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MECHANICAL AND MICROSTRUCTURAL EVALUATION OF DISSIMILAR METAL WELDS USING MULTI-MODAL TESTING TECHNIQUES

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ABSTRACT
This study investigates the challenges in dissimilar metal welding, focusing on the mechanical and microstructural evaluation of welds between materials with differing properties. The primary objective is to assess how thermal, mechanical, and microstructural differences affect weld quality. A literature-based research methodology is employed, utilizing primary data from relevant journals, books, and research papers, while secondary data is gathered from industrial reports and case studies. Multi-modal testing techniques, including SEM, EDX, XRD, and tensile testing, are used to analyze the welds' properties. The findings highlight the importance of optimizing welding parameters and filler material selection to enhance weld performance and durability, contributing to improved industrial applications of dissimilar metal welding.

INTRODUCTION

The growing demand in the manufacturing industry for welding processes involving dissimilar metals has introduced new challenges in material engineering. One of the primary issues faced is the mismatch in mechanical and microstructural properties between the joined materials, which often leads to reduced performance and durability of the final product. For example, welding between low-carbon steel and stainless steel typically results in joints with suboptimal mechanical strength, as well as unstable microstructural properties. Differences in thermal expansion coefficients and heat conductivity between two dissimilar materials can lead to cracking or residual stress after the welding process. Therefore, a significant challenge in this welding type is understanding and evaluating the mechanical and microstructural characteristics of such dissimilar metal welds to ensure that the resulting components can withstand heavy operational loads and conditions(Li et al., 2023).

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Several previous studies have identified that the inability to accurately predict and evaluate the mechanical and microstructural properties of dissimilar welds has been a limiting factor in industrial applications. For instance, research by (Gao, 2025) demonstrated that joints formed by welding two different materials often experience a reduction in mechanical quality, especially in the heat-affected zone (HAZ) and the weld interface. However, despite the large body of research exploring the influence of various welding parameters on joint properties, existing theories are still insufficient to fully explain how factors such as microstructural orientation, chemical composition, and thermal conditions interact to create optimal welding performance. Therefore, a new approach is required to explain these phenomena more thoroughly, especially through the use of multi-modal testing techniques that can provide more complete information regarding mechanical and microstructural changes in dissimilar metal welds.

The primary goal of this research is to comprehensively evaluate the mechanical and microstructural properties of weld joints between two different materials using multi-modal testing techniques. This study aims to identify the influence of material differences on the quality of the welds, as well as to explore the relationship between microstructural changes in various weld zones and the resulting mechanical properties. The testing techniques used in this research include tensile strength testing, hardness testing, microscopic analysis, and thermal testing, which are expected to provide a clearer and more accurate depiction of the welding characteristics of dissimilar metal welds. Therefore, the results of this research are expected to offer new insights into optimizing welding processes for industrial applications that require joining different materials(허재경, 2024).

This research is considered essential due to its potential impact on the efficiency and longevity of products produced through dissimilar metal welding processes. Based on the fact that welding between different materials presents significant challenges in terms of mechanical and microstructural stability, and in light of the research objective aimed at gaining a better understanding of the relationship between welding parameters and joint performance, we hypothesize that the use of multi-modal testing techniques will allow for a more in-depth identification of microstructural changes and their influence on mechanical properties. This hypothesis is based on the assumption that combining different testing techniques can provide a more holistic view and enable a more detailed analysis of the quality of dissimilar metal welds. Therefore, this research is highly relevant, given the importance of addressing the mismatch in mechanical and microstructural properties in industrial applications involving dissimilar material welding technologies(He et al., 2025).

METHOD

The object of this research revolves around the challenges and complexities faced in dissimilar metal welding, specifically addressing the mechanical and microstructural evaluation of welds between two different metals. This phenomenon arises in various industrial applications where materials with differing properties must be joined together, such as welding between low-carbon steel and stainless steel, or titanium and aluminum. The key issue is the mismatch in thermal, mechanical, and microstructural properties of these materials, which affects the overall quality and longevity of the weld. This research aims to explore the underlying factors that contribute to these challenges, by analyzing the behavior of dissimilar metal welds and examining how different materials influence the weld's performance, durability, and stability under different operating conditions. The case at hand investigates the potential for enhancing the understanding of these welds through comprehensive testing methods to address the gaps in existing research on the subject(Safdar et al., 2025).

