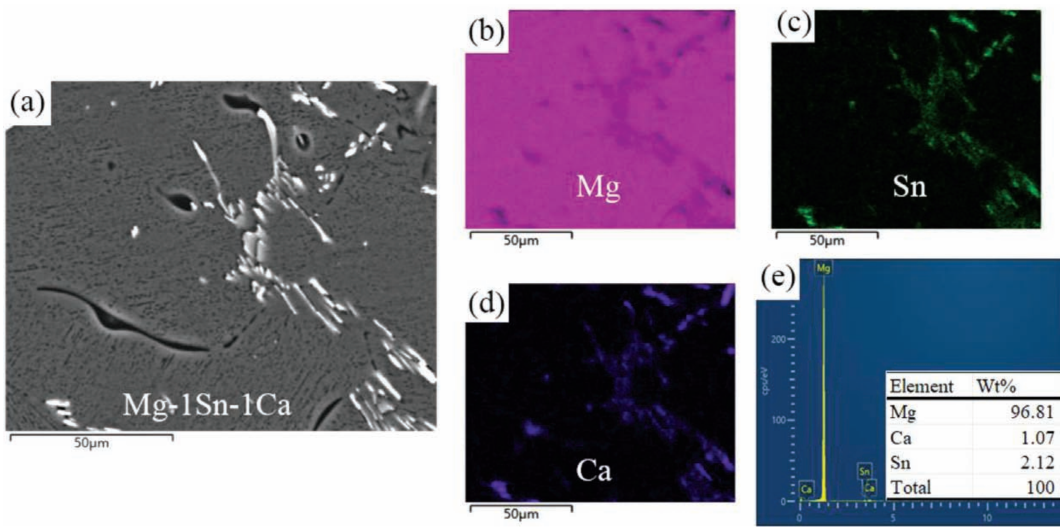

Figure 4: EDS Mapping of Mg-1Sn-1Ca Magnesium Alloy

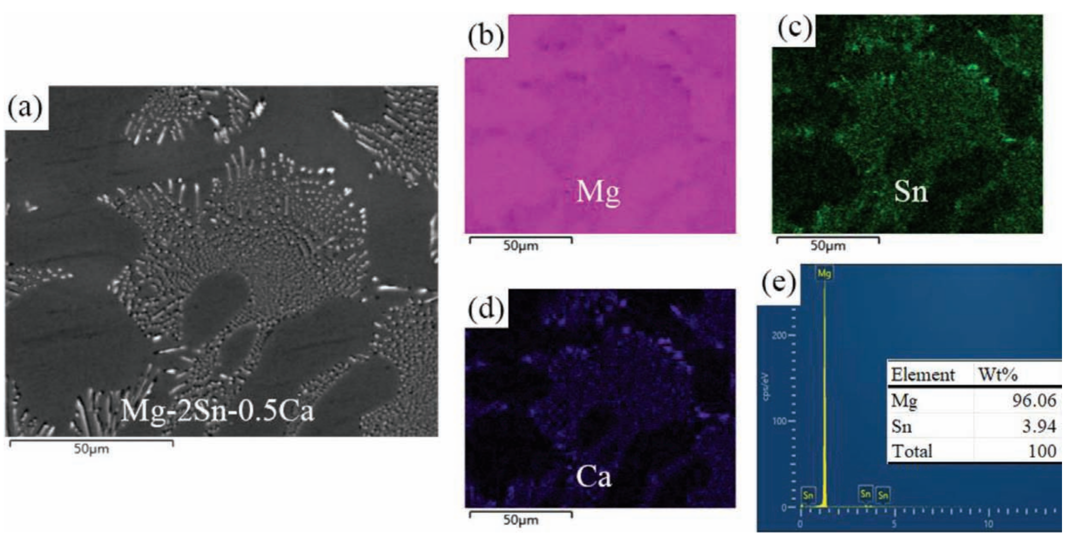

Figure 5: EDS Mapping of Mg-2Sn-0.5Ca Magnesium Alloy

The type, morphology, and distribution of second-phase particles in magnesium alloys are crucial microstructural factors that govern the overall material properties. [9,10] To systematically investigate the effect of Sn addition on the second-phase formation in Mg-Ca alloys, phase analysis of the as-cast alloys was conducted using X-ray diffraction (XRD) and energy-dispersive spectroscopy (EDS) mapping, integrated with scanning electron microscopy (SEM). The results, presented in **Figures 3–5**, reveal the presence of distinct phases, namely, α-Mg, CaMgSn, and Mg_2Ca, across all alloy compositions. These findings provide a comprehensive understanding of the phase evolution and the influence of Sn addition on the microstructural characteristics of the Mg-Ca alloy.

3 EXPERIMENTAL RESULTS

3.1 Microstructural Analysis of Dissimilar Welded Joints of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca Magnesium Alloys

Figures 6a to **6c** present the macroscopic morphology of the Mg-1Sn-1Ca and Mg-2Sn-0.5Ca welded joints under welding currents of 12 kA, 14 kA, and 16 kA, respectively, as observed under low-magnification optical microscopy. These images provide clear evidence of the effect of varying welding current on the morphology and dimensions of the weld nugget, exhibiting a positive correlation. As the welding current increases, the heat input to the weld joint also increases, resulting in a more extensive melting zone and a corresponding increase in the size of the weld nugget. This relationship underscores the critical influence of the welding current on the macrostructure of the weld.

This phenomenon can be attributed to the fact that, at lower welding currents, the heat input to the welded joint is relatively low, insufficient to bring the workpieces to a fully thermoplastic state. Consequently, only a small portion of the workpieces, typically around the area of closest electrode contact, undergoes melting, resulting in a smaller weld nugget. As the welding current increases, the heat input also increases, allowing for more extensive melting of the workpieces and subsequently leading to an increase in the weld nugget diameter. This trend is clearly demonstrated in **Table 3**, where the weld nugget diameter increases from 2.5 mm to 3.65 mm with the increase in welding current. Thus, it can be concluded that welding current plays a pivotal role in determining the weld nugget diameter.

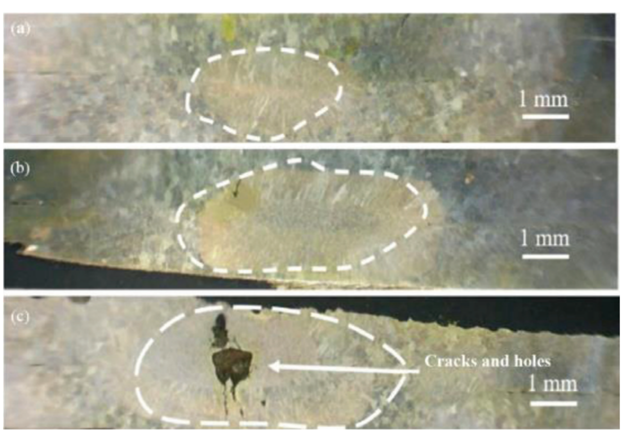

Figure 6: Macroscopic appearance of spot-weld joints

It is crucial to recognize that an excessively high welding current can induce the formation of welding defects, leading to suboptimal weld quality.[11] As illustrated in **Figure 6c**, when the welding current is increased to 16 kA, the weld-nugget diameter reaches its maximum. However, this larger heat input facilitates the emergence of welding cracks and porosity. These defects result in pronounced stress concentration at the crack and pore sites, which compromise the mechanical performance of the welded joint. Such adverse effects are further evident in the subsequent mechanical testing, which demonstrates a marked reduction in the strength and integrity of the weld. This underlines the importance of controlling welding parameters to ensure optimal joint quality.

Therefore, after comprehensively considering the aforementioned factors, to ensure both the feasibility of the welding process and the quality of the welded joints, a welding current of 14 kA is determined to be the most appropriate for the dissimilar welding of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca magnesium alloys. This welding current effectively balances the attainment of an optimal weld nugget size, while minimizing the formation of undesirable defects such as cracks and porosity. As a result, it ensures the mechanical integrity and structural performance of the welded joints, thereby demonstrating the suitability of this parameter for producing high-quality welds.