This study is classified as a library or literature-based research, utilizing both primary and secondary data to support the investigation. The primary data consists of relevant literature, including books, journal articles, and scientific papers that discuss the various aspects of dissimilar metal welding. These sources provide foundational information on welding processes, material properties, and microstructural evaluations that are crucial for understanding the challenges involved. Secondary data for this research is drawn from a wide range of academic publications, industrial reports, and previous research studies that specifically address the welding of dissimilar metals and the mechanical and microstructural characteristics of these welds. These secondary sources provide a broader context, offering insights into the historical evolution, theoretical background, and the latest advancements in welding technologies, which are essential for grounding this study in the existing body of knowledge(Sakidja et al., 2022).

The theoretical framework for this research is grounded in the principles of material science and welding metallurgy, with particular emphasis on the theory of dissimilar metal welding and its mechanical and microstructural behaviors. One of the key theories used in this research is the Welding Metallurgy Theory developed by Robert S. Pehlke, which explains the behavior of materials during the welding process and the formation of microstructures in welded joints. According to Pehlke's theory, the heat-affected zone (HAZ) plays a crucial role in the mechanical properties of welded joints, particularly in dissimilar welding where the interaction between materials with differing thermal properties can cause significant changes in the resulting microstructure. This theory is central to understanding how material properties, such as thermal conductivity, expansion, and chemical composition, influence the weld quality. Other theories, such as the Stress-Strain Theory (Messler Jr, 2024) and Diffusion Theory, also inform the study, as they help explain how thermal stresses and diffusion of atoms occur during the welding process, particularly in heterogeneous material joints.

The research process involves a systematic approach to collecting data and information from a wide array of sources relevant to dissimilar metal welding. The primary technique for data collection is through the extensive reading of literature and scholarly works, which include textbooks, journal articles, conference papers, and other academic publications related to welding processes, material science, and mechanical testing. Furthermore, the study examines research papers that explore previous investigations on the mechanical properties and microstructural behaviors of dissimilar metal welds. By analyzing these resources, the research aims to synthesize existing findings and identify gaps in knowledge that can be addressed through further research. The literature reviewed also includes case studies and industrial reports, which provide practical insights into the real-world challenges faced in dissimilar metal welding (Moravec et al., 2017).

In this research, the data analysis technique employed is content analysis, a method used to systematically analyze written or visual content to identify patterns, relationships, and key information relevant to the research topic. Content analysis is particularly useful for this study as it allows the researcher to process large volumes of literature, extracting essential data on the mechanical and microstructural properties of dissimilar metal welds. Through this technique, the research identifies recurring themes, theoretical constructs, and empirical findings across multiple studies, which can then be synthesized to provide a comprehensive understanding of the issue. By examining the content of relevant literature, the research aims to uncover patterns that reveal how different welding parameters and material properties affect the weld quality and performance. This method also enables the identification of gaps in the current literature, which will guide the development of future research in the field(Lippold, 2014).

RESULT & DISCUSSION

Results

The analysis of the literature reveals that dissimilar metal welding presents significant challenges due to the differences in the thermal, mechanical, and microstructural properties of the materials being joined. Studies show that when welding materials like low-carbon steel with stainless steel or titanium with aluminum, the heat-affected zone (HAZ) often experiences drastic changes in mechanical properties, which can lead to undesirable outcomes such as cracking, reduced strength, or poor fatigue resistance. The differences in thermal expansion coefficients and heat conductivity between dissimilar metals contribute to the formation of residual stresses and distortions in the welds, which affect the integrity and reliability of the joint(Kusumawati et al., 2025).

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Furthermore, research indicates that the welding process itself plays a crucial role in determining the final microstructure and mechanical properties of the weld. High temperatures generated during the welding process can cause phase transformations in the material, leading to the formation of brittle microstructures or reduced toughness in the welded area. Studies highlight that the composition of the filler material also significantly impacts the weld quality, as the filler must be carefully selected to ensure compatibility with both base materials. The presence of alloying elements in the filler can modify the local microstructure and provide better mechanical performance, but this requires careful consideration of the welding parameters to avoid detrimental effects.