Table 3: Nucleation diameter of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca at different currents

Welding current (kA)	12	14	16
Nucleation diameter (mm)	2.5	3.5	3.65

Figure 7 presents the microstructure of the nucleation zone formed under different welding currents, as observed through scanning electron microscopy (SEM). The weld joint is composed of three distinct regions: the base metal (BM), the heat-affected zone (HAZ), and the nucleation zone (NZ). The nucleation zone (NZ) is further subdivided into the columnar dendrite zone (CDZ) and the equiaxed grain zone (EDZ). The microstructural characteristics of both the CDZ and EDZ are critical factors that influence the stability and mechanical strength of the welded joint under applied external loads.

The nucleation zone of the magnesium alloy weld exhibits a distinct characteristic of dendritic crystallization.[13] The overall microstructure of the weld joint clearly reveals that the crystal growth direction is predominantly oriented perpendicular to the fusion boundary. This phenomenon can be explained by the compositional undercooling theory of nucleation during the cooling process, wherein the presence of a temperature gradient induces the grains at the periphery of the nucleation zone, adjacent to the heat-affected zone (HAZ), to preferentially grow in a direction normal to the center of the nucleation zone. This growth behavior contrasts with the internal structure of the nucleation zone, which is primarily composed of uniformly distributed equiaxed dendrites. The formation of these equiaxed dendrites provides further insight into the diminished influence of the temperature gradient within the nucleation zone, where the driving force for crystal growth in the direction perpendicular to the center of the nucleation zone is negligible, thereby facilitating the development of a relatively homogeneous microstructure.

As depicted in **Figure 7a**, the grains within the Nucleation Zone (NZ) exhibit a dendritic morphology. This phenomenon can be attributed to the relatively small welding heat input under the 12-kA welding current, which results in a short duration for the formation of the molten pool and consequently leads to a reduced extent of base-material melting.[14] According to the compositional undercooling theory, during the cooling and solidification process, nucleation predominantly occurs in the regions proximal to the heat-affected zone (HAZ). In these regions, the grains at the liquid-solid interface preferentially grow perpendicular to the solid-liquid direction, thereby resulting in the formation of columnar dendrites (CDZ). This crystallographic orientation is influenced by the thermal gradient present during solidifi-

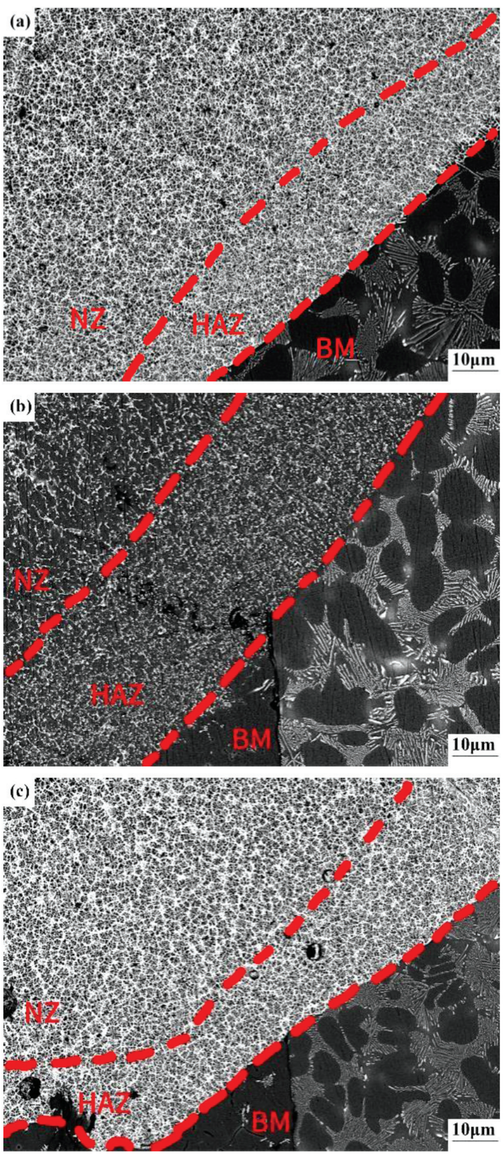

Figure 7: Comprehensive scanning electron microscope (SEM) microstructures of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys under varying welding parameters: a) 12 kA, b)14 kA, c)16 kA