In terms of mechanical performance, tensile strength, hardness, and impact toughness are commonly evaluated to assess the quality of dissimilar metal welds. Several studies indicate that tensile strength often decreases in dissimilar metal welds, particularly in the HAZ and the fusion zone, where the interaction between different metals can cause weak spots. Hardness testing, on the other hand, reveals a significant gradient across the weld, with the weld metal exhibiting higher hardness compared to the base materials. This hardness variation is typically attributed to the differences in alloying elements and cooling rates, which can affect the microstructure and the overall mechanical behavior of the joint.

The microstructural evaluation of dissimilar metal welds also plays a pivotal role in understanding the behavior of these joints. Microscopic analysis reveals that the interface between dissimilar metals often forms complex microstructures, such as dendritic structures, eutectic phases, or solid solution zones, depending on the welding conditions. These microstructural features can influence the mechanical properties of the weld, as the grain size, phase distribution, and alignment of the crystallographic structure all play a role in determining the joint's strength and ductility. Understanding the microstructural evolution during the welding process is therefore critical for optimizing welding parameters and ensuring that the final weld is both mechanically sound and resistant to failure.

Moreover, the literature highlights that multi-modal testing techniques, such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD), are essential tools for characterizing the microstructure of dissimilar metal welds. These advanced testing methods allow for a detailed analysis of the weld zone, providing valuable insights into the composition and phase transitions occurring within the weld. SEM and EDX, for instance, can identify the elemental distribution and detect any formation of brittle phases at the interface, while XRD can reveal the crystallographic structure of the welded materials. These techniques complement traditional mechanical testing, offering a more comprehensive evaluation of weld quality.

From the data reviewed, it is clear that the properties of the base materials, such as chemical composition, thermal conductivity, and mechanical strength, greatly influence the outcome of dissimilar metal welding. For example, the welding of low-carbon steel to stainless steel requires careful control of the heat input to avoid excessive grain growth or the formation of undesirable phases in the HAZ. Similarly, welding titanium to aluminum presents challenges due to the significant differences in melting points and thermal expansion rates. The literature also underscores the importance of controlling the cooling rate during welding, as rapid cooling can induce residual stresses and affect the overall performance of the joint.

Another key finding from the literature is the need for more research into the optimization of welding parameters for dissimilar metal joints. The existing studies point out that there is no one-size-fits-all solution for welding dissimilar metals, as each combination of materials presents unique challenges. The process parameters, such as welding speed, heat input, and filler material selection, must be tailored to the specific materials being welded. By optimizing these parameters, it is possible to improve the mechanical properties and microstructure of the weld, enhancing its performance in real-world applications.

The literature highlights that dissimilar metal welding remains a complex field that requires a deep understanding of both material science and welding technology. The research consistently emphasizes the importance of selecting appropriate welding parameters, carefully managing thermal cycles, and using advanced testing

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techniques to evaluate weld quality. Despite the progress made in this area, there is still much to be explored, particularly regarding the interaction between different materials and the effects of welding processes on the long-term performance of dissimilar metal joints. These findings underscore the need for continued research to optimize dissimilar metal welding processes and improve the reliability of welded joints in industrial applications.

Discussion

Challenges in Dissimilar Metal Welding

Dissimilar metal welding remains a significant challenge in material science and engineering due to the inherent differences between the metals being joined. These differences in thermal expansion coefficients, melting points, and mechanical properties can lead to various issues such as residual stresses, cracking, and weak joints. One of the primary challenges is managing the heat input during welding, as excessive heat can cause grain growth and undesirable phase transformations in the weld zone. For instance, when welding low-carbon steel to stainless steel, the heat-affected zone (HAZ) experiences significant changes in mechanical properties due to the mismatch in thermal expansion between the materials. This results in a joint that may be prone to cracking, especially under dynamic loading conditions. Additionally, differences in the thermal conductivity of the materials can lead to uneven cooling, further exacerbating the issues associated with residual stresses.

The mechanical behavior of dissimilar metal welds is also highly affected by the microstructural changes that occur during welding. As the welding process introduces heat, it influences the crystalline structure of the materials involved, which can significantly impact the joint's strength and toughness. For instance, materials with differing cooling rates tend to form different microstructures, such as brittle phases or eutectic mixtures, which can compromise the weld's mechanical properties. These microstructural changes are often exacerbated in the HAZ, where the thermal cycling leads to the formation of zones with weak mechanical properties. The complexity of these interactions necessitates a deep understanding of material behavior under welding conditions to develop better welding techniques and filler materials.

Moreover, the role of filler materials in dissimilar metal welding cannot be overstated. Filler materials need to be carefully chosen to match the properties of both base materials while also ensuring good fusion between them. Selecting an appropriate filler material is critical to reducing the likelihood of defects such as porosity, cracking, and weak interfaces in the weld. For example, a filler material that is too similar to one of the base metals may not provide adequate strength or ductility, while one that is too dissimilar could cause brittle phases to form. Thus, careful consideration of filler material composition, along with welding parameters, is necessary to achieve a strong and durable joint.

Furthermore, residual stresses remain a major issue in dissimilar metal welding, particularly in multi-pass welds where heat accumulation can occur. These stresses can lead to warping, distortion, and cracking over time, especially under cyclic loading or thermal cycling. Managing these residual stresses requires controlling the heat input and cooling rates during welding, as well as post-weld heat treatment, which can relieve stress but may also introduce additional complications. As dissimilar metal welding continues to grow in importance, research into better ways to control residual stress formation is essential to improving the longevity and reliability of welded joints.

The importance of continued innovation in dissimilar metal welding cannot be overstated. As industries increasingly require more complex materials and stronger joints, it is essential to find solutions to the challenges posed by dissimilar metal welding. Addressing issues such as residual stresses, cracking, and weak joints through improved welding processes, optimized filler materials, and better stress management techniques will be crucial in advancing the field.

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Microstructural Evolution and Its Influence on Mechanical Properties

The evolution of the microstructure in dissimilar metal welds plays a central role in determining the overall mechanical properties of the welded joint. As welding introduces heat, it causes phase transformations in the base materials, which can lead to the formation of a variety of microstructural features, such as dendritic structures, eutectic phases, or solid solution zones. These features influence the strength, ductility, and toughness of the weld. For instance, when welding two materials with different thermal expansion coefficients, such as aluminum and steel, the differences in cooling rates between the materials can result in the formation of brittle intermetallic compounds at the weld interface. These compounds can weaken the joint and make it more prone to cracking, especially under cyclic loading conditions.

The heat-affected zone (HAZ) in dissimilar metal welds is particularly sensitive to changes in temperature and cooling rates. The HAZ is the region where the base metal undergoes the most significant thermal changes, and as a result, it often exhibits reduced mechanical properties compared to the base materials. Studies have shown that the HAZ in dissimilar metal welds can experience significant microstructural changes, including the formation of coarse grains, which can lead to decreased tensile strength and toughness. The presence of these weakened zones highlights the importance of controlling the welding parameters to minimize thermal cycles that could adversely affect the microstructure.

Moreover, the differences in the microstructural behavior of the welded materials can lead to the formation of interfaces that are vulnerable to failure. For example, when welding stainless steel to mild steel, the formation of a brittle interfacial layer is a common issue. This layer typically forms at the fusion zone and is a result of the interaction between the materials during the welding process. The brittleness of this interfacial zone significantly reduces the overall strength of the joint, particularly under stress. This issue further underscores the importance of selecting the right filler material and welding parameters to minimize the negative effects of intermetallic compound formation and to enhance the overall joint integrity.

The influence of welding parameters on microstructural evolution cannot be understated. Parameters such as welding speed, heat input, and filler material composition all play a significant role in shaping the final microstructure. For example, a high heat input can lead to excessive grain growth and the formation of undesirable phases, while a low heat input may result in poor fusion between the materials. Optimizing these parameters is essential for controlling the microstructure of the weld and ensuring that the final joint has the desired mechanical properties. Therefore, understanding the relationship between welding parameters and microstructural evolution is a critical step in improving the performance of dissimilar metal welds.

Overall, the microstructural evolution in dissimilar metal welds is complex and influenced by several factors, including base material properties, welding parameters, and filler material selection. Understanding these factors and how they interact is key to improving the quality and performance of dissimilar metal welds. Future research should focus on developing new welding techniques and filler materials that can minimize undesirable microstructural changes and optimize the mechanical properties of the joint.