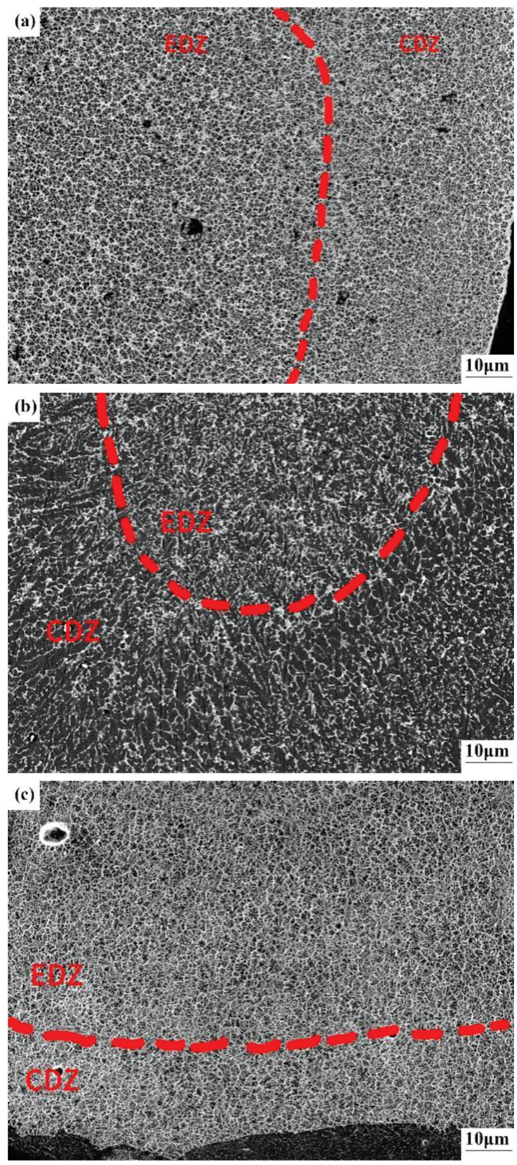

Figure 8: Scanning electron micrographs of the columnar dendritic zone (CDZ) and equiaxed dendritic zone (EDZ) in the nugget zone (NZ) of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys under varying welding parameters: a) 12 kA, b) 14 kA, c)16 kA

cation, which dictates the alignment of the crystal growth direction along the solidification front. The reduced thermal input under the given welding conditions facilitates the establishment of a sharp thermal gradient, contributing to the columnar structure observed in the dendritic grains of the NZ.

Meanwhile, at the center of the weld nugget, the heat dissipation is impeded, leading to a reduced cooling rate and a diminished temperature gradient.[15] This reduction in thermal gradient effectively inhibits the growth of columnar dendrites, causing compositional undercooling to shift from the liquid-solid interface to the center of the weld nugget. Consequently, extensive nucleation occurs at the center, with grains growing in multiple directions, resulting in the formation of a central equiaxed grain zone (EDZ).

Figures 8a to **8c** presents the evolution of the columnar dendritic zone (CDZ) under varying welding currents. Despite changes in heat input, the grain size in the heat-affected zone (HAZ) does not exhibit significant variations, which can be attributed to the high thermal conductivity of the magnesium alloys, facilitating rapid dissipation of the welding heat.[16] As the welding current increases, the total heat input increases, resulting in a gradual contraction of the CDZ within the weld nugget, while the central equiaxed grain zone (EDZ) expands. Concurrently, the grain size tends to coarsen. These phenomena are primarily driven by the compositional undercooling effect during solidification.[17]

3.2 Mechanical Performance Evaluation of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca Welded Joints

As illustrated in **Figure 9**, the fracture morphology of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca after the tensile testing is depicted. In panels **a** and **b**, the fracture at a welding current of 12 kA is observed at the interface between the