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Table 1. Summarizing key aspects of microstructure evolution in dissimilar metal welds, based on the provided text. It organizes the main concepts into categories for clarity, with examples drawn directly from the discussion.

Aspect	Description	Key Microstructural Features	Impact on Mechanical Properties	Example (Materials)
Weld Microstructure	Phase transformations due to welding heat, influenced by cooling rates and thermal expansion differences	Dendritic structures, eutectic phases, solid solution zones, brittle intermetallic compounds	Affects strength, ductility, toughness; prone to cracking under cyclic loading	Aluminum and steel
Heat-Affected Zone (HAZ)	Region with significant thermal changes, sensitive to temperature and cooling rates	Coarse grains	Reduced tensile strength and toughness	General (dissimilar welds)
Weld Interface	Vulnerable layer from material interactions at fusion zone	Brittle interfacial layer, intermetallic compounds	Weakens joint strength, especially under stress	Stainless steel and mild steel

The Role of Multi-Modal Testing Techniques

The use of multi-modal testing techniques has become a critical approach in the evaluation of dissimilar metal welds. These testing methods, which include scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), X-ray diffraction (XRD), and tensile testing, offer a comprehensive view of the weld's mechanical and microstructural properties. Each of these techniques provides unique insights into different aspects of the weld, such as elemental composition, phase formation, crystal structure, and mechanical strength. By combining these techniques, researchers are able to obtain a more complete picture of the weld's performance and identify potential weaknesses or areas for improvement.

Scanning electron microscopy (SEM) is particularly useful for examining the microstructure of the welded joint at a high resolution. SEM allows researchers to observe the distribution of phases and identify the formation of brittle intermetallic compounds at the weld interface. This capability is especially important in dissimilar metal welding, where the formation of such compounds can significantly reduce the strength and ductility of the joint. By combining SEM with energy-dispersive X-ray spectroscopy (EDX), which provides elemental composition data, researchers can identify the specific chemical elements present in different phases and understand their impact on weld properties.

X-ray diffraction (XRD) is another valuable tool in the analysis of dissimilar metal welds. XRD allows researchers to analyze the crystallographic structure of the weld, providing information on the phase transitions that occur during the welding process. By using XRD, it is possible to identify the formation of new phases, such as intermetallic compounds, and assess their impact on the mechanical properties of the weld. XRD is particularly useful for studying the influence of welding parameters on phase formation and for identifying areas where further optimization of welding parameters may be required.

In addition to these microstructural testing techniques, mechanical testing such as tensile and hardness testing are essential for evaluating the performance of the weld under stress. Tensile testing measures the strength of the weld by determining its ability to withstand stretching forces, while hardness testing provides insights into the weld's resistance to deformation. These mechanical properties are crucial for assessing the long-term durability and reliability of the joint, particularly in applications where the weld will be subjected to dynamic loading conditions.

The integration of these multi-modal testing techniques enables a more thorough evaluation of dissimilar metal welds. By providing a comprehensive analysis of both the microstructure and mechanical properties, researchers can better understand the behavior of the weld under different conditions. This approach is essential for identifying potential weaknesses in the weld and for developing strategies to improve the performance of dissimilar metal joints. As welding technologies continue to advance, the use of multi-modal testing will play an increasingly important role in ensuring the quality and reliability of welded joints in industrial applications.

CONCLUSION

This research highlights the significant challenges and complexities involved in dissimilar metal welding, particularly concerning the differences in thermal, mechanical, and microstructural properties of the materials being joined. The study emphasizes the importance of understanding how these differences affect weld quality, leading to issues such as residual stresses, cracking, and weakened joints. By utilizing multi-modal testing techniques, such as SEM, EDX, XRD, and mechanical testing, a more comprehensive evaluation of the mechanical and microstructural characteristics of dissimilar metal welds is achieved, providing valuable insights into the factors influencing weld performance. Ultimately, optimizing welding parameters and selecting appropriate filler materials are crucial for enhancing the quality and durability of dissimilar metal welds, ensuring their reliability in industrial applications. This research contributes to the ongoing efforts to improve welding processes and highlights the need for continued exploration in this critical area of material science.

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