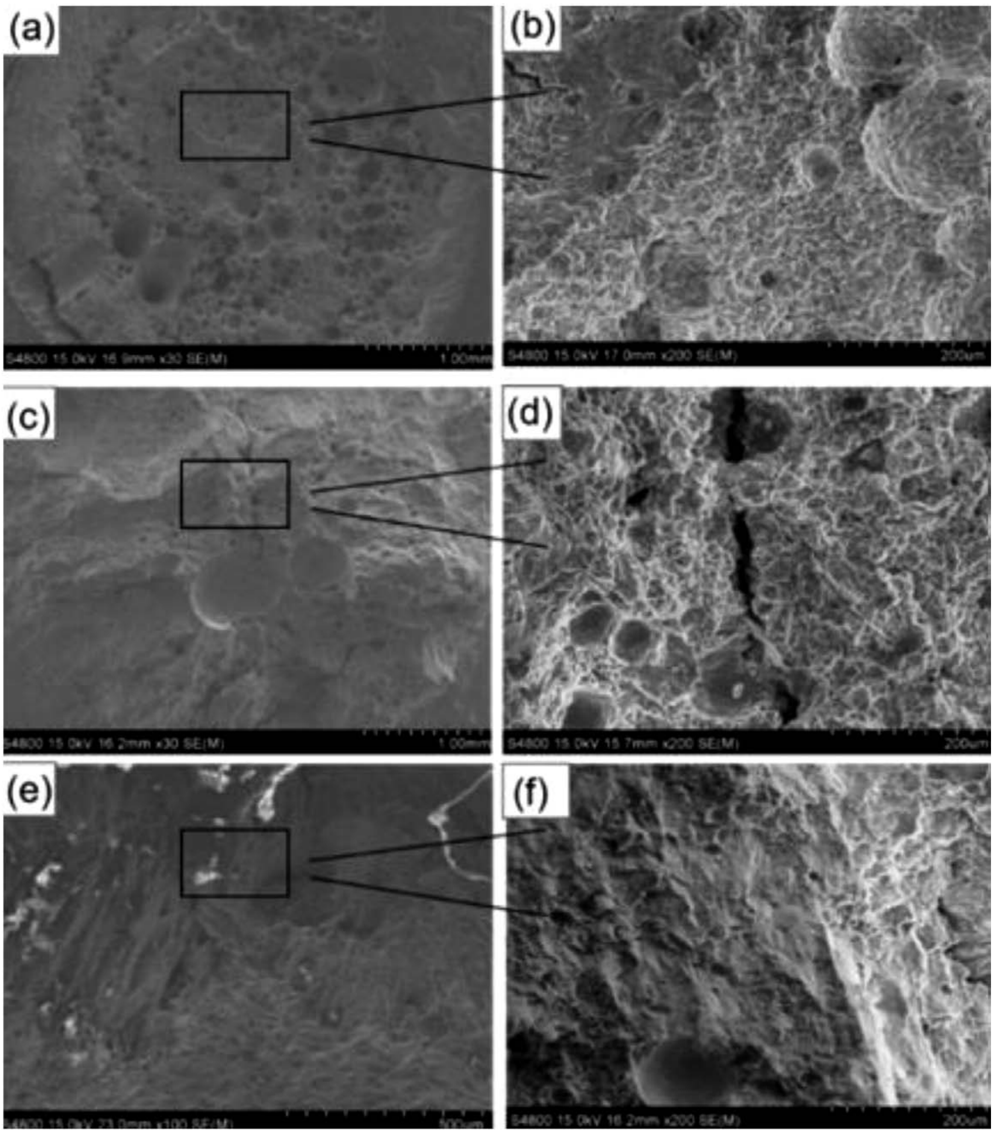

Figure 9: Fracture SEM Morphology Image

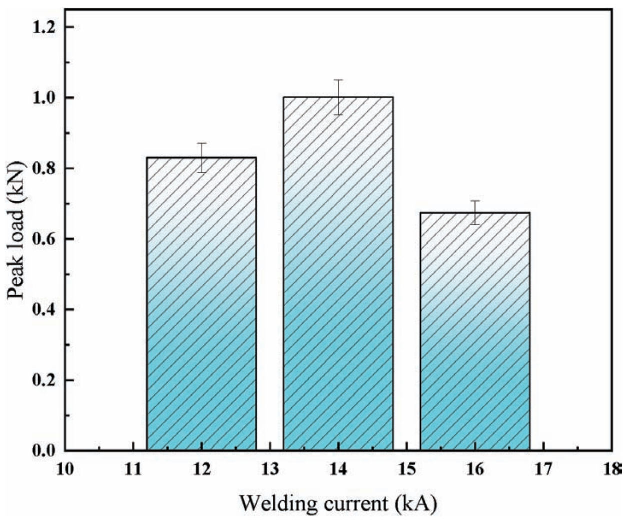

Figure 10: Variation in peak test force as a function of welding current

two plates, with the failure mode being classified as interfacial failure. This phenomenon can be attributed to the relatively small heat input, which results in a reduced size of the fusion zone and suboptimal bonding between the dissimilar alloy base materials. As a consequence, the joint is only capable of withstanding limited shear stresses. When the applied tensile load exceeds the shear strength of the fusion zone, crack initiation occurs at the interface between the dissimilar base materials, leading to rapid crack propagation and, ultimately, interfacial fracture.

At a welding current of 16 kA, the post-weld microstructure exhibits a fracture predominantly at the interface between the Mg-1Sn-1Ca base material and the heat-affected zone (HAZ), with the failure mode being classified as pull-out failure. This failure initiates at the boundary between the nugget zone (NZ) and the HAZ, as clearly seen in the figure.[18,19] The underlying mechanism for this phenomenon can be attributed to the thermal input during the welding process, which generates a thermal cycle that induces grain coarsening within the HAZ. Moreover, the presence of microstructural defects such as voids and cracks at the edges of the fusion zone exacerbates the mechanical properties of the region. During tensile testing, the application of shear stress leads to the accumulation of internal stresses near the HAZ and defect sites, resulting in crack nucleation and subsequent crack propagation, ultimately culminating in fracture. Notably, the addition of Sn in the Mg alloy exerts a strengthening effect, and consequently, the fracture is primarily observed on the Mg-1Sn-1Ca alloy side, where the strengthening influence of Sn is more pronounced.

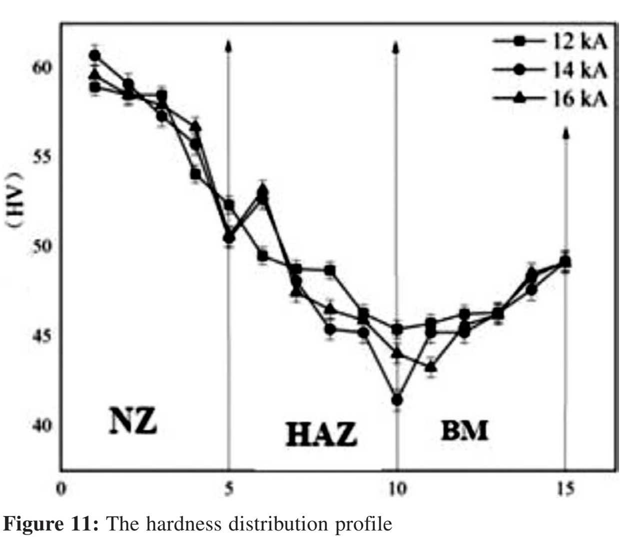

Figure 11: The hardness distribution profile

The examination of the tensile fracture surfaces using Scanning Electron Microscopy (SEM) reveals that when the welding currents are set at 12 kA and 14 kA, the fracture morphology exhibits distinct features, predominantly characterized by brittle fracture. Under these conditions, the fracture surfaces exhibit flow-like patterns and tear ridges, although such brittle fracture features are confined to localized regions. In contrast, most of the fracture area is characterized by ductile fracture, predominantly featuring dimples of varying shapes and sizes, both circular and elliptical. The overall fracture surface displays a typical honeycomb structure.

Under lower welding-current conditions, the fracture surfaces of the welded joints of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys predominantly exhibit a mixed brittle-ductile fracture mode, with ductile fracture being the dominant feature. However, as the welding current increases to 16 kA, a pronounced alteration in the fracture morphology is observed, characterized by an increased density of tear ridges and a significant reduction in the number of dimples. The fracture surface thus primarily displays brittle-fracture characteristics. This phenomenon suggests that, at high welding currents, the increased thermal input leads to a more pronounced thermal gradient within the molten pool, which subsequently accelerates the coarsening of the grains. Grain coarsening results in a deterioration of the material's plasticity, thereby facilitating a transition in the fracture mode towards predominantly brittle fracture. These observations highlight the considerable influence of welding current on the fracture behavior of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys, emphasizing the pivotal role of the welding current in modulating the balance between ductility and brittleness in the material.

In the welding process of magnesium alloys and their joints with dissimilar magnesium alloys, the influence of the welding current on the tensile shear force is very important. As the welding current increases from 12 kA to 16 kA, the tensile shear force of the joint first increases and then decreases. This phenomenon occurs because, at 16 kA, cracks and voids develop in the molten zone, leading to the propagation of existing cracks and voids during tensile shear loading. These pre-existing defects act as crack initiation sites, eliminating the need for external forces to generate new crack sources, which ultimately results in a decrease in the peak load.[20] As shown in **Figure 10**, when the welding current is 14 kA, the grain boundaries in the molten zone are more distinct, and defects are fewer, leading to the maximum tensile shear force of 1001 N for the magnesium-alloy welded joint. Based on this analysis, it can be concluded that for applications requiring high-strength connections, a larger welding current should be selected within a certain range.

3.3 Hardness Analysis of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca Welded Joints

Figure 11 illustrates the hardness values of the welded joint, encompassing the fusion zone, heat-affected zone (HAZ), and base material, as measured using a Vickers microhardness tester. The findings reveal that the fusion zone exhibits the highest hardness, while the heat-affected zone demonstrates the lowest hardness. This can be attributed to the relatively high thermal conductivity of magnesium alloys, which results in heat dissipation and rapid cooling rates. Consequently, the grain structure within the fusion zone is markedly refined, leading to an increase in hardness. In comparison, the hardness of the base material is slightly lower than that of the fusion zone. As the heat input increases, the grain size within the HAZ becomes coarser, which induces a reduction in material hardness.

4 DISSCUSSION

This study systematically examines the factors influencing the performance of magnesium alloys, with particular focus on the integrated effects of welding parameters. Specifically, the research evaluates the Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys to investigate how variations in welding current, which result in differential heat input, influence the characteristics of the welds. The results underscore the crucial role of the welding current in determining the mechanical properties of the welded joints. Initially, a strong correlation between the size of the weld nugget and the mechanical properties of the weld is established. Larger weld nugget sizes facilitate the melting and solidification of a larger volume of metal, thereby improving the welding quality, increasing the weld strength, and enhancing the tensile properties of the workpiece. In addition, the heat input during the welding process is shown to directly affect the formation of the weld surface. Welding currents of 12 kA and 14 kA resulted in satisfactory weld surface formation, whereas a current of 16 kA led to the occurrence of defects such as spattering, porosity, and cracking on the weld surface, which substantially compromised the mechanical properties of the material. Therefore, controlling heat input to avoid excessive levels is critical in ensuring optimal weld surface integrity and maintaining high-quality welds in practical production scenarios. Finally, the heat input during welding is found to have a major impact on the hardness of the welded material. The fusion zone demonstrates the highest hardness, while the heat-affected zone exhibits the lowest hardness. This behavior can be attributed to the impaired heat dissipation resulting from excessive heat input, which promotes grain coarsening and subsequently reduces the material's hardness.

5 CONCLUSIONS

This study presents an investigation into the dissimilar welding of Mg-1Sn-1Ca and Mg-2Sn-0.5Ca magnesium alloys using resistance spot welding under varying welding currents. The phase composition of the alloys was characterized via X-ray diffraction (XRD) and energy-dispersive spectroscopy (EDS) surface scanning. The macroscopic and microscopic morphologies of the welded joints were examined, while the mechanical properties and hardness of the welds were evaluated. The influence of welding current on the microstructure and performance of the welded joints was thoroughly analyzed, leading to the formulation of several conclusions.

(1) In the Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys, both Sn and Ca elements are present, with the Mg_2Ca phase being a prevalent constituent. As the Sn content increases, the proportions of the Mg_2Sn and CaMgSn phases also exhibit a corresponding increase.

(2) The Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys primarily exhibit a mixed fracture mode, with a predominance of ductile fracture, transitioning to brittle fracture under conditions of elevated welding current.

(3) The optimal welding parameter combination for the Mg-1Sn-1Ca and Mg-2Sn-0.5Ca alloys was identified as an electrode pressure of 0.6 kN, a welding time of 0.4 s, and a welding current of 14 kA. Under these conditions, the maximum peak load attained was 1.001 kN, demonstrating the effectiveness of these parameters in achieving superior joint strength.

Acknowledgements

The authors acknowledge the financial support from the Liaoning Province Natural Science Foundation Project of China (2023-MS-321) and the Liaoning Province International Cooperation Project (Project Number: 2023030491-JH2/107).

6 REFERENCES

[1] L. Zhang, Study on the Microstructure and Properties of Resistance Spot Welding in Rare Earth Magnesium Alloys D. Nanchang University, 2022

[2] Y. Wang, Z. Zhang, Defects in resistance spot welded joints of magnesium alloys, J. Journal of Welding, 07 (**2006**) 9–12+113

[3] W. Wang, X. Li, Z. Hou, et al. Study on the microstructure and properties of AZ31 magnesium alloy alternating pulse TIG welding, J. Science & Technology Vision, 36 (**2019**), 72–74

[4] N. Xia, Microstructure Control and Plastic Deformation Behavior of Low-Alloyed Mg-Zn-Zr-(Ca) Series Alloys, D. Jilin University, 2022
[5] D. Zhang, J. Peng, P, Ding, et al. Thoughts on the Development Strategy of the Magnesium Alloy Industry in China, J. World Nonferrous Metals, 7 (**2004**) 5
[6] X. Yang, A brief introduction to the properties of magnesium and its compounds and methods of investigation, J Secondary School Chemistry, 2 (**2013**) 3
[7] C. Gu, G. Chen, L. Mei, et al. Comparative analysis of laser lap welding and resistance spot welding for automotive body parts, J. Hot Working Technology, 40(17), 136-138+142
[8] X. Chen, M. Liu, Z. Shan, et al. Study on the automatic ultrasonic C-scan inspection technology of diffusion welded joints between electrical pure iron and stainless steel, J. Electric Welding Machine, 55 (**2025**) 01, 115–121
[9] L. Zhang, Research on the Strengthening and Toughening of Mg-Gd-Y Magnesium Alloys D. Huazhong University of Science and Technology, 2009
[10] W. H W, Q. Y C, H. Z G. Numerical simulation of intersecting line workpiece welded by arc robot welding, J. Metalurgija, 63 (**2024**) 3–4, 407–409
[11] S. Feng, Application of welding robots in the manufacturing of rail transit equipment, J. Metal Processing (Cold Processing), (S1), 770–772
[12] H. M M E, Nour G E, H. M E, et al. Synthesis, characterization, and Vickers microhardness for (YIG)x/ (Bi, Pb)-2223 superconducting phase, J. Ceramics International, 49 (2023) 13, 22400–22422
[13] X. Yang, Numerical Simulation and Microstructure-Property Study of TTS443 Resistance Spot Welding D .Taiyuan University of Technology, 2016
[14] Awni R. A deep learning-based SEM-ANN analysis of the impact of AI-based audit services on client trust. J. Journal of Applied Accounting Research, 25 (**2024**) 3, 594–622
[15] R M, D M. Metallographic preparation, contrasting, and examination of layers of scale on hot-rolled low-alloy steelsJ. Practical Metallography, 61 (2023) 1, 16–27
[16] T. Wang, W. Jing, J. He, Numerical simulation of the CMT arc additive manufacturing process for magnesium alloysJ. Journal of Tianjin University of Technology, 1–9
[17] S. Jin, Precipitation and Grain Refinement Strengthening of Al-Mg-Si-Cu Alloys for Structural Materials D. South China University of Technology, 2019
[18] P. Liu, E. Zhao, J. Meng et al. On-line measurement of nugget diameter in automatic resistance spot welding based on embedded ultrasound probe, J. Measurement, 2024, 22–61
[19] M. Y. Abbas, I. M. Khan, Efficacious application of data-driven machine learning models for predicting and optimizing the flexural tensile strength of fiber-reinforced concrete, J. Structures, 2024, 64–106
[20] Q. Wu, Microstructure and Mechanical Properties of Resistance Spot Welded Joints of Magnesium Alloy (AZ31B)D. Jilin University, 2008